2009-2010 Research and Education Highlights from NNIN

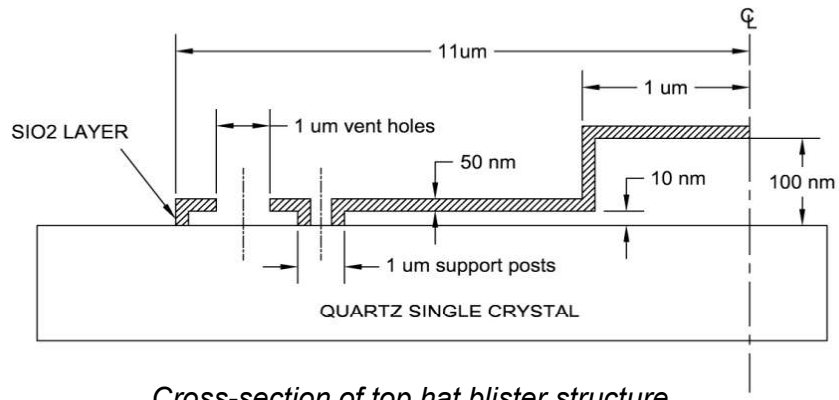
October, 2010

Table of Contents

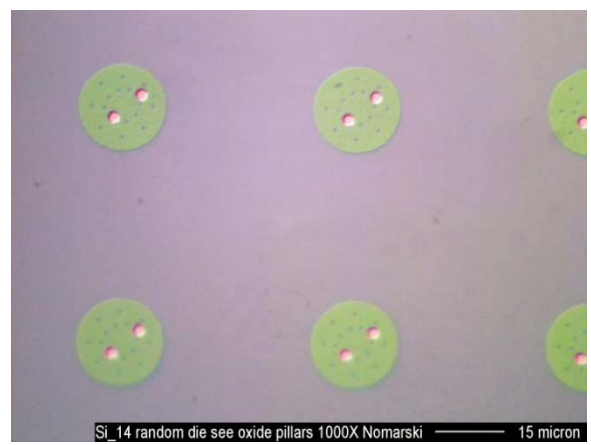
Arizona State University

Bose-Einstein Condensation Of Positronium

First Point Scientific, Inc. (FPSI), is developing target structures that will be irradiated with a mono-energetic positron beam and will facilitate the formation of positronium and its condensation into the Bose-Einstein state. The schematic shows a cross section of the cylindrically symmetric hat-shaped silica (SiO_2) structure formed on a quartz single crystal wafer. Proof-of-principle targets, without the central section raised, have been successfully fabricated at ASU NanoFab using oxidized poly-silicon and XeF_2 etching. These structures are now under test in the FPSI positron beam facility in California.



Cross-section of top hat blister structure



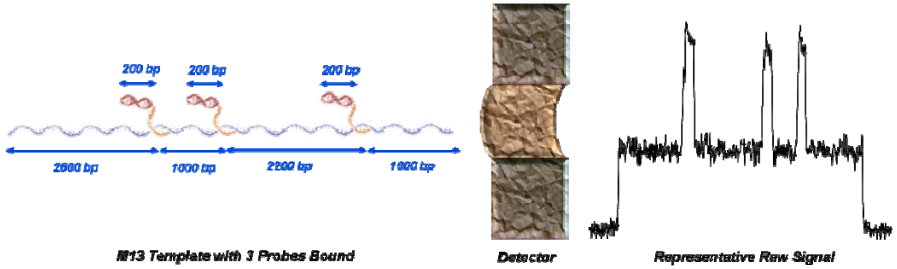
Nomarski image of prototype test structure

John R. Bayless, First Point Scientific, Inc.

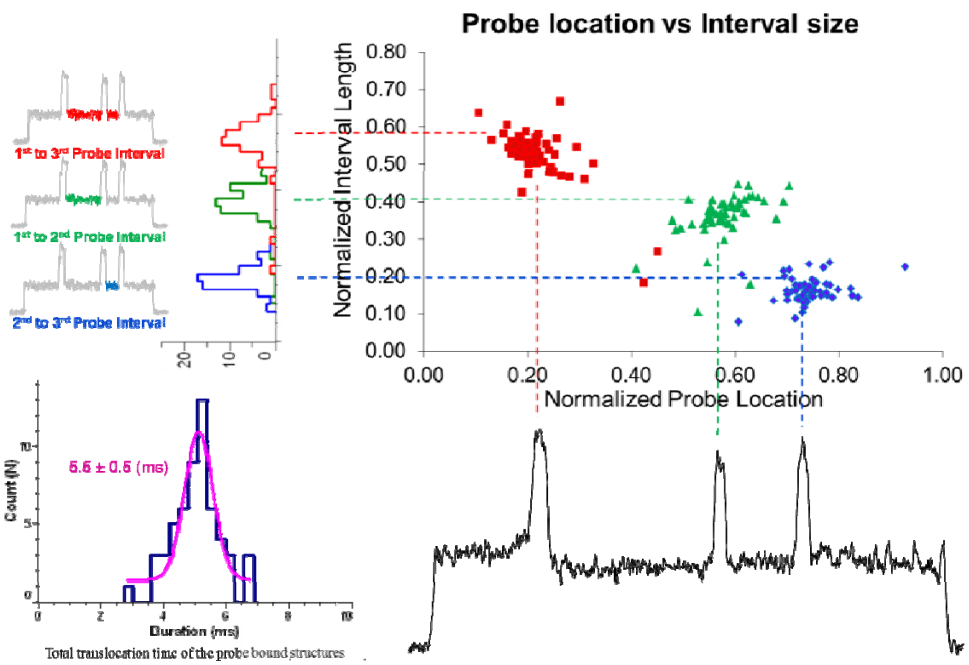
Work performed at ASU NanoFab

Translation DNA Sequencing

NABsys aims to make whole-genome DNA sequencing fast, inexpensive, and accurate enough to be used in clinical care. Our approach builds on existing solid-state technologies to create a whole-genome sequencing technology that employs electronic detection, does not depend on a polymerase, and directly obtains DNA sequence information over hundreds of thousands of bases. ASU NanoFab fabricated components of this system include fluidic devices for DNA dynamics experimentation and optimization.



Summary of DNA translocation methodology



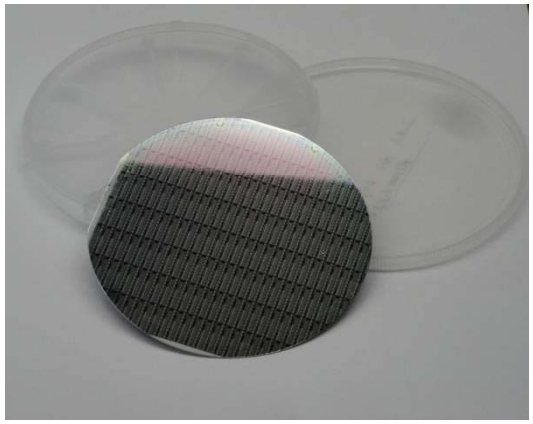
Statistical reproducibility of translocation experiments

Leo Petrossian, NABsys Inc

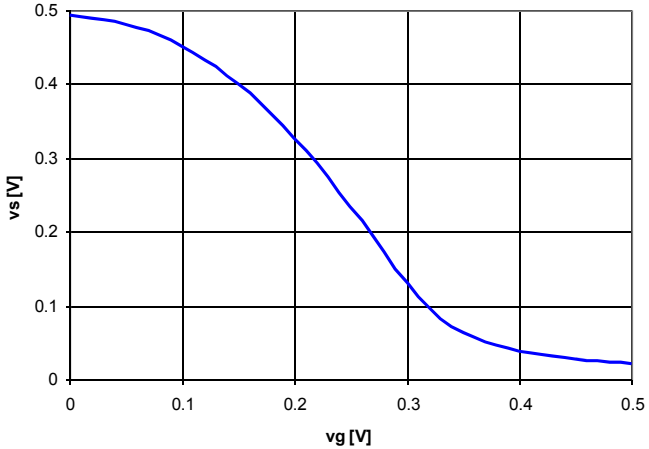
Work performed at ASU NanoFab

Functionalized CMOS-WMJ Technology

We are investigating a new approach to meet the demands for speed and density in modern IC circuits. Our novel approach is based on increasing the functions of an individual MOSFET device rather than shrinking its dimensions. This will be possible by using a new CMOS technology for the manufacturing of high-density integrated circuits invented by the University of Padova, Italy. Such technology, said CMOS With Metal Junction (WMJ), utilizes field effect devices that perform the functions of more traditional FET transistors. This property allows tremendous advantages in the realization of Static Random Access Memory (SRAM) cells and combinatorial logic circuits. The first wafers containing these new prototype devices have been fabricated at ASU NanoFab.



Wafer containing the first prototype structures of the new technology.



Transfer characteristic of a single WMJ device: a single device behaves as a conventional inverter.

Fabio Alessio Marino, UNIPD, Padova, Italy

Work performed at ASU NanoFab

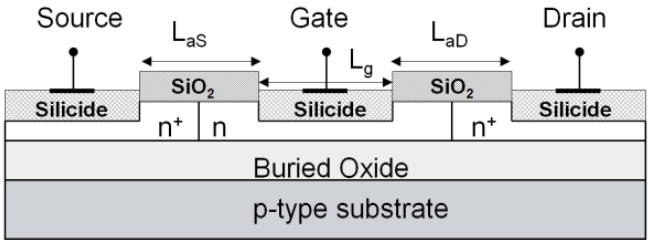
RF Characterization of High Breakdown Voltage SOI MESFETs

Silicon-on-insulator (SOI) MESFETs fabricated at a commercial 150 nm CMOS foundry have been characterized for applications at X-band frequencies. Although devices with gate lengths as short as 150 nm have been demonstrated, optimum performance is achieved with gate lengths in the range 250-350 nm due to short channel effects.

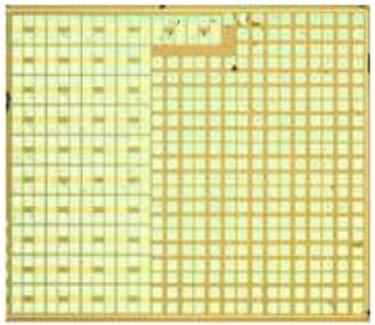
The MESFET architecture is considerably more robust than highly scaled CMOS. A device with L_g=400nm and L_{aD}=1mm has a breakdown voltage >11V, greatly exceeding the 1.8V of the CMOS devices. Such a device has a peak f_T of ~ 19 GHz. Design trade-offs between breakdown voltage and RF performance will allow high linearity RF power applications at X-band frequencies.

Seth Wilk and William Lepkowski, SJT Micropower Inc.

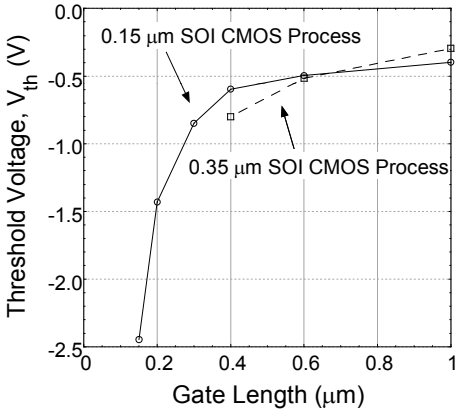
Work performed at ASU NanoFab



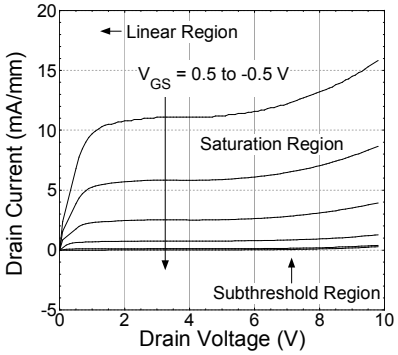
Cross-section of the prototype MESFETs



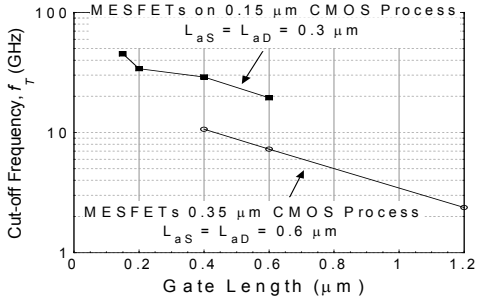
SOI MESFET test structures



Short channel effects



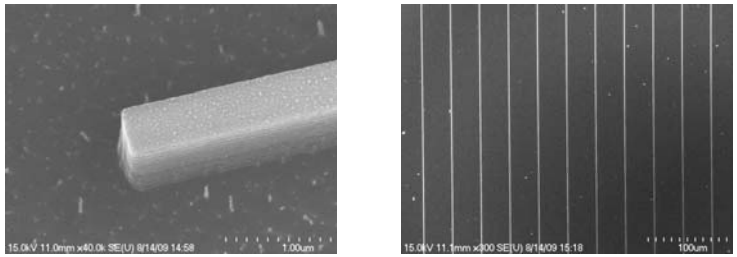
MESFET exceeds the 1.8V breakdown of the CMOS



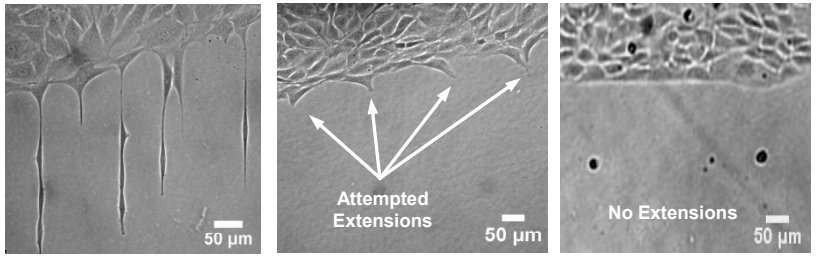
Peak fT exceeds that of earlier technologies

Cell-Nano-Environment Interactions

The purpose of the Cell-Nano-Environment Interactions project is to study cellular interfaces with nano-scale stimuli similar to what occurs in the body. The patterns created by ASU NanoFab served as 3D master surfaces for creating PDMS molds used to chemically pattern surfaces via shielded plasma exposure. The chemical patterns have enabled insight on cellular decision making and interactions with nano-scale stimuli for understanding processes such as cell migration and axon growth. The millimeters long nano-scale lines were critical to these investigations as the nano-sized lines had to be patterned over large areas and conventional photolithography could not produce dimensions at relevant biological scales.

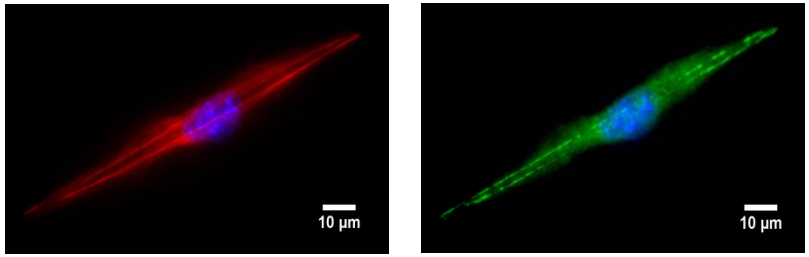


Close-up and wide view of 3D structures used to create PDMS molds



2 µm wide lines | 500 nm wide lines | 100 nm wide lines

Cell interaction with progressively smaller patterns. Below a certain size (~500 nm), the cell machinery can no longer successfully sense the pattern and cells do not extend membrane segments



Actin/cytoskeleton expression (red) and vinculin/focal adhesion (green) of fibroblasts grown on patterned surfaces

Michael Junkin, and Pak Kin Wong,
Systematic Bioengineering Laboratory
University of Arizona

Work performed at ASU NanoFab

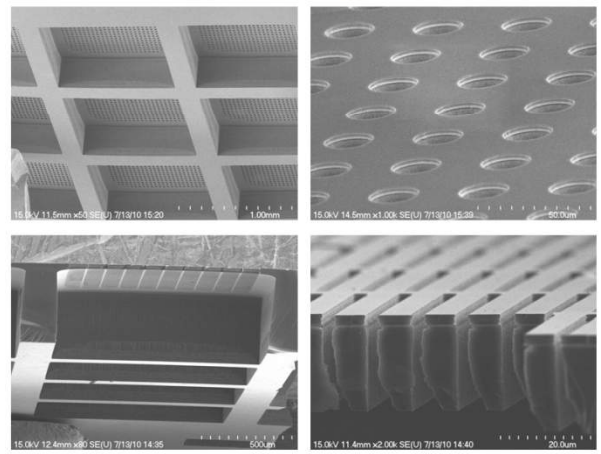
Microchip Ionizer

The objective of the Microchip Ionizer Project is to create an efficient, low power, low form factor ion source for mass spectrometry and ion pump applications. The device is fabricated using SOI wafer and consists of a cathode electrode and an anode electrode separated by a sub-micron gap. Application of voltage, either AC or DC, between the electrodes generates high electric field that ionizes gas molecules that passes through the electrode apertures. The first generation test structures are currently under electrical evaluation.

Stanley Pau
College of Optical Sciences
University of Arizona

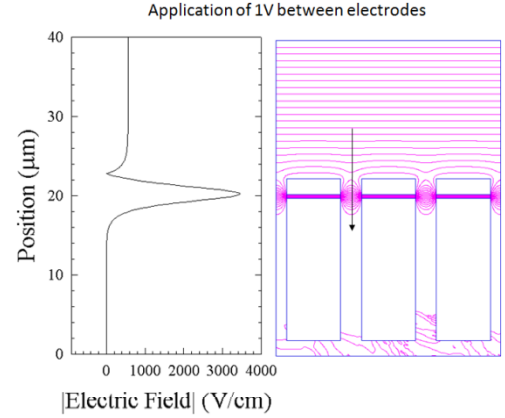
Work performed at ASU NanoFab

SEM of ionizers, after dicing



FESEM of ICP etched front and back-side SOI

Application of 1V between electrodes

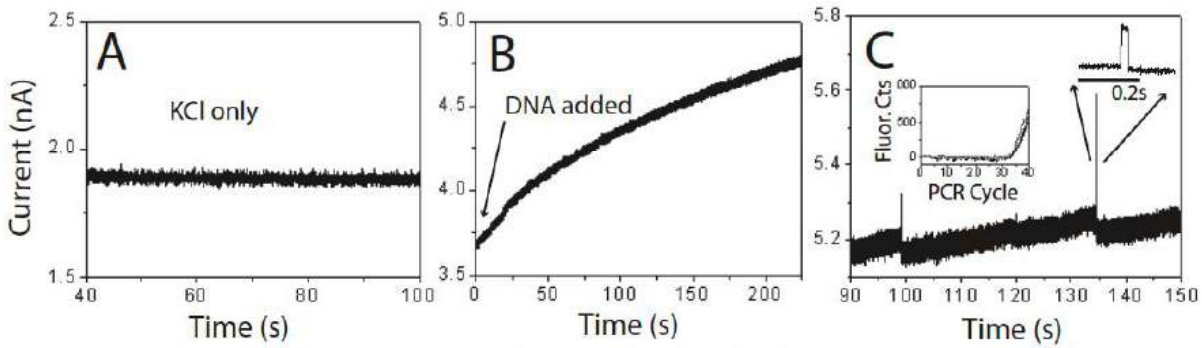


Schematic of soft ionizer response

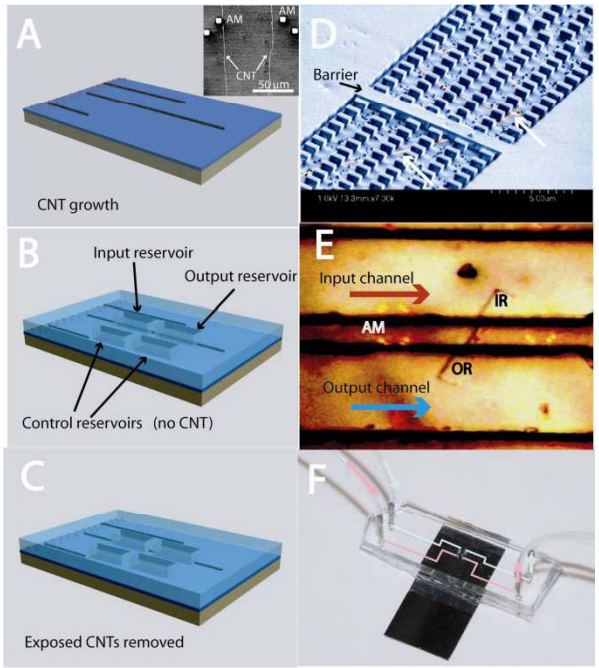
Single Walled Carbon Nanotubes as Nanopores

We have demonstrated that single walled nanotubes can be used as nanopores without the need for nanofabrication like drilling. Our approach offers new routes to controlling translocation of molecules such as DNA. The measurement electrode and nanopore are combined to provide new ways to sequence DNA.

Liu et al. Science 327 64 (2010)



Huge Ion Current Spikes Signal Translocation of DNA



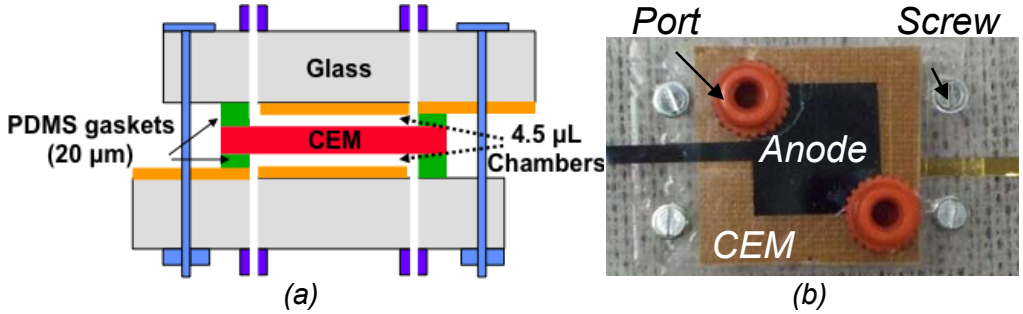
Processing steps used to integrate the single walled CNT with the microfluidic delivery system.

S. M. Lindsay et al. Columbia University, Arizona State University and Oak Ridge National Laboratory

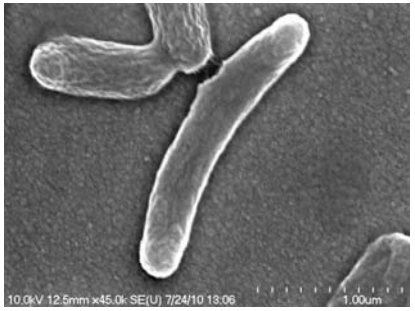
Device fabrication performed in part using the ASU NanoFab

MEMS-based Microbial Fuel Cell

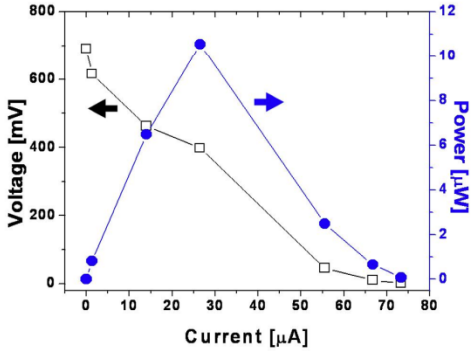
The purpose of the MEMS-base microbial fuel cell project is to explore a potential of a environmentally-friendly micro-sized power source. The micro-device, fabricated at ASU Nanofab, is equipped with micro-litter (4.5 µL) sized chambers defined by 20-µm-thick photodefinable PDMS. Inside the micro-chamber, *Geobacteraceae*-enriched mixed bacterial culture produces electrons by consuming acetate. Such bacteria are often called anode-respiring-bacteria (ARB), which respirate at the anode. The MEMS-based fuel cell harvests the electrons to power loads; ie. small electronics. The fuel cell produces 2.3 mW/cm^3 volumetric power density, aiming for small-size power source applications.



Schematic of MEMS-based microbial fuel cell; (a) cross section shows cation exchange membrane (CEM) sandwiched by photodefinable PDMS gaskets and glass slides and (b) top view of the fabricated MEMS device



SEM of Geobator on the anode (Au)



Polarization curve (black square) and power output (blue circle) measured as a function of current

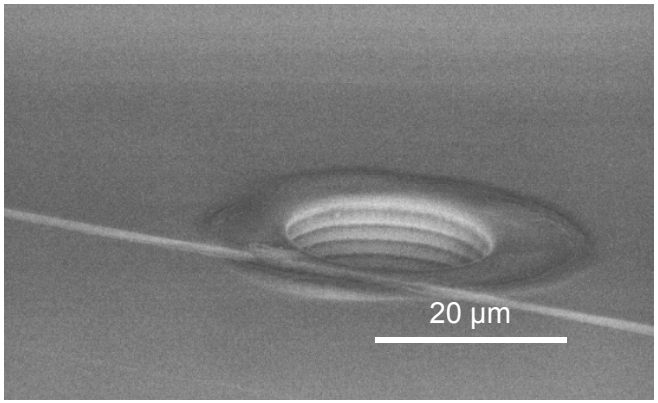
Junseok Chae and Bruce Rittmann
Arizona State University

Work performed at ASU Nanofab

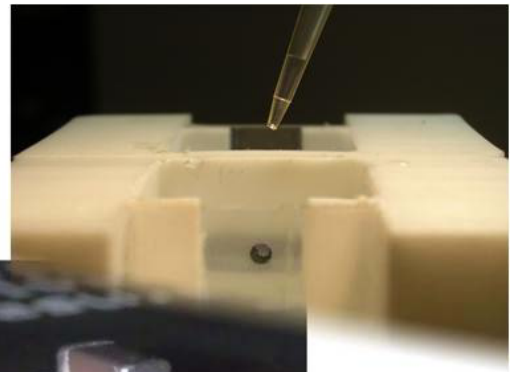
Integrated Silicon Ion Channel Screening Platform

Ion channels are critical for vital functions of a wide variety of organisms. However, some of these channels, in particular viral ion channels have not been studied in detail, although this would be crucial for being able to develop new drugs or vaccine.

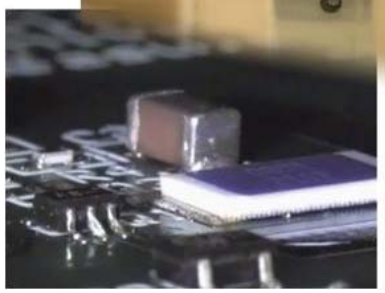
We are developing a fast and reliable platform to conduct ion channel screening studies. By employing a micro-fabricated silicon chip that acts as the host for the lipid bilayer membrane the bilayer capacitance will be reduced, enabling signal recording at an increased bandwidth while maintaining a low noise. The amplification electronics developed in our group reduces the cost of a traditional setup and enables pursuit of a multi-channel approach.



Scanning electron micrograph of a 15 µm pore patterned via dry reactive ion etching that has been oxidized and coated with a polytetrafluoroethylene film deposited via plasma-chemical vapor deposition



Silicon micropore chip mounted in a Teflon holder

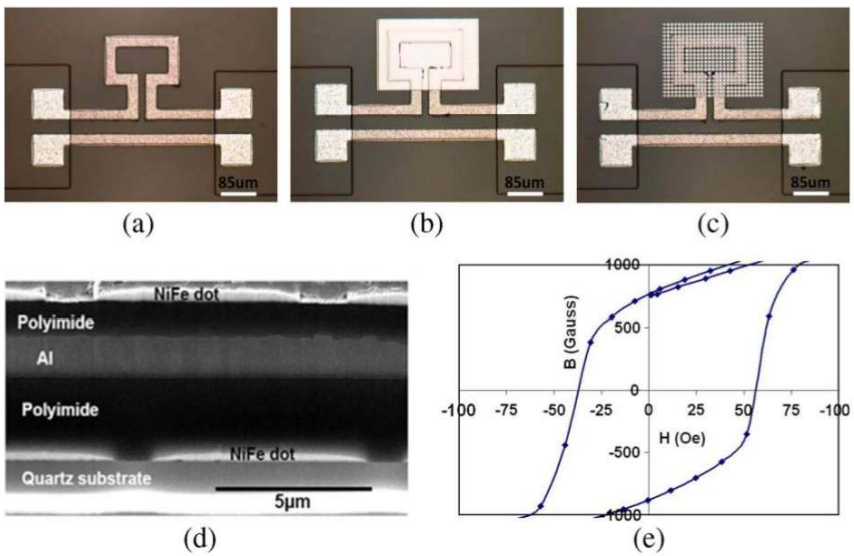


Amplifier electronics developed and constructed at the Center for Solid State Electronics Reseach at ASU

Michael Goryll and Nipun Chaplot, ASU

Work performed at Arizona State University, Center for Solid State Electronics Research

Improved Frequency Response for On-Chip Inductor

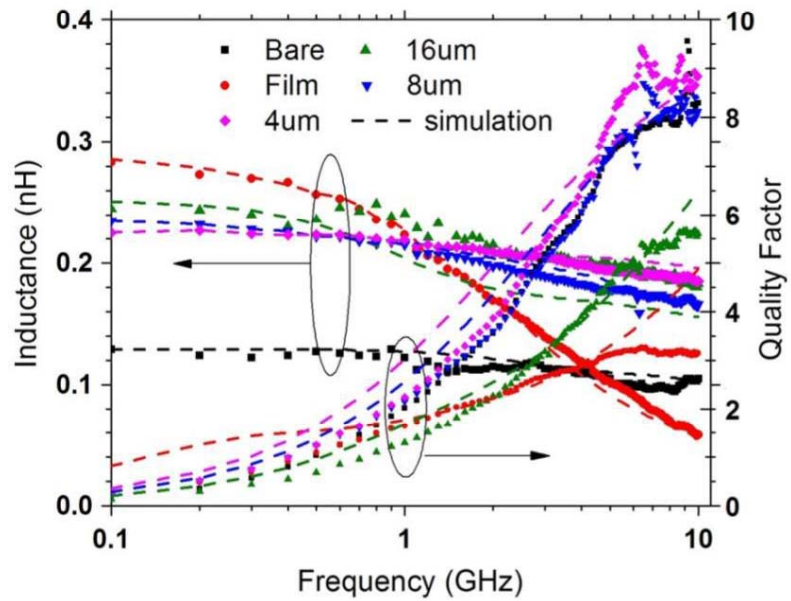


'Improved Frequency Response of On-Chip Inductors With Patterned Magnetic Dots',
IEEE Electron Device Lett. 31, 207 (2010).

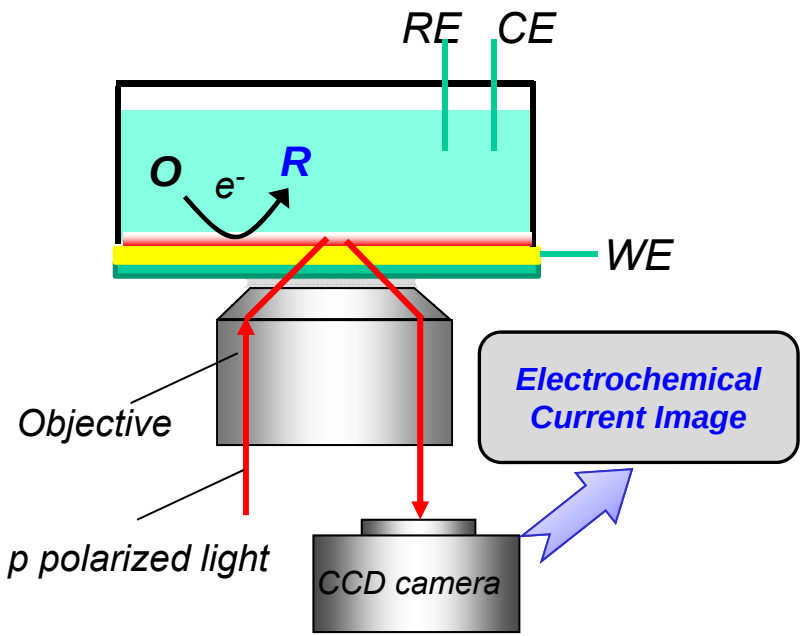
Wei Xu, Saurabh Sinha, Feng Pan, Tawab Dastagir, Yu Cao, and Hongbin Yu, Arizona State University

Work performed at ASU NanoFab

Single-turn spiral inductors with magnetic material to enhance inductance are fabricated. Using double-layered Permalloy dots above and below the inductor metal, inductance improves and remains constant beyond 10 GHz with a Q factor around 11 and a peak frequency around 9 GHz. By employing single-turn small-sized inductors, the self-resonance frequency of the inductors is shifted to very high frequencies. It is illustrated that the superior frequency response is mainly attributed to the significant reduction in mutual inductive coupling between a magnetic layer and inductor metal wires.

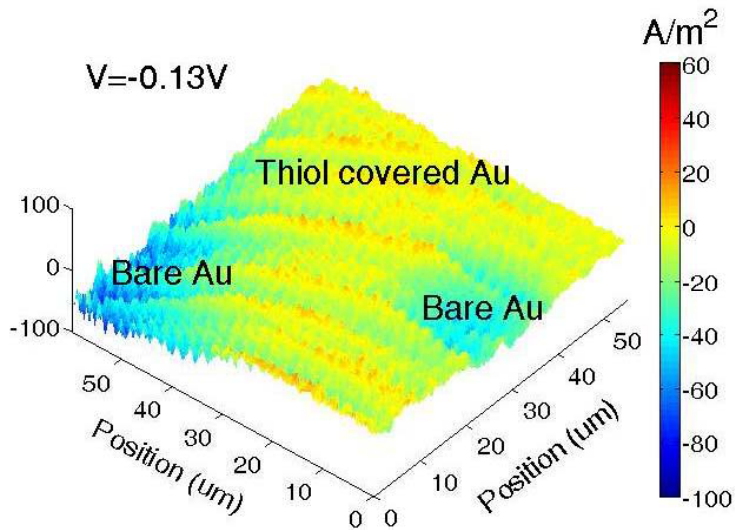


Plasmonic Imaging of Electrochemical Current



*Shan, Patel, Wang, Iglesias and Tao, Science, **2010***

We demonstrated an electrochemical microscopy technique based on the detection of variations in local electrochemical current from optical signals arising from surface plasmon resonance. It enables local electrochemical measurements (such as voltammetry and amperometry) with high spatial resolution and sensitivity, because the signal varies with current density rather than current. The imaging technique is noninvasive, scanning-free, and fast, and it constitutes a powerful tool for studying heterogeneous surface reactions and for analyzing trace chemicals.



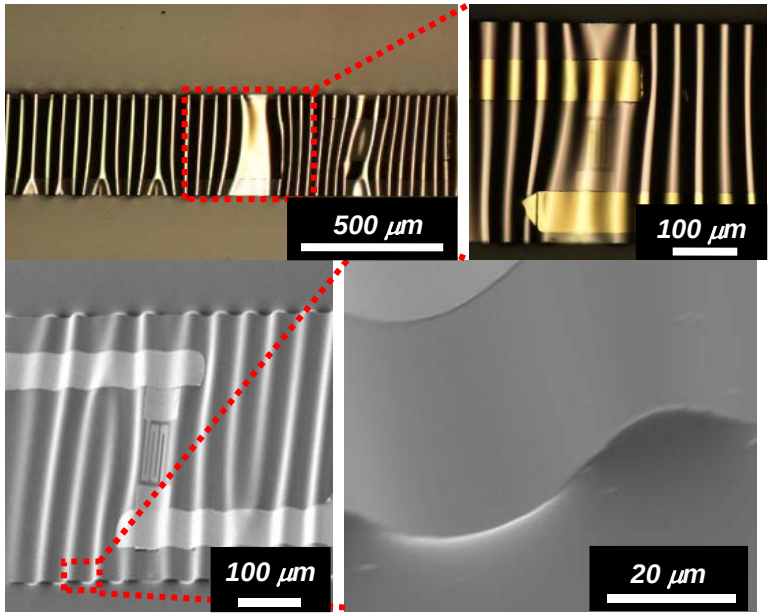
Electrochemical current imaging of a Au surface covered with self-assembled monolayer.

N.J. Tao et al. Arizona State University
Work performed at ASU NanoFab

Flexible and Stretchable Sensors

Flexible and Stretchable electronics and sensors have been attracting significant attention due to their unique characteristics and wide applications. Our research demonstrates universal manufacture technologies for these 3D devices.

1) Thin film transferring fabrication technology for fully flexible and stretchable temperature sensor on an elastomeric substrate.
2) Laser dynamic forming of thin film devices on 3D surface.

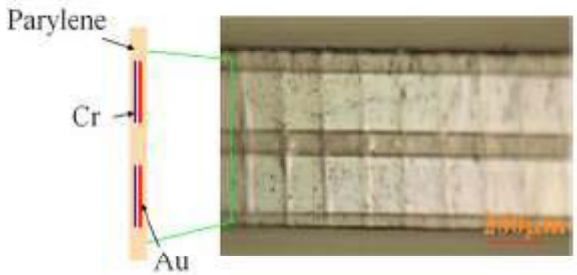


Optical and SEM picture of flexible and stretchable temperature sensors

Collaborative-IDR: Manufacturing Functional Laminated Composite Structures on Patterned Uneven Three-Dimensional Surfaces (NSF)

Hongyu Yu and Hanqing Jiang (Arizona State University)
Gary Cheng (Purdue University)

Work performed at ASU Nanofab



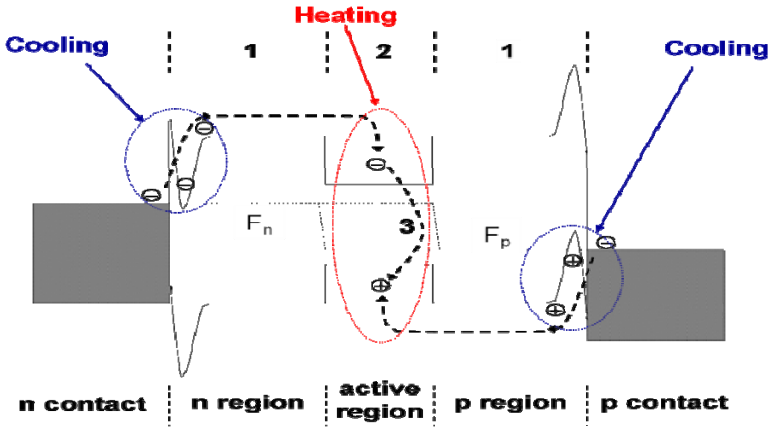
3D laminated structure formation using laser forming technology.

Electro-luminescence Refrigeration

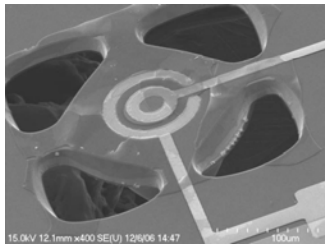
Electro-luminescence refrigeration requires an LED with greater than 100% energy conversion efficiency. To achieve this there are two requirements:

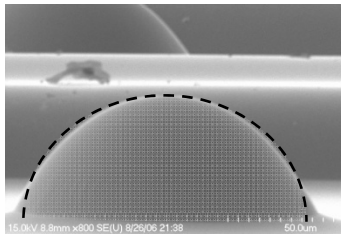
- Requirement 1: High internal quantum efficiency. Improvement of the material quality (98.6%); Low temperature (~100 K).

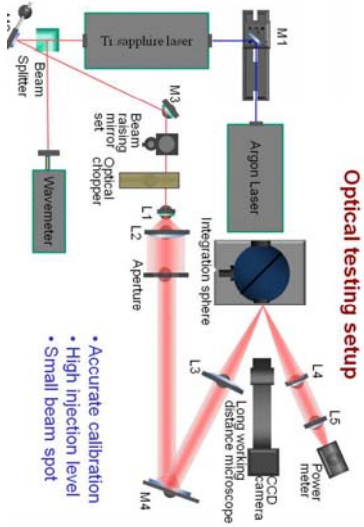
- Requirement 2: High extraction efficiency. Perfect index-matched hemispherical dome with AR coating with close to 100% extraction



Spatially separated cooling/heating: Better thermal management







Device and testing: Complicated device fabrication processes with backside alignment and sophisticated testing with absolute power measurements.

Yong-Hang Zhang et al., Arizona State University

Work performed at ASU NanoFab

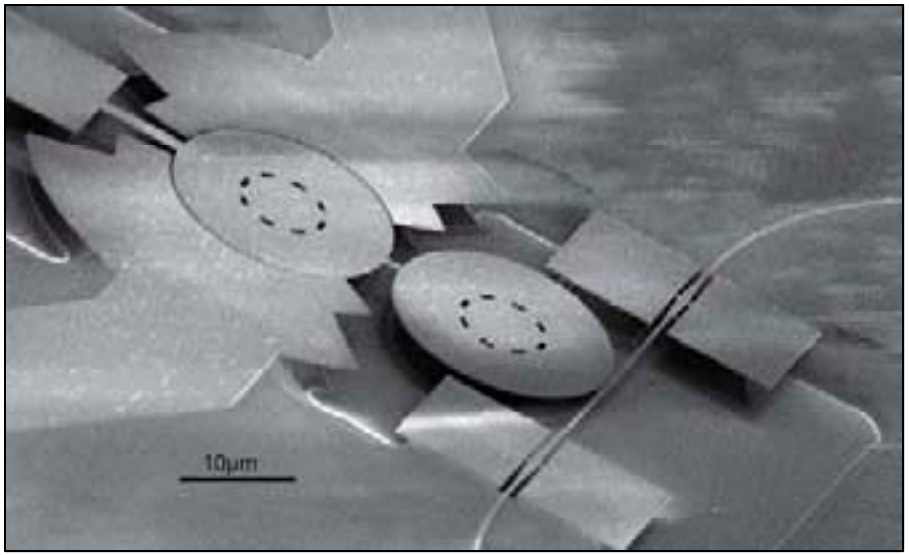
Cornell University

MEMs Based Optical Modulator

To shrink the acousto-optic modulator to chip-scale, we propose a scheme of modulation using MEMS disk resonators for exciting mechanical motion, and to use the mechanical motion to modify the intensity transmission characteristics of a photonic disk resonator. As significant mechanical motion in the disk is only excited when the electrical drive is at the resonant frequency, the modulator is narrowband.

This projects has demonstrated co-fabrication of radio frequency microelectromechanical systems (RF MEMS) radial contour mode resonators and photonic whispering gallery mode disk resonators on the same SOI substrate. By mechanically coupling the MEMS and photonic resonators, a silicon RF MEMS based optical modulator can modulate a 1550 nm laser at 235 MHz.

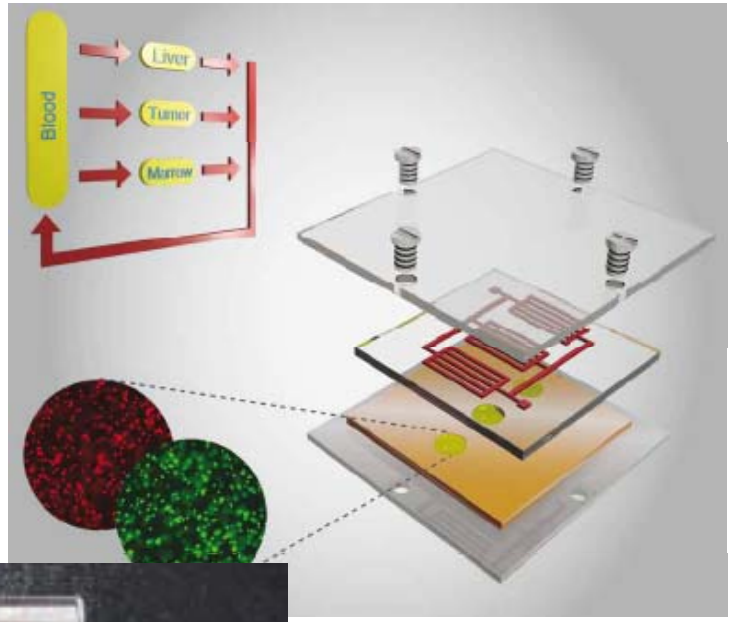
Sunil Bhave and Suresh Sridaran, Electrical and Computer Engineering, Cornell University
Work performed at Cornell NanoScale Facility

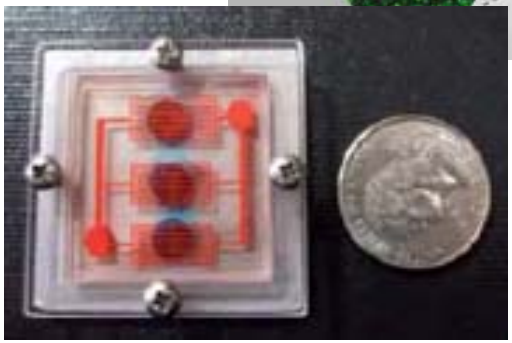


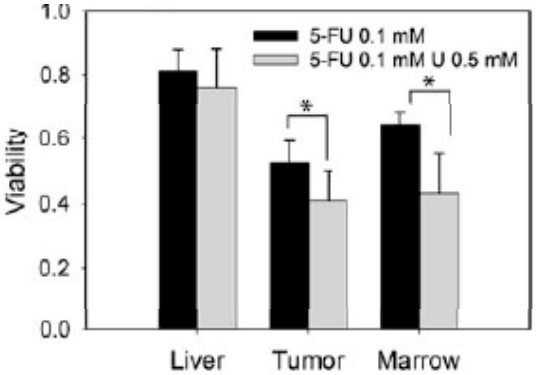
The SEM image of the disk shows the suspended waveguide of width 350 nm spaced 150 nm away from the optical disk resonator. The gap between the electrode and the suspended mechanical disk is 160 nm. A multimode interference crossing is used to anchor the waveguide and prevent it from collapsing during release.

Physical Representations of Pharmacokinetic–Pharmacodynamic (PK–PD) Models

Microscale cell culture analogs (μCCA) are microfluidic devices designed to physically represent pharmacokinetic–pharmacodynamic (PK–PD) models. Each device contains multiple cell culture chambers that are connected via fluidic channels to allow for blood surrogate re-circulation. Using the devices multi-organ interactions can be simulated and drug toxicities can be tested based on each drug's pharmacokinetics. The devices have been used to simulate the first the pass metabolism of acetaminophen and to test the toxicity of the anticancer drug, 5-fluorouracil alone and in combination with uracil.







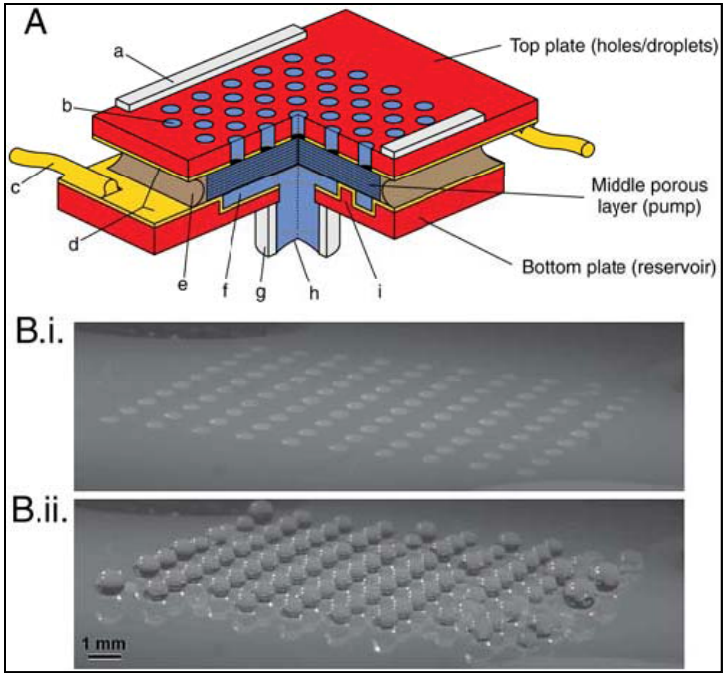
Michael L. Shuler, Jong Hwan Sung, Cornell University
Work performed at Cornell NanoScale Facility

Capillarity-based switchable adhesion

Drawing inspiration from the adhesion abilities of a leaf beetle found in nature, we have engineered a switchable adhesion device. The device combines two concepts: The surface tension force from a large number of small liquid bridges can be significant (capillarity- based adhesion) and these contacts can be quickly made or broken with electronic control (switchable). The device grabs or releases a substrate in a fraction of a second via a low-voltage pulse that drives **electro-osmotic flow**. Energy consumption is minimal because both the grabbed and released states are stable equilibria that persist with no energy added to the system. Notably, the device maintains the integrity of an array of hundreds to thousands of distinct interfaces during active reconfiguration from droplets to bridges and back, despite the natural tendency of the liquid toward coalescence. We demonstrate the scaling of adhesion strength with the inverse of liquid contact size. This suggests that strengths approaching those of permanent bonding adhesives are possible as feature size is scaled down. In addition, controllability is fast and efficient because the attachment time and required voltage also scale down favorably. The device features compact size, no solid moving parts, and is made of common materials.

PNAS / February 23, 2010 / vol. 107 / no. 8 / 3377–3381

Michael J. Vogel and Paul H. Steen, Cornell University
Work performed at Cornell NanoScale Facility

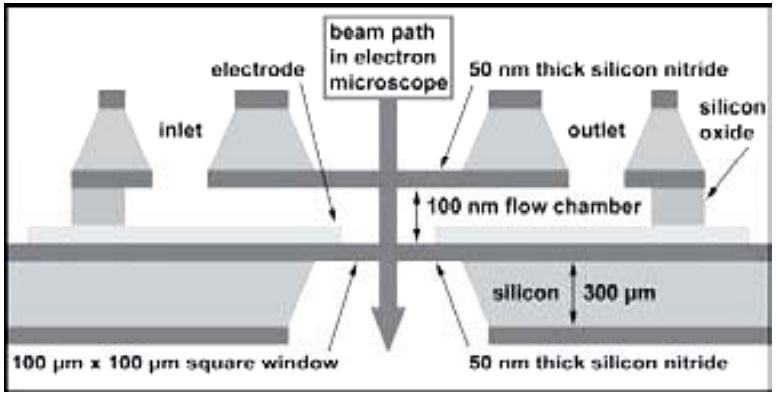


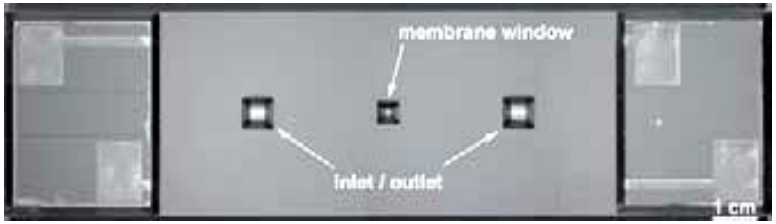
(A) Main components in cutaway (not to scale). Letters indicate: (a) spacers; (b) holes from which droplets/bridges protrude; (c) wire interconnects to power supply; (d) electrodes; (e) epoxy seal; (f) fluid reservoir; (g) luer connector as reservoir continuation and filling port; (h) reservoir meniscus; and (i) representative support post.

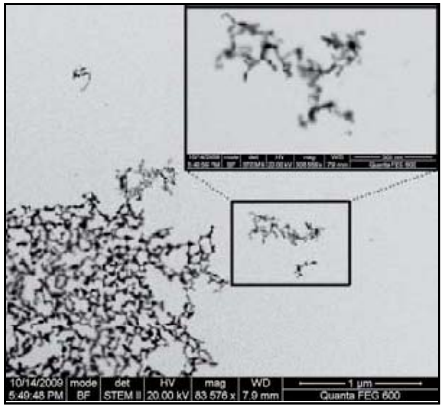
(B) Operation of device with no substrate present. (B.i.) is just before voltage pulse, t=0 s, (B.ii.) is at t=2.0 s.

Nanoaquarium for In Situ Electron Microscopy

We have developed a nanofluidic platform for *in situ transmission (TEM) and scanning transmission (STEM)* electron microscopy of liquid samples called the nanoaquarium. Dynamic processes involving particle and fluid motion are imaged with high resolution, in real-time, by TEM/STEM. The nanoaquarium consists of a hermetically-sealed, liquid-filled chamber sandwiched between two freestanding silicon nitride membranes. Embedded electrodes are integrated into the device for sensing and actuation. Sealed devices remained filled with solution for several days with no apparent loss of fluid. Images and videos of the liquid-filled chamber were taken with a FEG SEM with STEM detector, operated in high vacuum mode at an acceleration voltage of 20 kV. Diffusive motion of the particles in solution was apparent. Individual particles as well as aggregates were seen diffusing through the field of view, sometimes forming larger aggregates (lower figure).



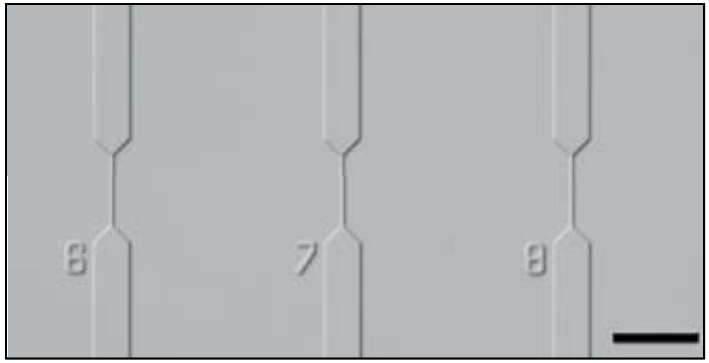




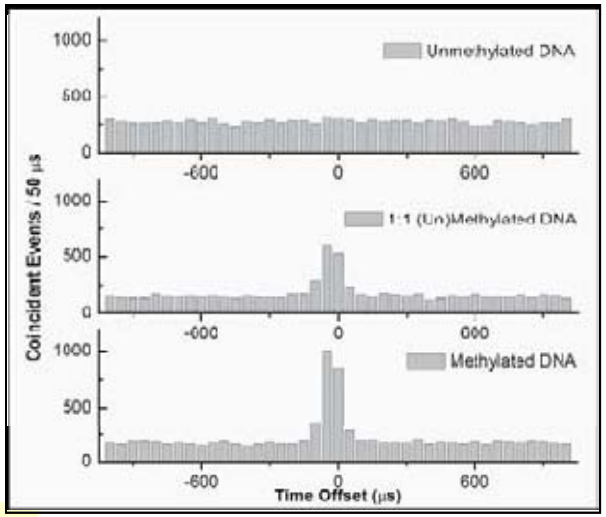
Haim Bau, and Joseph Grogan, U. Pennsylvania
Work performed at Cornell NanoScale Facility

Single Molecule Epigenetic Analysis

Epigenetic states are governed by DNA methylation and a host of modifications to histones bound with DNA. These states are essential for proper developmentally regulated gene expression and are perturbed in many diseases. Current epigenomic analyses employ bisulfite sequencing and chromatin immunoprecipitation, but query only one type of epigenetic mark at a time, DNA methylation, or histone modifications also requiring substantial input material. To overcome these limitations, we established a method using nanofluidics and multicolor fluorescence microscopy to detect DNA and histones in individual chromatin fragments at about 10 Mbp/min. We demonstrated its utility for epigenetic analysis by identifying DNA methylation on individual molecules. This technique will provide the unprecedented opportunity for genome wide, simultaneous analysis of multiple epigenetic states on single molecules.



fluidic channel array in which molecules entered through the bottom and were analyzed in the constriction. Scale bar is 25 µm

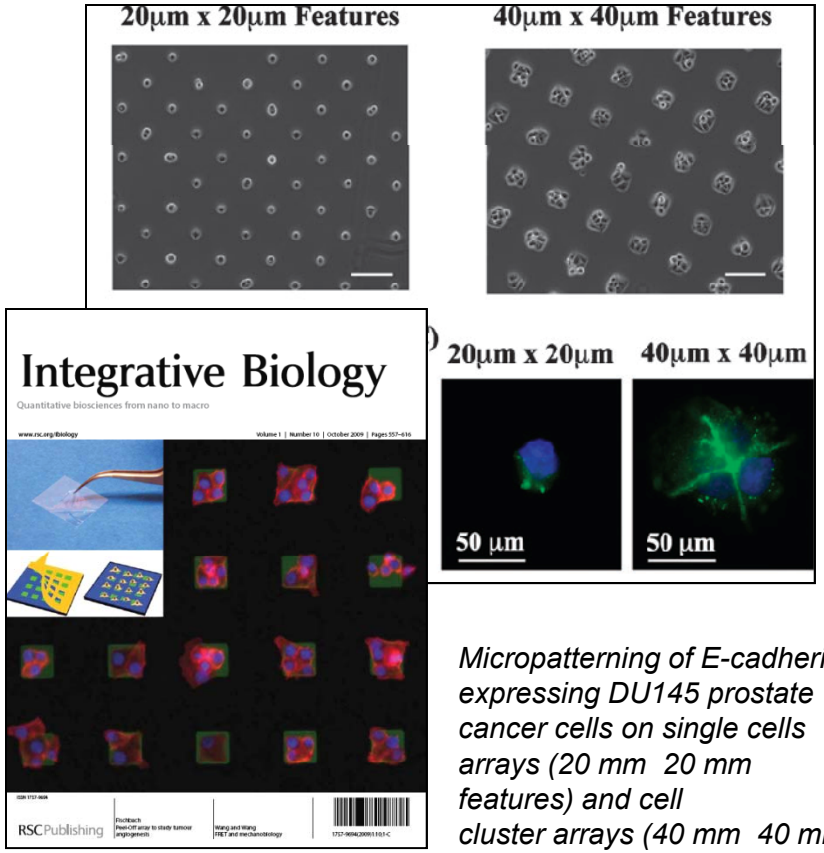


The epigenetic mark, DNA methlyation, was identified in mixtures of methylated and unmethylated DNA using an MBD protein. In response to increasing levels of methylated DNA in the mixture, our single molecule analysis detected an increase in two-color, bound MBD-DNA complexes that emerge above a background of detection events.

Benjamin R. Cipriany, Ruqian Zhao, Patrick J. Murphy, Stephen L. Levy, Christine P. Tan, Harold G. Craighead, and Paul D. Soloway, Cornell University
Work performed at Cornell NanoScale Facility

Cell-Cell Interactions in Tumor Angiogenisis

Microenvironmental conditions impact tumour angiogenesis, but the role of cell–cell interactions in modulating the angiogenic capability of tumour cells is not well understood. We have microfabricated a peel-off cell-culture array (PeelArray) chip to spatiotemporally control interactions between tumour cells in a large array format and to analyse angiogenic factor secretion in response to these conditions. The PeelArray chip consists of a polyethylene glycol (PEG) treated glass coverslip coated with a parylene-C template that can be easily peeled off to micropattern biomolecules and cells. The PeelArray chip reproducibly deposits large uniform arrays of isolated single cells or isolated cell clusters on fibronectin features of defined surface areas. We have used this to study the secretion of angiogenic factors by tumour cells, in the presence or absence of cell–cell contact as controlled by micropatterning. Our results indicate that cell–cell interactions play a synergistic role in regulating the expression of angiogenic factors (i.e., vascular endothelial growth factor [VEGF] and interleukin-8 [IL-8]) in various cancer cell lines, independent of other more complex microenvironmental cues (e.g. hypoxia). PeelArray chips enable quantitative profiling of protein secretions and hence, a better understanding of the mechanisms by which cell–cell interactions regulate tumour cell behaviour and angiogenesis.



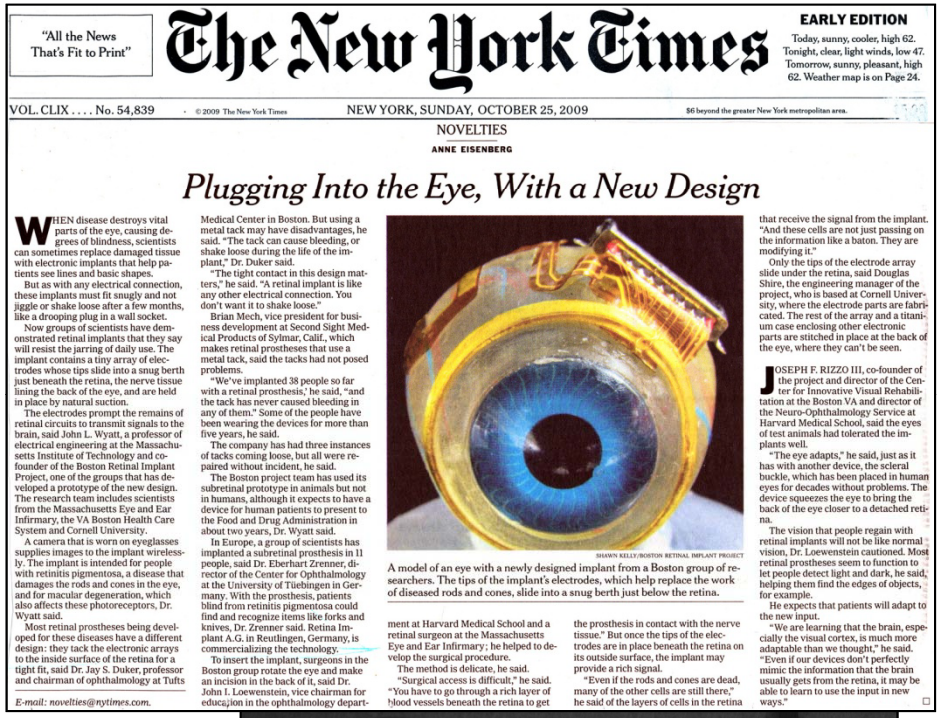
Micropatterning of E-cadherin expressing DU145 prostate cancer cells on single cells arrays (20 mm 20 mm features) and cell cluster arrays (40 mm 40 mm features) as visualised by phase contrast microscopy.

Christine P. Tan, Bo Ri Seo, Daniel J. Brooks, Emily M. Chandler, Harold G. Craighead and Claudia Fischbach, Cornell University

Work performed at Cornell NanoScale Facility

Retinal Implant Project

The Retinal Implant Project aims to restore useful vision to patients who are blind with degenerative retinal diseases. The primary illnesses targeted are retinitis pigmentosa (a primary cause of inherited blindness) and age-related macular degeneration (the leading cause of blindness in the developed world). Both of these diseases cause the eventual destruction of the photoreceptor cells in the retina, leaving intact the ganglion cells which transmit electrical impulses (and hence visual information) to the brain. The ganglion cells may be stimulated, however, with biphasic current pulses from a microfabricated electrode array. Blind surgical volunteers have consistently described visual percepts that resulted from such stimuli. The group has therefore created a new generation device with outbound telemetry that allows us to wirelessly monitor the electrode voltage waveforms and dynamically adjust the power supplied to the implant to accommodate demand. Excellent progress has been made toward a future high density implant with a much higher 'pixel' count, which will be better suited for human use. A recent prototype is shown on a model eyeball was featured in a recent NY Times article shown at the right.



"All the News That's Fit to Print"

The New York Times

EARLY EDITION

Today, sunny, cooler, high 62. Tonight, clear, light winds, low 47. Tomorrow, sunny, pleasant, high 62. Weather map is on Page 24.

VOL. CLIX . . . . No. 54,839 · © 2009 The New York Times · NEW YORK, SUNDAY, OCTOBER 25, 2009 · $6 beyond the greater New York metropolitan area.

NOVELTIES

ANNE EISENBERG

Plugging Into the Eye, With a New Design

WHEN disease destroys vital parts of the eye, causing degrees of blindness, scientists can sometimes replace damaged tissue with electronic implants that help patients see lines and basic shapes.

But as with any electrical connection, these implants must fit snugly and not jiggle or shake loose after a few months, like a drooping plug in a wall socket.

Now groups of scientists have demonstrated retinal implants that they say will resist the jarring of daily use. The implant contains a tiny array of electrodes whose tips slide into a snug berth just beneath the retina, the nerve tissue lining the back of the eye, and are held in place by natural suction.

The electrodes prompt the remains of retinal circuits to transmit signals to the brain, said John L. Wyatt, a professor of electrical engineering at the Massachusetts Institute of Technology and co-founder of the Boston Retinal Implant Project, one of the groups that has developed a prototype of the new design. The research team includes scientists from the Massachusetts Eye and Ear Infirmary, the VA Boston Health Care System and Cornell University.

A camera that is worn on eyeglasses supplies images to the implant wirelessly. The implant is intended for people with retinitis pigmentosa, a disease that damages the rods and cones in the eye, and for macular degeneration, which also affects these photoreceptors, Dr. Wyatt said.

Most retinal prostheses being developed for these diseases have a different design: they tack the electronic arrays to the inside surface of the retina for a tight fit, said Dr. Jay S. Duker, professor and chairman of ophthalmology at Tufts Medical Center in Boston. But using a metal tack may have disadvantages, he said. "The tack can cause bleeding, or shake loose during the life of the implant," Dr. Duker said.

"The tight contact in this design matters," he said. "A retinal implant is like any other electrical connection. You don't want it to shake loose."

Brian Mech, vice president for business development at Second Sight Medical Products of Sylmar, Calif., which makes retinal prostheses that use a metal tack, said the tacks had not posed problems.

"We've implanted 38 people so far with a retinal prosthesis,' he said, "and the tack has never caused bleeding in any of them." Some of the people have been wearing the devices for more than five years, he said.

The company has had three instances of tacks coming loose, but all were repaired without incident, he said.

The Boston project team has used its subretinal prototype in animals but not in humans, although it expects to have a device for human patients to present to the Food and Drug Administration in about two years, Dr. Wyatt said.

In Europe, a group of scientists has implanted a subretinal prosthesis in 11 people, said Dr. Eberhart Zrenner, director of the Center for Ophthalmology at the University of Tüebingen in Germany. With the prosthesis, patients blind from retinitis pigmentosa could find and recognize items like forks and knives, Dr. Zrenner said. Retina Implant A.G. in Reutlingen, Germany, is commercializing the technology.

To insert the implant, surgeons in the Boston group rotate the eye and make an incision in the back of it, said Dr. John I. Loewenstein, vice chairman for education in the ophthalmology department at Harvard Medical School and a retinal surgeon at the Massachusetts Eye and Ear Infirmary; he helped to develop the surgical procedure.

The method is delicate, he said.

"Surgical access is difficult," he said. "You have to go through a rich layer of blood vessels beneath the retina to get the prosthesis in contact with the nerve tissue." But once the tips of the electrodes are in place beneath the retina on its outside surface, the implant may provide a rich signal.

"Even if the rods and cones are dead, many of the other cells are still there," he said of the layers of cells in the retina that receive the signal from the implant. "And these cells are not just passing on the information like a baton. They are modifying it."

Only the tips of the electrode array slide under the retina, said Douglas Shire, the engineering manager of the project, who is based at Cornell University, where the electrode parts are fabricated. The rest of the array and a titanium case enclosing other electronic parts are stitched in place at the back of the eye, where they can't be seen.

JOSEPH F. RIZZO III, co-founder of the project and director of the Center for Innovative Visual Rehabilitation at the Boston VA and director of the Neuro-Ophthalmology Service at Harvard Medical School, said the eyes of test animals had tolerated the implants well.

"The eye adapts," he said, just as it has with another device, the scleral buckle, which has been placed in human eyes for decades without problems. The device squeezes the eye to bring the back of the eye closer to a detached retina.

The vision that people regain with retinal implants will not be like normal vision, Dr. Loewenstein cautioned. Most retinal prostheses seem to function to let people detect light and dark, he said, helping them find the edges of objects, for example.

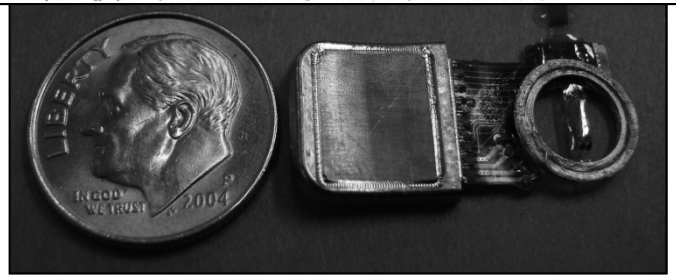
He expects that patients will adapt to the new input.

"We are learning that the brain, especially the visual cortex, is much more adaptable than we thought," he said. "Even if our devices don't perfectly mimic the information that the brain usually gets from the retina, it may be able to learn to use the input in new ways." □

SHAWN KELLY/BOSTON RETINAL IMPLANT PROJECT

A model of an eye with a newly designed implant from a Boston group of researchers. The tips of the implant's electrodes, which help replace the work of diseased rods and cones, slide into a snug berth just below the retina.

E-mail: novelties@nytimes.com.

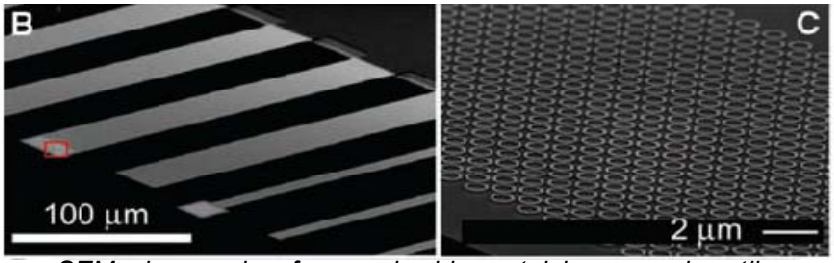


An implantable retinal prosthesis assembly showing the titanium case, external flexible circuit, RF coils and electrode array

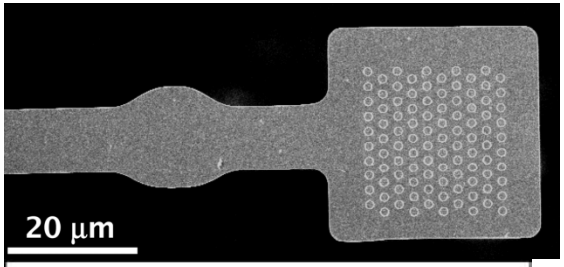
Douglas Shire,Marcus Ginghrich and John Wyatt, MIT, Cornell, and Veterans Administration
Work performed at Cornell NanoScale Facility

Persistent Currents in Normal Metals

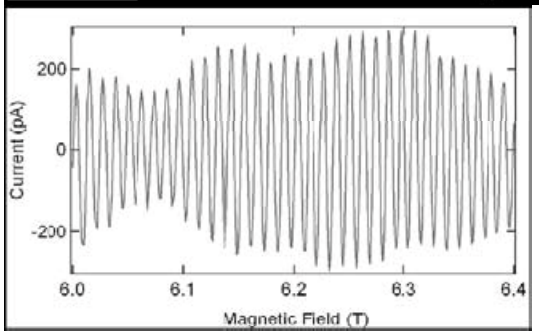
The feasibility of observing persistent currents in a lossy, disordered conductor was first predicted nearly thirty years ago. Experimental verification of this prediction has been hampered by the small size of the magnetic moment associated with the persistent current. This persistent current is quantum in nature and is similar to the net orbital angular momentum of the electrons orbiting some atoms. For this persistent current to be appreciable, the circumference of the ring must be of the same order of magnitude as both the electron phase coherence length in the metal and the thermal length, both of which are on the micron size scale for milli-Kelvin temperatures. The persistent current in a normal metal ring can only be observed when the ring is closed, meaning that a direct current measurement is not possible. We have therefore fabricated micromechanical cantilevers with metal rings integrated near the cantilever tips which act as sensitive torque magnetometers. We measured the typical magnitude of the persistent current over a wide range of parameters, finding good agreement with single particle diffusive theory, and made preliminary measurements of the distribution of the current beyond its variance, for which no theoretical description is currently known.



SEM micrographs of a sample chip containing several cantilevers (left) and a detail of array of ring located on the end of one cantilever (right). The cantilevers are 340 nm thick. On the chip, both single rings and arrays of rings have been fabricated at the cantilever tips.



SEM micrograph of a fabricated silicon cantilever with an array of rings.



Measured persistent current versus magnetic field for an array of 990 rings with 2.6 µm circumference. The observed oscillation frequency is as expected for the ring size and the applied magnetic field angle.

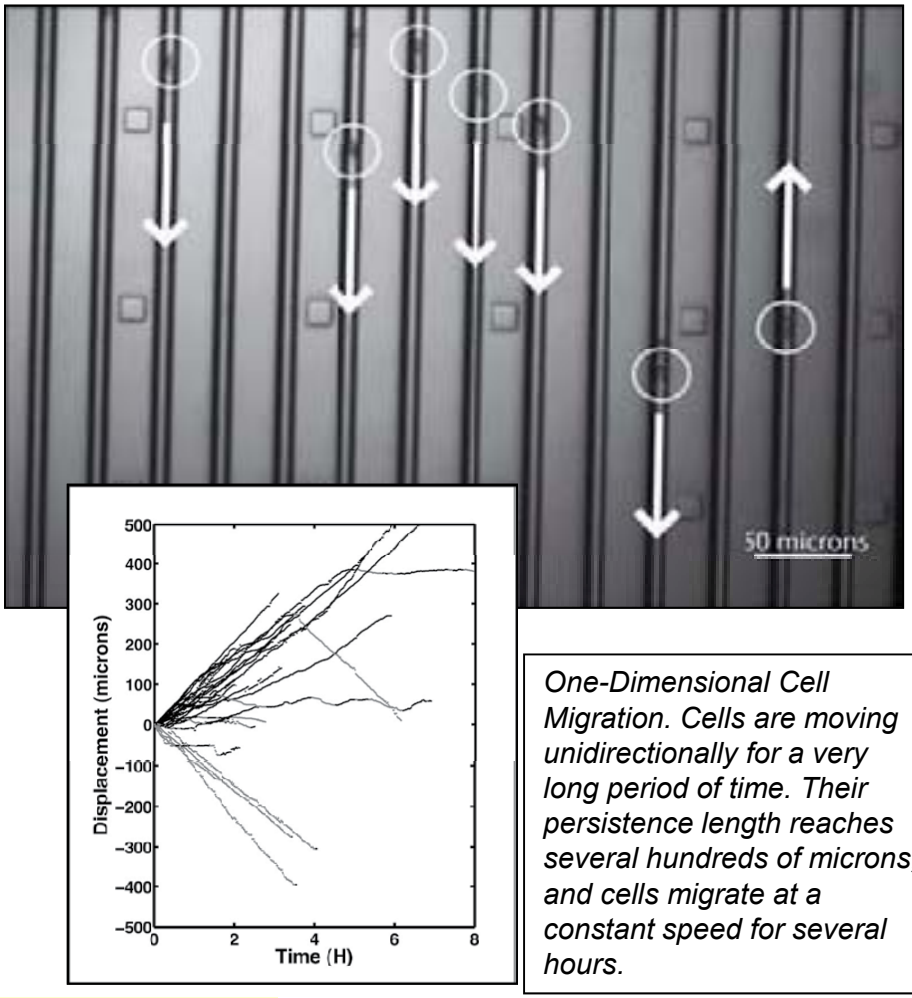
Science AAAS

9 Oct 2009 Vol 326 Science

Ania Bleszynski-Jayich (UCSB) and Jack Harris, Yale University
Work performed at Cornell NanoScale Facility

Cancer Metastasis on a Chip

The physical pressures and limitations associated with metastasis, the process through which cancer cells leave a primary tumor and disseminate through the blood flow, are not well understood. This project employs microstructured devices which allow a study the motion of cancer cells inside one-dimensional, blood vessel-like constrictions. We observe that the motion of a cancer cells inside 10 µm wide channels is enhanced compared to their motion on a planar surface. We find that cells migrate at a constant speed, and their unidirectional motion persists over several hours. These observations indicate that cells constrained to one dimension are much more motile than in a 2D or 3D micro environment. Physiologically, these results indicate that the highly metastatic PC3 prostate cancer cell line is more apt to invade a tissue when it travels through a one dimensional constriction.

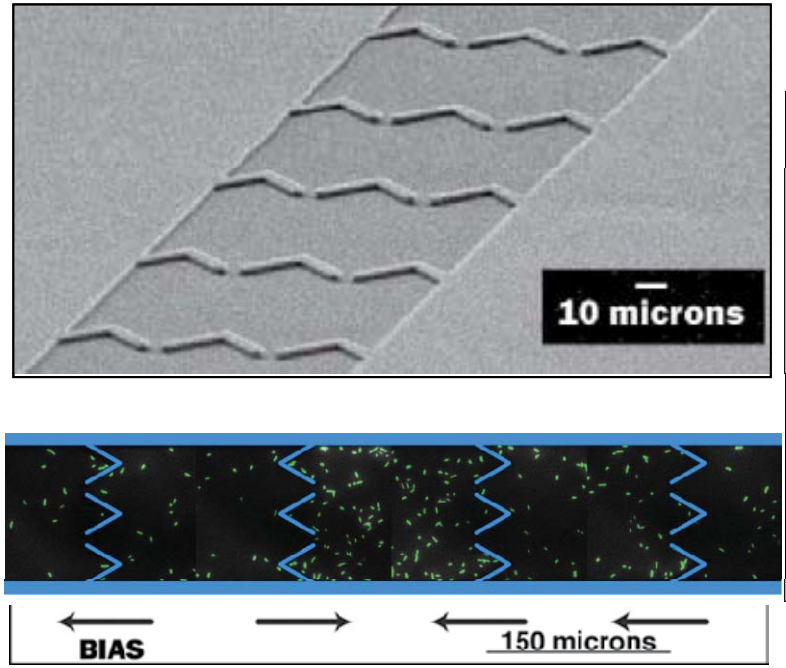


One-Dimensional Cell Migration. Cells are moving unidirectionally for a very long period of time. Their persistence length reaches several hundreds of microns, and cells migrate at a constant speed for several hours.

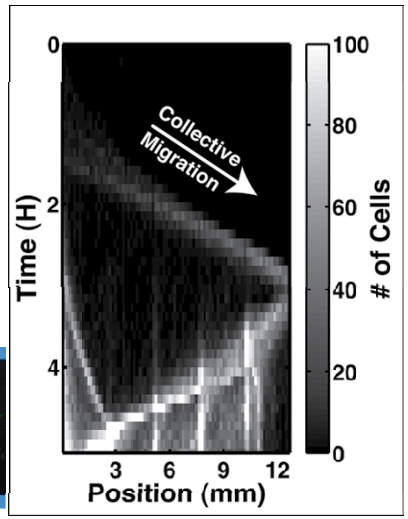
Guillaume Lambert and Robert Austin, Princeton University
Work performed at Cornell NanoScale Facility

Collective Behavior of Entrapped Bacteria

Microchannels containing funnel-shaped barriers ("ratchets") were created using conventional micro-fabrication techniques. The barriers act like fish traps: it is easy to go through them when cells come from one direction but difficult from the other direction. We then inoculated bacteria at one end of the channel (the side from which it is hard to cross the barriers) and continuously monitored the density of cells along the channel. We observe that cells are able to overcome the effect of the funnels through collective motion. A transition between pure rectification and chemotaxis-driven collective motion is predicted from theoretical models, and is observed experimentally as the initial inoculation density is varied.



Cell Trapping. We observe individual cells inside the microchannel. Cell traps, where the rectification bias is reversed, have a higher concentration of cells.



Grayscale image showing the number of cells in each chamber as a function of time

Lambert, G., Liao, D., and Austin, R.H. Collective Escape of Chemotactic Swimmers through Microscopic Ratchets. Phys. Rev. Lett. 104, 168102 (2010).

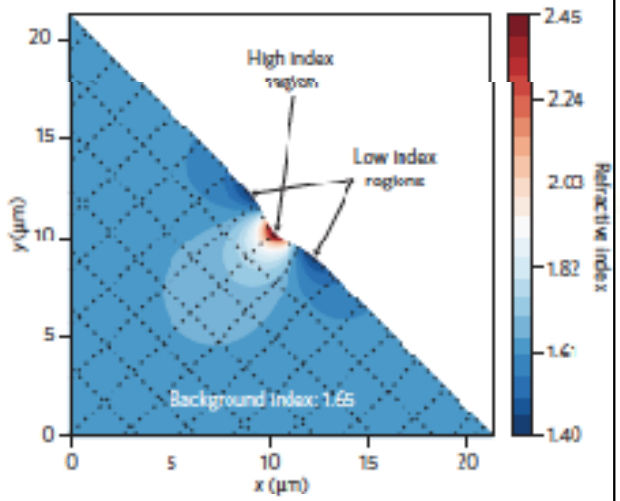
Guillaume Lambert and Robert Austin, Princeton University
Work performed at Cornell NanoScale Facility

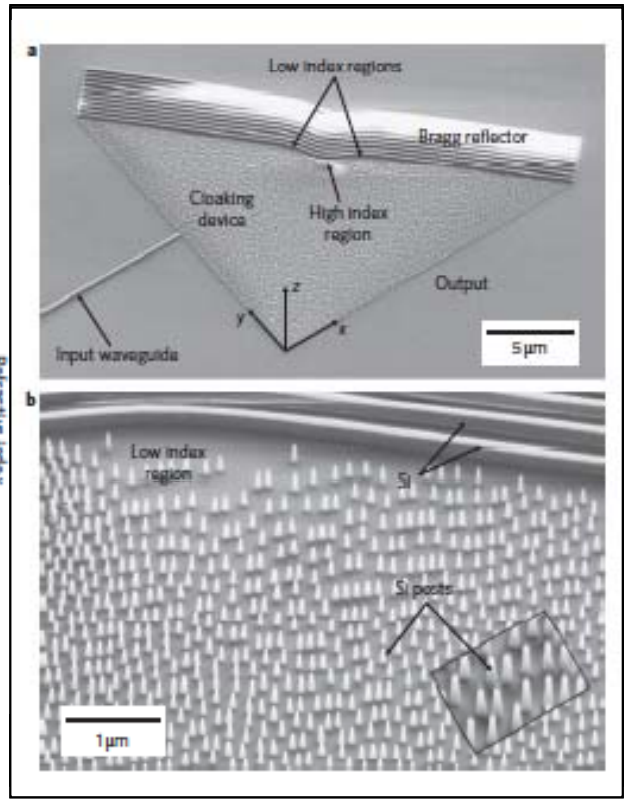
Optical Cloaking

nature photonics
LETTERS
PUBLISHED ONLINE: 20 JULY 2009 | DOI: 10.1038/NPHOTON.2009.117

Silicon nanostructure cloak operating at optical frequencies

The ability to render objects invisible using a cloak (such that they are not detectable by an external observer) has long been a tantalizing goal. This work demonstrates a cloak operating at a wavelength of 1550 nm. The cloak conceals a deformation on a flat reflecting surface, under which an object can be hidden. The device has an area of 225 μm2 and hides a region of 1.6 μm2. It is composed of nanoscale silicon structures with spatially varying densities across the cloak. The density variation is defined using transformation optics to define the effective index distribution of the cloak.

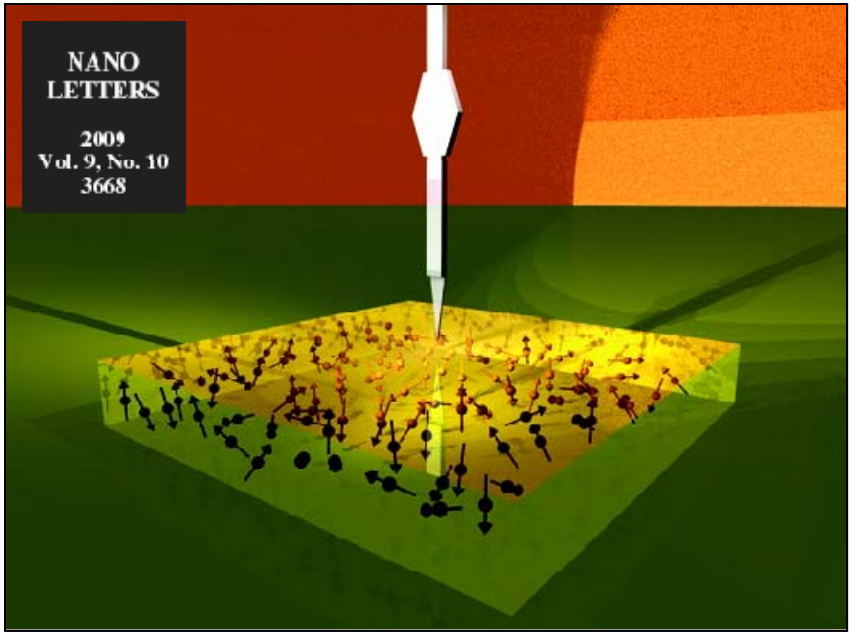


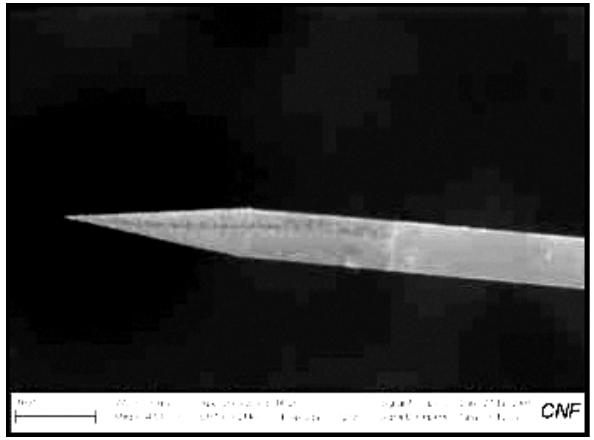


Lucas Gabrielli, Jaime Cardenas, Carl Poitras, Michal Lipson, Cornell University
Work performed at Cornell NanoScale Facility

AttoNewton Force Sensitivity for Measuring Dielectric Fluctuations

An ultrasensitive cantilever, oscillating parallel to a surface in vacuum, is used to probe weak thermal electric field gradient fluctuations over thin polymer films. The power spectrum of cantilever frequency fluctuationswas measured as a function of cantilever height and voltage over polymers of various compositions and thicknesses. The data are well described by a linear-response theory that calculates stochastic electric fields arising from thermally driven dielectric fluctuations. The cantilevers were made of crystal silicon and are 340 nm thick, 250 µm long and 50-100 nm in diameter at their thinnest point. The spring constants of these cantilevers are as low as 10N/m, which permits detecting forces as small as an attonewton far below those available commercially.



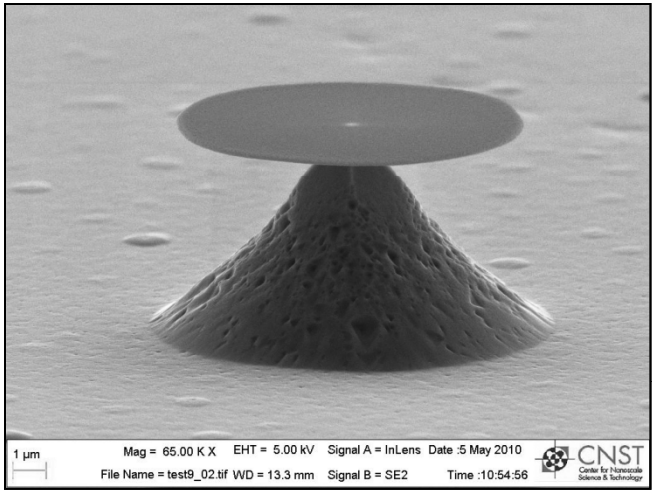


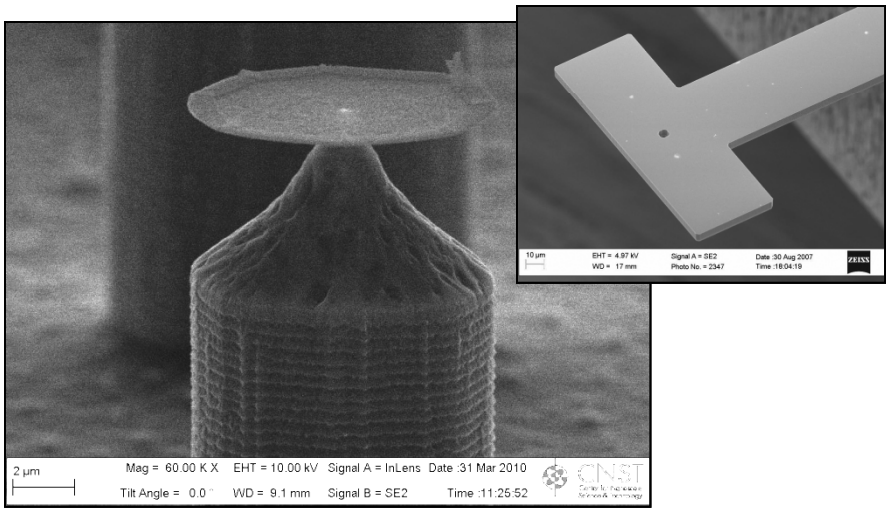
John Marohn and Nikolas Hoepker, Chemistry and Chemical Biology, Cornell University
Work performed at Cornell NanoScale Facility

Cantelevers for AFM Nanomechanical Standards

This project creates cantilever devices for calibration and nanomechanical property measurement. The current designs refine the performance and add integrated special purpose AFM tips to simplify the measurement process for users. Early prototypes of this cantilever design were tipless hammerhead (small inset) and could only be used after a sphere was attached. More recently, we have been investigating the use of reactive ion etching (RIE) and combinations of RIE and deep reactive ion etching (DRIE) to fabricate tips.Two types of tips (regular (top) and “rocket” (bottom)) are being investigated. The rocket design provides a longer lever arm for torque during sliding, making the cantilever more sensitive to this lateral force. These will be integrated with the hammerhead cantilever.

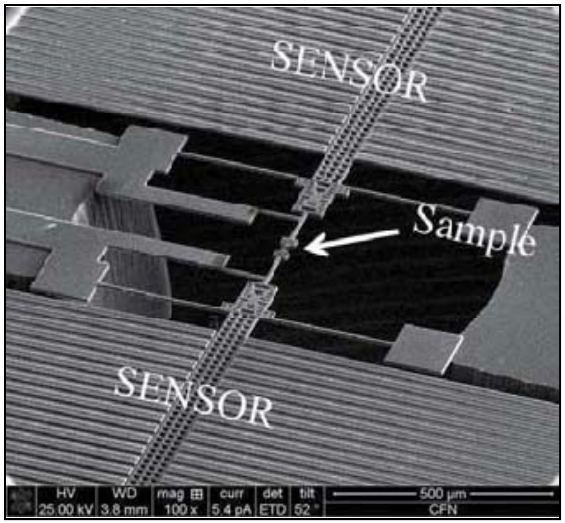
Richard S. Gates, and Mark G. Reitsma, National Institute of Standards and Technology
Work performed at Cornell NanoScale Facility

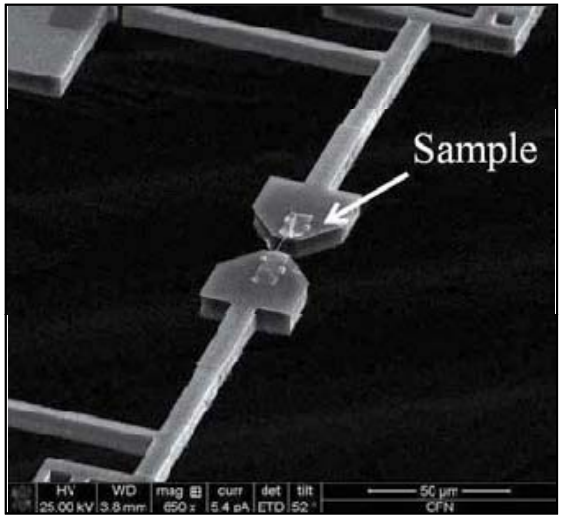


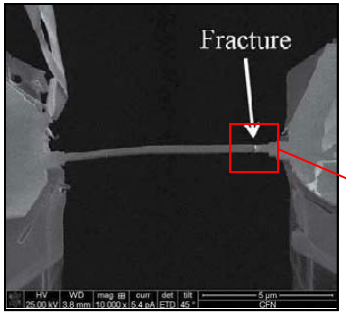


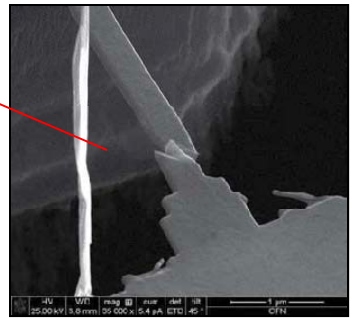
MEMs Platform for SEM and TEM InSitu Tension Experiments

This study is about microfabrication of an integrated MEMS device capable of real-time and in situ SEM and/or TEM observation of the deformations on nanoscale samples including extracting quantitative properties of the test samples. Recently demonstrated the functionality of the MEMS device (top) with a nanoscale gold leaf sample that was integrated on top of our MEMS device with a platinum welding technique (seen in the lower figure). The MEMS device has the capability to deform the platinum welded and focused ion beam (FIB) patterned gold leaf samples within the desired working range, as evidenced by the fracture noted in the SEM image.





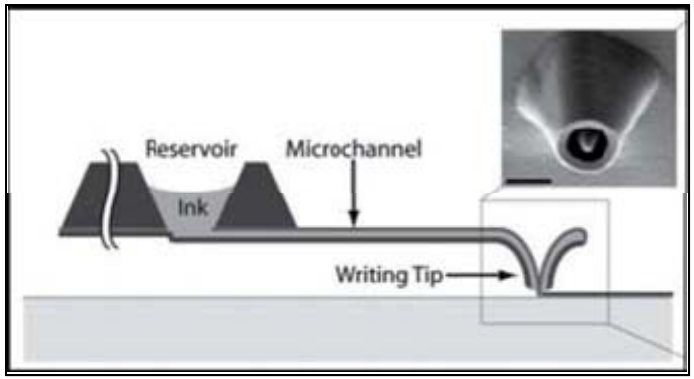


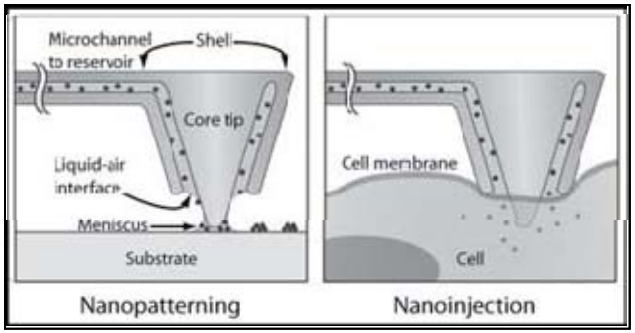


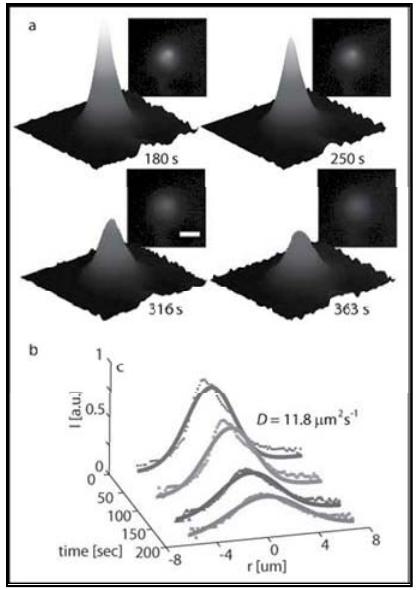
Haim Bau, and Joseph Grogan, U. Pennsylvania
Work performed at Cornell NanoScale Facility

Nanofountain Probe for Molecular Ink Delivery

Nanofountain probes (NFPs) are atomic force microscopy (AFM) probes designed for direct-write delivery of liquid molecular “inks” with sub-100 nm resolution. Liquid inks’ stored in an on-chip reservoir are fed through integrated microchannels to apertured dispensing tips by capillary action. This allows continuous delivery either to a substrate for direct-write nanopatterning, or to a cell for in vitro injection. Recently demonstrated
applications focus on **direct delivery of chemotherapy drug-coated diamond nanoparticles for single cell studies**. The nanodiamonds were delivered by both nanopatterning and nanoinjection method enabling drug dosing and kinetics studies.







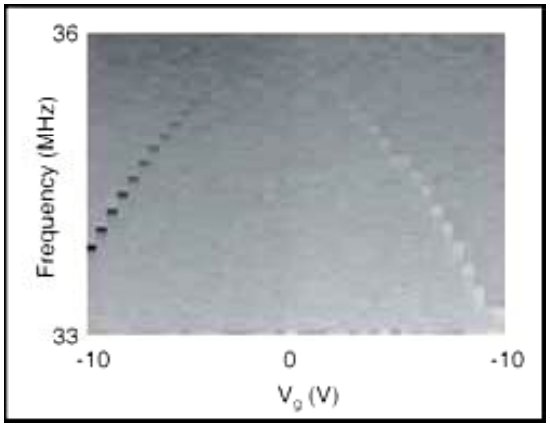
Characterization of fluorescent nanodiamond diffusion in an MCF-7 cell. Sequence of fluorescence images captured following ND injection. (scale bar: 5 μm). And fluorescence intensity profiles A diffusion coefficient was estimated at 11.8 μm2 s-1 by fitting the data.

Horatio Espinosa, Owen Lob, and Nicolaie Moldova, Northwestern University
Work performed at Cornell NanoScale Facility

Graphene NEMS Electrical Transducer

Here we report the preparation of ultra-clean graphene mechanical resonators for high-speed electrical readout, also in the pursuit to understand some intrinsic properties. To improve on top down processed devices (top inset) the group used exfoliated graphene to deposit graphene on to the pre-made chips (see figure at right). The new approach avoids the chemical contamination associated with the fabrication and thereby allows measurement of the intrinsic material properties. The pre-fabricated chips also employ a local gate that is better suited to RF operation.

SEM pictures of the top down processed graphene resonator (upper right) and the new pre-patterned substrate, with local gate electrode embedded in the trench.

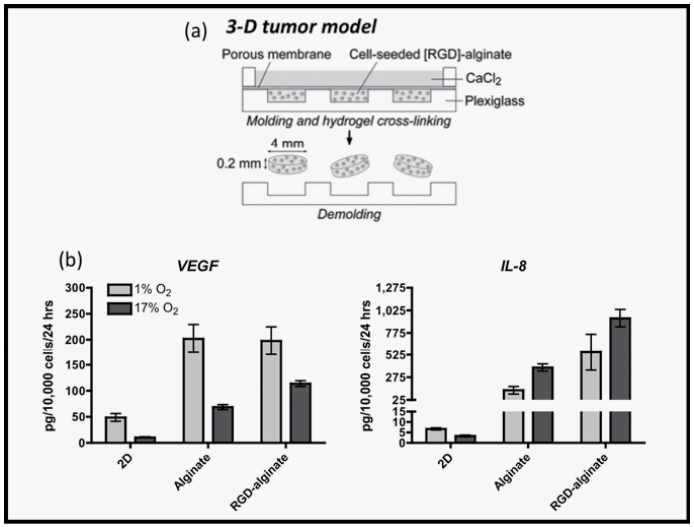


Resonant frequency of graphene NEMS as a function of DC gate voltage, at 77K. The resonance is clearly tunable over 20 V of DC gate voltage span.

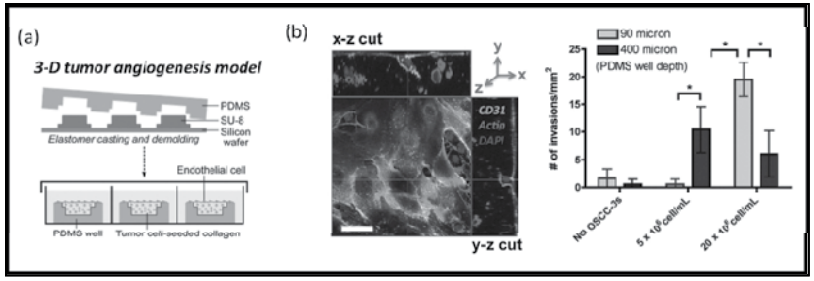
James Hone, Changyo Chen , Alexander Gondorenko, Columbia University
Work performed at Cornell NanoScale Facility

Three Dimensional Microscale Niches for Studies of Tumor Angiogenesis

Spatiotemporal variations in oxygen level represent an important aspect of the tumor microenvironment. Tumor cell response to reduced oxygen level can lead to an overbalance of pro-angiogenic factors, and up-regulation of tumor angiogenesis, however the details of this process are not well understood. We have developed three dimensional (3D) microfabricated culture systems to investigate tumor angiogenesis in vitro. We have used microfabricated hydrogel cell scaffolds to examine tumor cell pro-angiogenic response to uniform oxygen, as well as cell-matrix interaction in 3D environments that better mimic the in vivo tumor microenvironment as compared to 2D culture. Thin disc cultures have been used to examine tumor cell response to varied but spatially homogeneous oxygen levels, and resulting endothelial cell behavior, while scaffolds with embedded microfluidic channels and oxygen imaging capabilities have been used to create heterogeneous oxygen environments, and to examine resulting paracrine pro-angiogenic tumor cell behavior and endothelial cell response.



(a) Schematic of thin alginate disc cell-scaffold fabrication. (b)measured secretions of vascular endothelial growth factor (VEGF) and interleukin-8 (IL-8) by oral squamous cell carcinoma (OSCC-3) cells cultured in 2D, or inert/RGD-modified alginate hydrogels, and at varied oxygen.

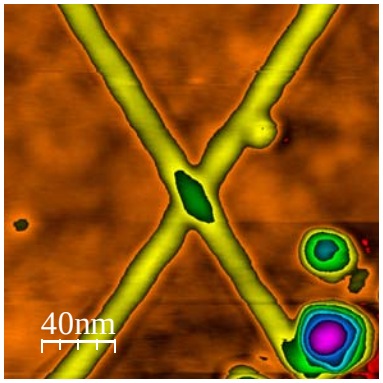


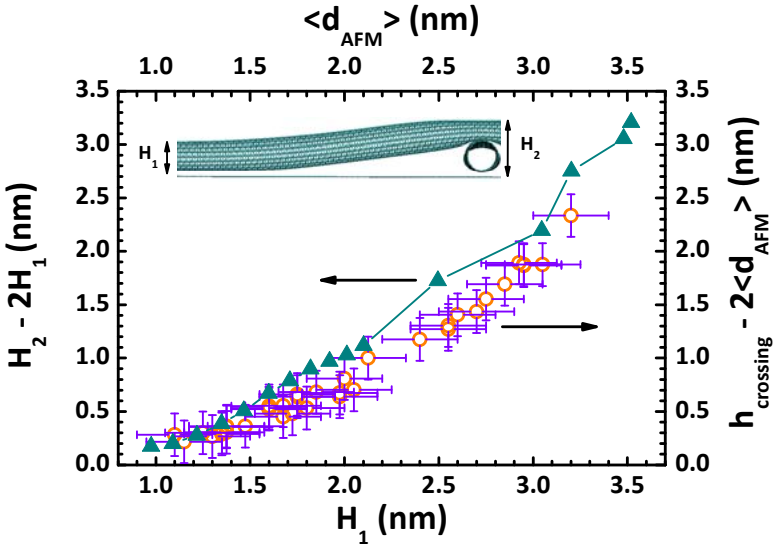
(a) Schematic of tumor angiogenesis microwell fabrication. (b) Confocal image of fluorescently labeled endoethelial cells invading an OSCC-seeded collagen bulk, with invasion frequency as a result of tumor cell density and scaffold thickness.

Claudia Fischbach-Teschl, Abraham D. Stroock
User(s): Scott S. Verbridge, Nakwon Choi, Cornell University
Work performed at Cornell NanoScale Facility

Local Deformation at the Crossing of Carbon Nanotubes

When two carbon nanotubes cross, they both deform from circular cross sections. This changes their local electronic structure and alters the electrical resistance of the junction. To understand the electrical properties of nanotube-nanotube contacts, we have used the CNF computing cluster to perform molecular mechanics simulations of nanotube crossings, with up to 120,000 atoms in the simulations. The calculations are in good agreement with atomic-force microscope measurements of tube deformations.





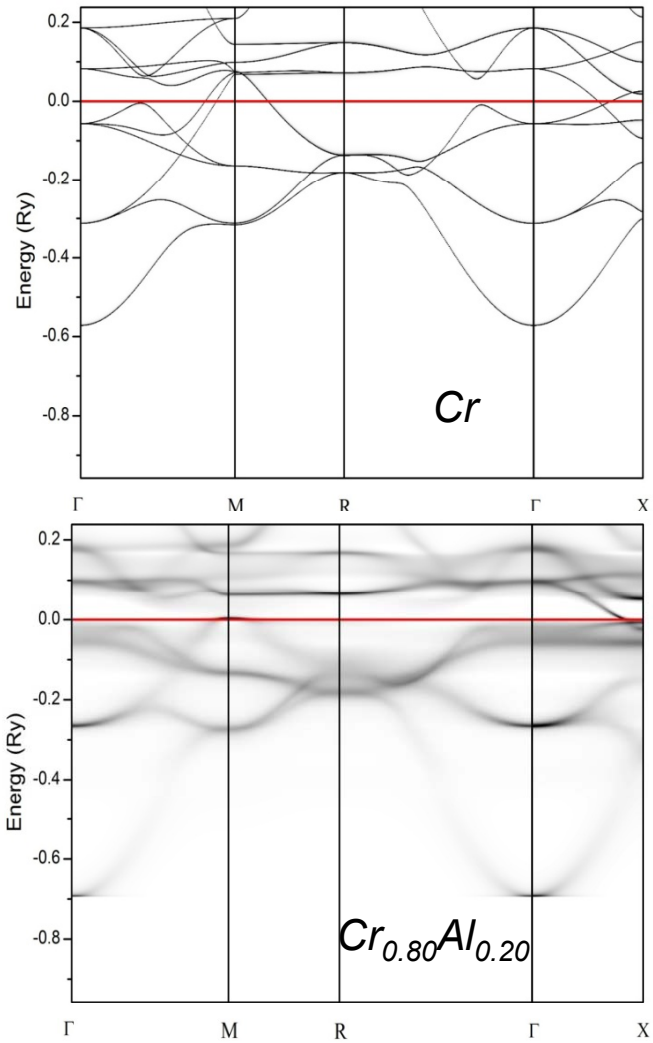
Comparison between molecular mechanics simulation and AFM data concerning the difference between the height at the crossing point and the sum of the nanotube apparent heights as a function of the nanotube average apparent height.

Z. Wang, LCRE/DTMN/LITEN, CEA-Grenoble, France
Work performed at Cornell NanoScale Facility

Electronic Structure Calculations for $Cr_{1-x}Al_x$

Intermetallic compounds containing transition metals and sp elements often form a gap at the Fermi energy due to hybridization. This gap can be exploited for applications such as thermoelectric devices. Cr_3Al is anomalous in that experiments demonstrate that it is an insulating antiferromagnet with a gap at the Fermi energy, while standard theories predict that it should be a metal. We investigated this odd behavior using the computational resources of the CNF by performing electronic structure calculations for Cr and $Cr_{1-x}Al_x$ alloys. We observed shifts in the band structure upon alloying that explain the evolution of Hall effect measurements and a significant reduction in the Fermi surface in $Cr_{0.80}Al_{0.20}$, but not a full gap. Ongoing work is examining whether the gap is the result of an ordered structure.

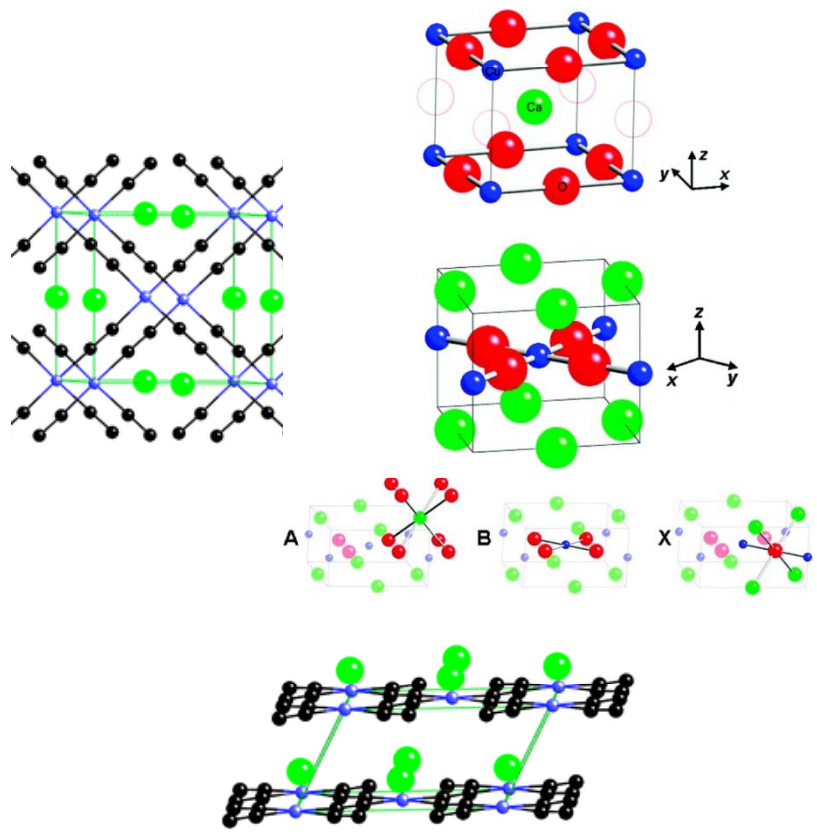
Z. Boekelheide, F. Hellman, University of California, Berkeley
Work performed at Cornell NanoScale Facility



Calculated Bloch spectral function of pure Cr and disordered $Cr_{0.80}Al_{0.20}$ alloy.

Playing the Quantum Chemical Slot Machine: An Exploration of ABX_2 Compounds

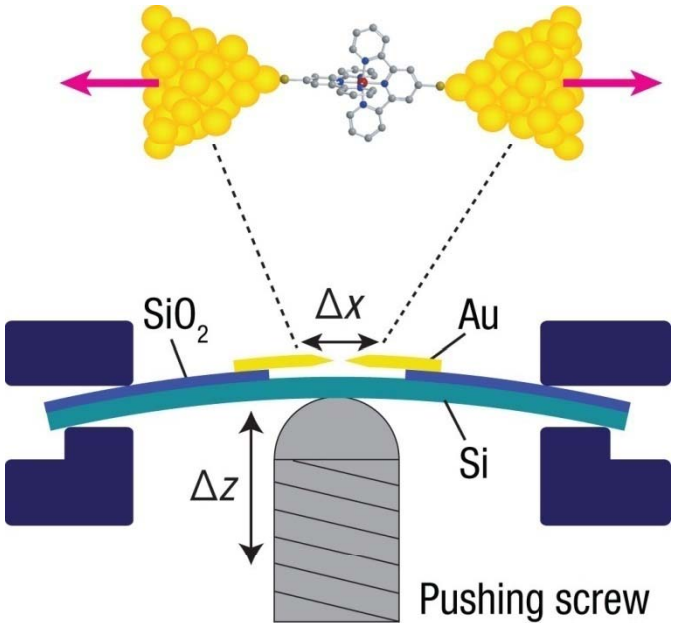
We performed calculations to explore the structures and electronic properties of a number of real and hypothetical ABX_2 compounds, where A = alkali metal, alkaline earth metal, or La; B = Ti, Fe, Cu, or Pt, and X = C, O, S, C_2, H_2, or F. A number of different possible structural variations were investigated, some obvious and some exotic. Careful attention was given to the d-orbital splitting patterns and magnetic states of the compounds, as well as their stability. The most interesting compounds that emerged were: (a) the carbide $SrFe(C_2)_2$, containing an unusual C-C distance of 1.267 Å, (b) the $AeTiO_2$ series with Ti bonding that is part σ and part π, and (c) $NaPtF_2$, for which an unusal hexagonal layering of $(PtF_2)^-$ molecules was found.



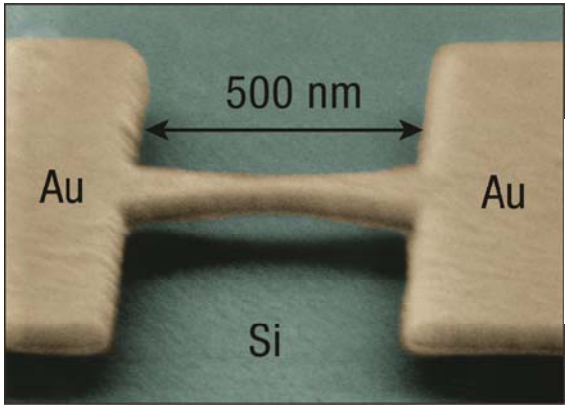
T. J. Cahill, N. M. Gerovac, M. J. Bucknum, R. Hoffmann, Cornell University
*Inorganic Chemistry, **49**, 249 (2010)*
Work performed at Cornell NanoScale Facility

Mechanical Control of Spin States in Individual Spin-1 Molecules

Techniques for making electrical contact to single molecules have advanced to the stage that single-molecule devices can now be used as model systems for performing controlled tests of theories about electron interactions on nanometer scales. We have fabricated devices in which single molecules possessing an intrinsic spin angular momentum can be stretched mechanically while we simultaneously measure electron flow through the molecule. We show that the spin states of the molecule can be manipulated by stretching, and that these devices can therefore provide the first detailed tests of theories about what is known as the spin-1 Kondo effect – a dramatic consequence of strong interactions between electrons in the electrodes and the localized spin in the molecule.



Sample schematic of the mechanically-adjustable single-molecule device with electron microscopy picture of the device prior to molecule insertion.



J. J. Parks, A. R. Champagne, T. A. Costi, W. W. Shum, A. N. Pasupathy, E. Neuscamman, S. Flores-Torres, P. S. Cornaglia, A. A. Aligia, C. A. Balseiro, G. K.-L. Chan, H. D. Abruña, and D. C. Ralph, Cornell University, *Institute for Advanced Simulation (Julich, Germany), and Centro Atómico Bariloche (Argentina)*
Science ***328**, 1370 (2010).*
Work performed at Cornell NanoScale Facility

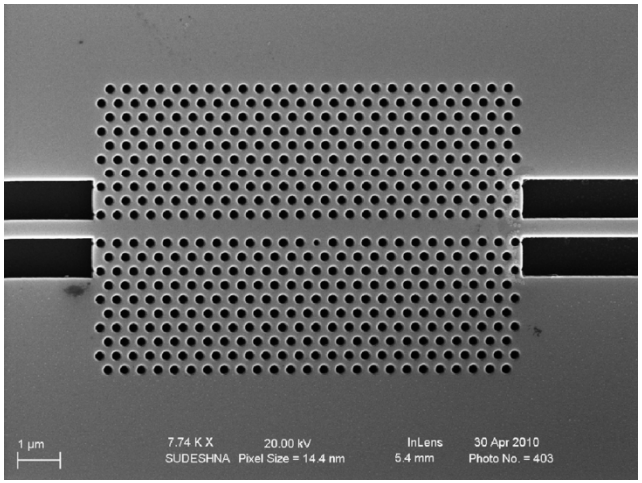
Photonic Crystal Nanocavities for Biosensing Applications

In this study, photonic crystal (PhC) nanocavities have been investigated for biosensing applications.. The device architecture consists of a PhC waveguide with a defect line for guiding the transmission of light. Resonant nanocavities are coupled to the PhC waveguide by changing the radius of a hole adjacent to the defect line. The devices were fabricated on silicon-on-insulator (SOI) wafers using electron beam lithography and reactive ion etching.

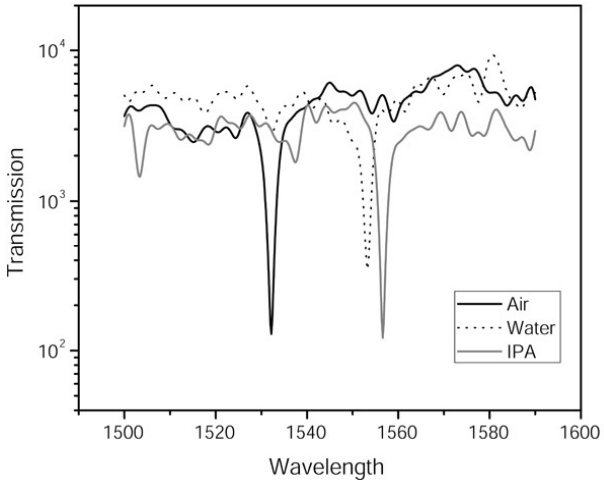
The sensing principle involves changes in the local refractive index of a central defect hole and the surrounding holes due to biomolecule attachment Preliminary results have demonstrated successful detection of human IgG molecules. The PhC waveguide devices are advantageous for medical diagnostics and biosecurity applications as they allow rapid, label-free, and sensitive detection of multiple analytes in a single platform.

Prof. Philippe M. Fauchet and Dr. Sudeshna Pal
Department of Electrical & Computer Engineering,
University of Rochester

Work performed at Cornell NanoScale Facility



SEM image of a "small defed" PhC waveguide device.



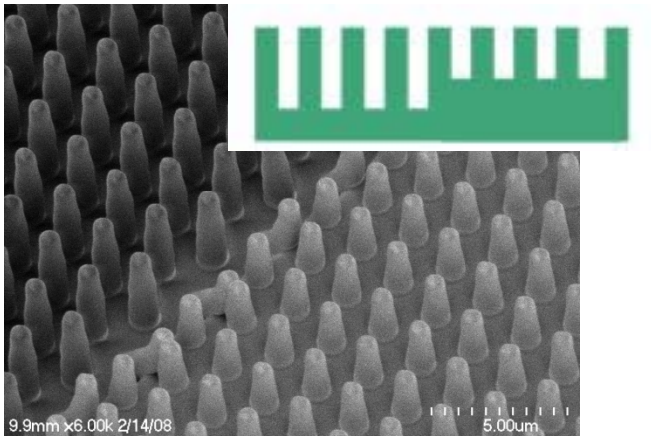
Experimental red-shifts fo the PhC device in liquids of different refractiveindices.

Elastomer Pillar Arrays with Modulated Stiffness for Cellular Force Measurements

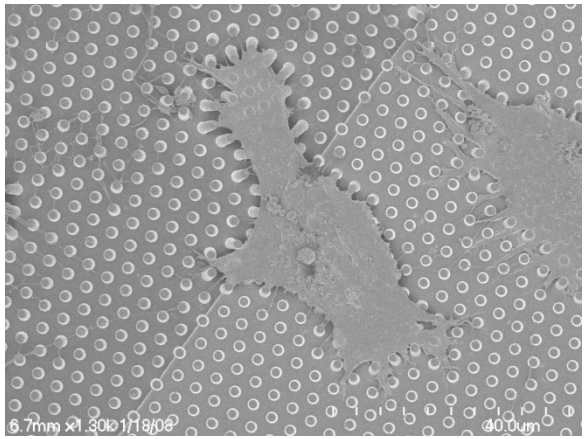
Cells generate traction forces in the nN range during adhesion and migration.The mechanical properties of a cell's environment can alter behavior such as migration and spreading, and control the differentiation path of stem cells. To this end, we use a high-density microfabricated array of elastomeric pillars, which provide direct measurement of the traction forces from observation of the deflection of the surface pillars.. Here we describe a technique for fabricating substrates whose rigidity can be controlled locally without altering the contact area for cell spreading, allowing for the direct measurement of cell traction forces under controlled conditions.

In this work, we want to study the effect of a boundary between two different rigidity substrates on cell behavior. Test surfaces of PDMS pillar arrays were fabricated by imprint lithography resulting in samples in which the pillar diameter and top surface remains constant, but the pillar height, and therefore the stiffness, changes abruptly across a boundry.

Observation was made with *mesenchymal* stem cells plated on elastomer pillars with different heights and therefore different rigidity. A marked difference in phenotype can be observed in either side: they look more round on the soft part and more spread out on the stiff part. This behavior could lead to different differentiation paths in the two areas.



SEM of pillar array, including inset cross section of boundary.



Cell adhered to pillar array. Note the distortion of the pillars near the top of the cell.

Prof. James Hone and Saba Ghassemi, Columbia University

Work performed at Cornell NanoScale Facility

Graphene/Carbon Nanotube Cross-Junction Devices

The novel forms of carbon, grapheme and carbon nanotubes, are of considerable interest for novel electronic devices. Despite extensive research into the properties and applications of both graphene and carbon nanotubes (CNTs) over the last decade, fabrication challenges have prevented the scientific community from studying electronic interactions between the two materials. In this work recent advances in the creation of both large-area, single-layer CVD-grown graphene and aligned arrays of parallel CNTs have been used to explore the junction between the two materials. Graphene/carbon nanotube junctions have been fabricated using graphene grown by chemical vapor deposition (CVD) and aligned arrays of CVD-grown carbon nanotubes. Electrical transport measurements were made demonstrating that the two materials make good contact over a length scale of one micron, with a total junction resistance on the order of the carbon nanotubes' resistance over one micron. Our results suggest that it should be possible to use graphene as the contacts and carbon nanotubes as the active element in a transparent, flexible, carbon-only transistor.

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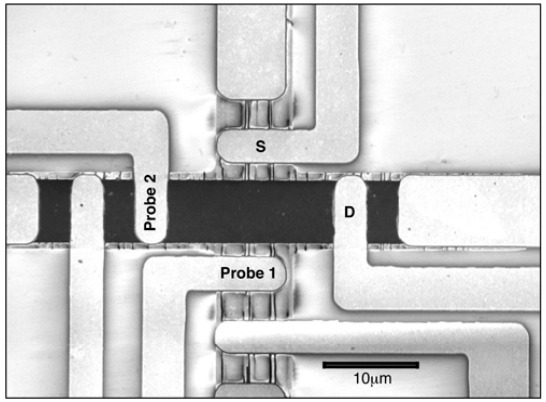
Prof. Paul L. McEuen group, Cornell University
Work performed at Cornell NanoScale Facility

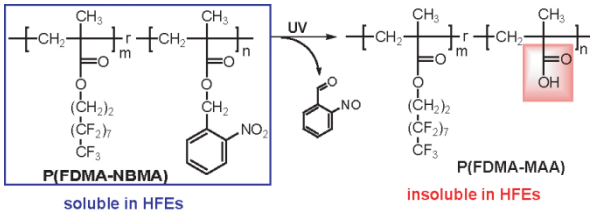


Scanning electron microscope (SEM) image of completed device, with electrodes labeled with the source, drain, and two voltage probes used for measurement of the junction. CNTs lie on top of the graphene strip.

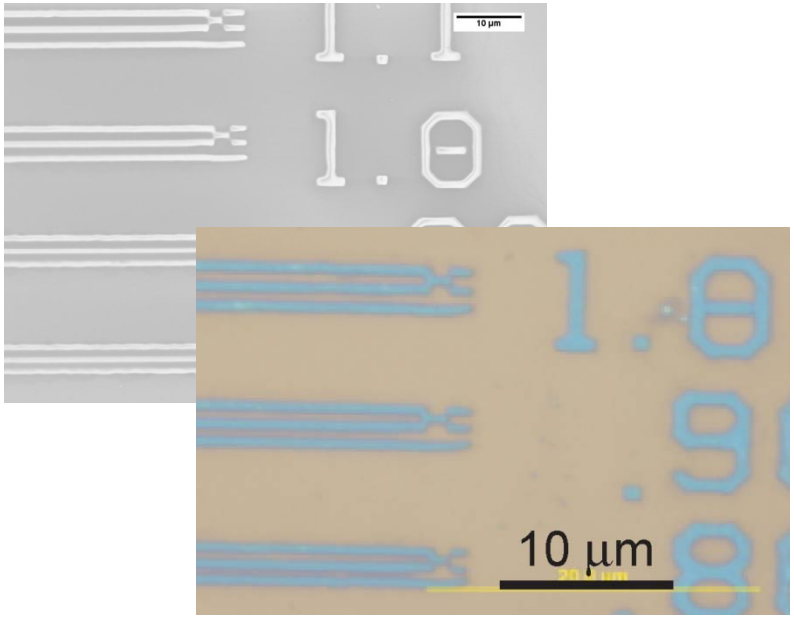
Orthogonal Patterning of PEDOT:PSS for Organic Electronics

Organic electronics has received considerable attention as a technology platform enabling flexible, large-scale devices, by exploiting solution-processable organic materials. However, for this vision to be realized, several challenges must be overcome, particularly with regard to patterning. Patterning of electronic materials allows construction of microscale device architectures for organic light-emitting displays and thin-film transistors. Conventional photolithography is not recognized as a suitable method for patterning organic materials as there can be significant deterioration of active materials upon exposure to process solvents for photolithography. By introducing a set of benign processes (Orthogonal Patterning) including tailored fluorinated photopolymers and fluorous solvents, this problem can be circumvented.

In this project, a non-chemically amplified, acid-stable imaging material for patterning organic electronic devices has been developed. The highly fluorinated resist can be patterned at 248 nm and 365 nm conditions and shows 100 nm resolution under e-beam exposure. Sub-micron patterning of poly(3,4-ethylenedioxythiophene):poly(styrenesulfonate) (PEDOT:PSS) has been demonstrated. Finally, e a bottom-contact transistor patterned with this new photoresist which shows better performance than previously achieved by other patterning methods has been fabricated.
This material is being commercialized by Orthogonal Inc., Ithaca, NY.



Exposure Process

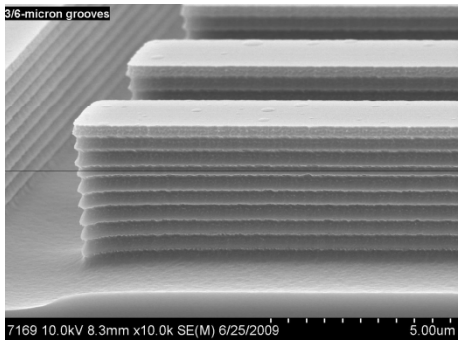


Exposed photoresist and etched PEDOT:PSS film (test pattern)

Prof. Chris Ober and Prof. George Malliaras, Cornell University
Work performed at Cornell NanoScale Facility

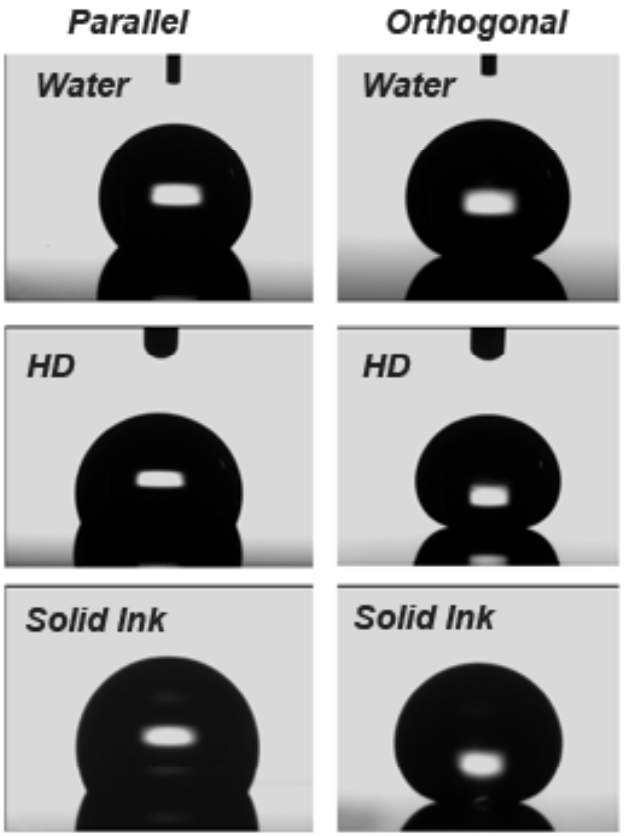
Design and Property fo Directional Self-Cleaning Superoleophobic Surfaces

Functional surfaces with self-cleaning property are highly desirable in many applications in the printing industry. In this study, we report the creation of textured surfaces on Si wafer by photolithography, followed by chemical modification, that are superoleophobic and exhibit directional self-cleaning property. The textured surfaces are made of micro grooves which demonstrate interesting anisotropic wetting behavior. In the direction parallel to the grooves, low surface tension testing liquids show very low sliding angle (i.e. directional self-cleaning) which is a key enabler for the self-cleaning effect.



Textured surface obtained by deep silicon etching

Kock-Yee Law and Hong Zhao
Xerox Research Center Webster, Webster, New York
Work performed at Cornell NanoScale Facility

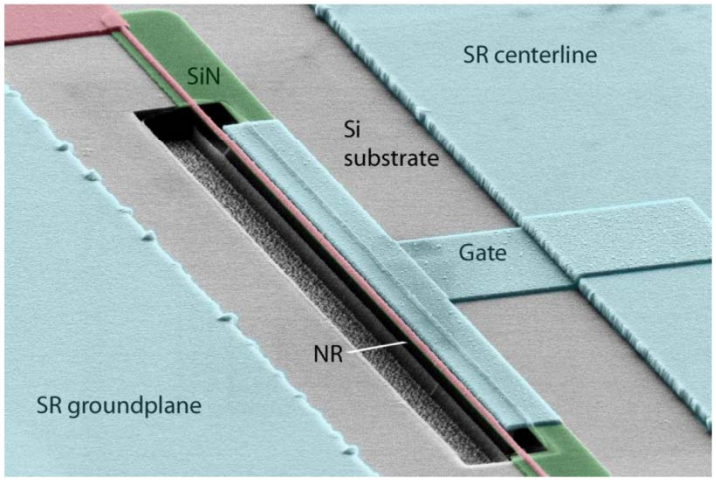


Droplets of water, Hexadecane, and Xerox colid ink on superhydrophobic surfaces.

Measurement of Nanomechanical Devices near their Quantum Ground State

By coupling nanomechanical resonators (NRs) to superconducting microwave resonators (SR), we have been able to prepare and detect mechanical motion near the ground state. Capacitive coupling between the mechanical and electrical resonances enables the electromagnetic wave to act on the mechanical motion and vice versa. At cryogenic temperatures, careful driving and probing of the microwave field favors the back-action cooling of a mechanical mode of the NR towards its motional ground state. Ground state cooling is possible in principle if the high-Q NR frequency is much larger than the line width of the SR. We have designed and fabricated high-Q NRs that are parametrically coupled to high-Q SRs . We have been able to achieve significant cooling to 3.8 +/- 1.2 quanta for our NR mode which indicates a probability of 20% of it being in the ground state.

The cooled mechanical resonator should be a near-quantum-limited position detector.



Nanomechanical Resonator coupled to a superconducting microwave resonator

Prof. Keith C. Schwab (Applied Physics Department, CALTECH)

Work performed at Cornell NanoScale Facility

Large Scale Arrays of Single Layer Graphene Resonators

Graphene, a single layer of carbon atoms bonded in a hexagonal lattice, is the prototypical two-dimensional membrane. Graphene's unparalleled strength, small mass per unit area, ultra-high aspect ratio, and unusual electronic properties make it an ideal candidate for nano-electro-mechanical systems (NEMS) . Until recently, high quality graphene membranes could only be made in small batches using mechanical exfoliation[1] or on a silicon carbide substrate[3]. In this report, we demonstrate a new method to produce large arrays of suspended, single layer graphene membranes on an arbitrary substrate using graphene grown by chemical vapor deposition (CVD). We mechanically resonate the graphene membranes and control the frequency and quality factor by electrostatic tuning and temperature

The techniques described here provide a step toward practical graphene-based devices. This work shows that it is possible to fabricate large arrays of low mass, high aspect ratio, CVD-grown single-layer graphene membranes while maintaining the excellent electronic and mechanical properties that make graphene such a desirable material. These membranes produce low-mass, high-frequency, and highly-tunable nanomechanical resonators that are useful for applications in sensing and signal processing.

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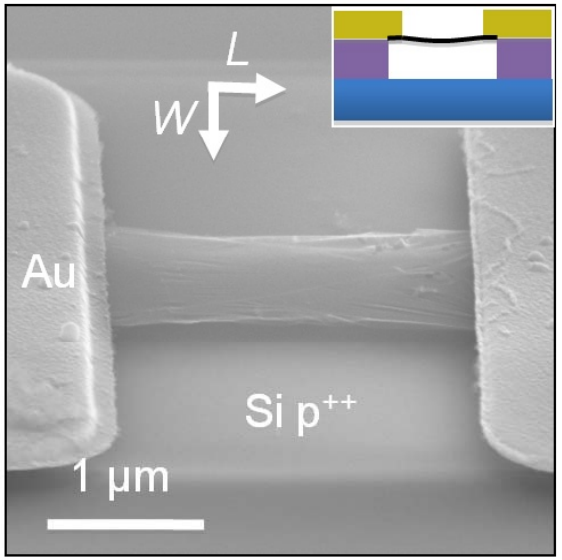


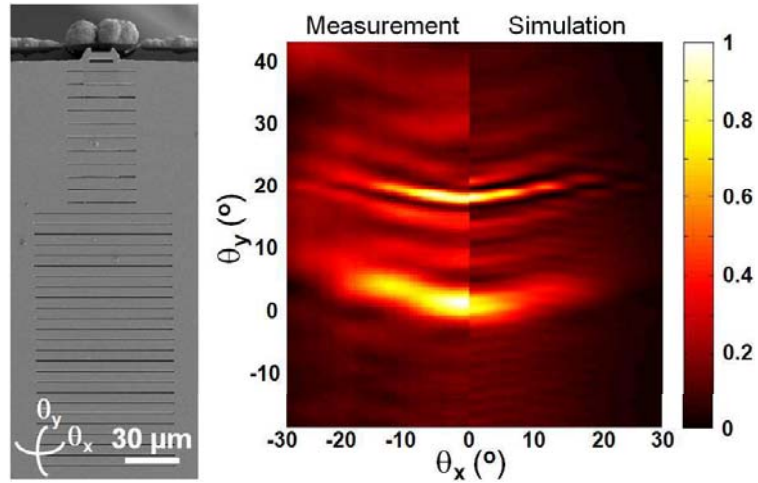
Angled SEM image of a suspended graphene membrane clamped to gold electrodes. Inset is the cross-section.

Profs. Paul L. McEuen, Jeevak M. Parpia, and Harold G. Craighead , Cornell University
Work performed at Cornell NanoScale Facility

Harvard University

Multi-beam Quantum Cascade Laser Project

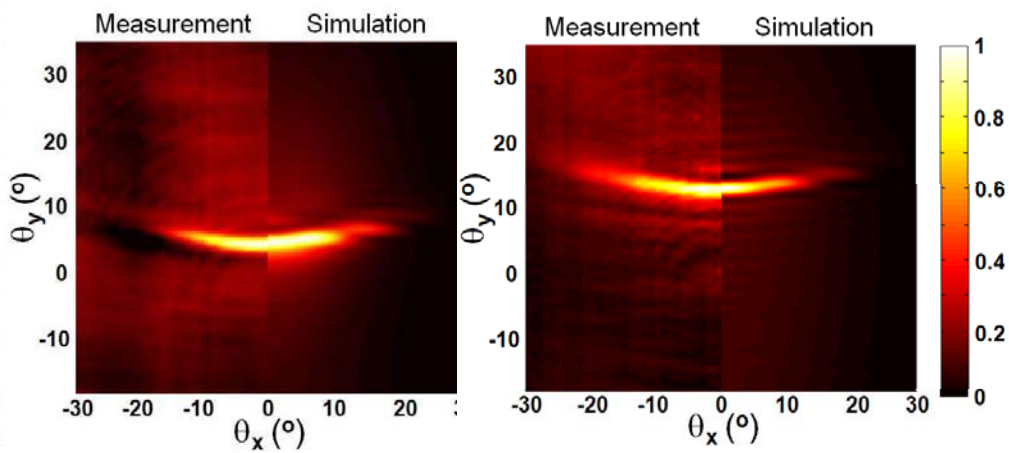
The purpose of the Multi-beam Quantum Cascade Laser Project is to create semiconductor lasers that can create multiple emissions with the same or different wavelengths. Such devices are potentially useful for applications such as interferometry, holography, and differential absorption LiDAR (light detection and ranging). The devices work by efficiently transferring laser emission onto surface plasmon modes on the laser facet and using plasmonic Bragg gratings to coherent scatter the energy of the surface plasmons into certain directions in the far-field.



A single-color quantum cascade laser emitting two beams. Left panel: SEM image of the facet of the λ=8 μm laser. Right panel: measured and simulated far-field intensity profile of the device.

Nanfang Yu, Mikhail Kats, Christian Pflügl, Markus Geiser, Qijie Wang, Mikhail Belkin, and Federico Capasso (Harvard);
Milan Fischer, Andreas Wittmann, and Jérôme Faist (ETH); Tadataka Edamura, Shinichi Furuta, Masamichi Yamanishi, and Hirofumi Kan (Hamamatsu)

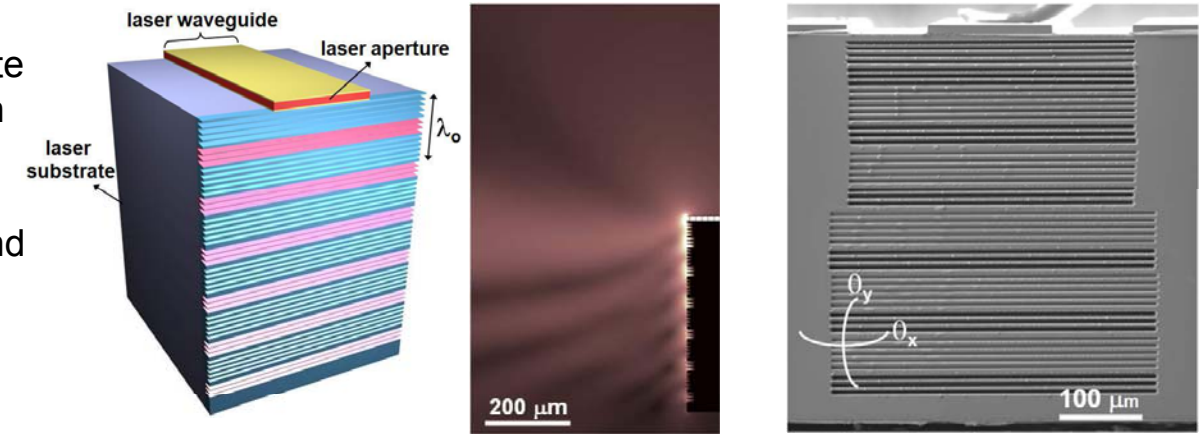
Work performed at the Harvard Center for Nanoscale Systems (CNS).



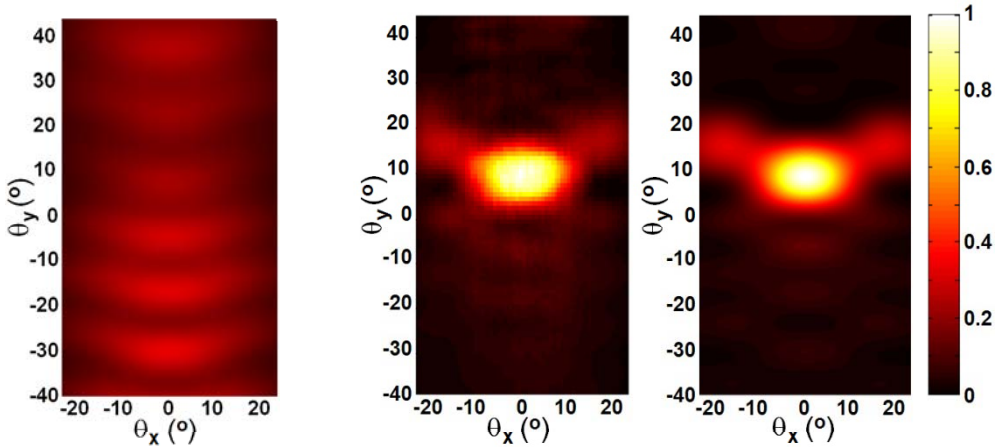
A dual-color quantum cascade laser emitting its two wavelength component into different directions. Left panel: SEM image of the laser facet. Middle and Right panels: far-field intensity profiles of the λ=9.3 μm and λ=10.5 μm components.

Metasurface Terahertz Collimator Project

The purpose of the Metasurface Terahertz Collimator Project is to create terahertz quantum cascade lasers with highly directional emissions. They will be of vital importance for applications such as terahertz imaging, sensing, and heterodyne detection of chemicals. Metasurface structures (i.e., grooves with subwavelength periodicity) are extension of the concept of metamaterials to planar optics. They enable us to tailor the dispersion properties of surface plasmons by coupling surface plasmon modes into cavity resonant modes of the grooves of the metasurface structures.



Left panel: schematic of a terahertz quantum cascade laser integrated with a metasurface collimator. Middle panel: simulated electric-field distribution (|E|) of the device. Right panel: SEM image of the facet of a fabricated device.



Far-field intensity profiles. Left panel: simulated far-field of an original unpatterned λ=100 μm (f=3 THz) quantum cascade laser. Middle and Right panels: measured and simulated far-field of the laser after patterning a metasurface collimator. The lateral and vertical divergence angles of the laser beam are reduced from ~180° to ~10°, leading to much more efficient power collection.

Nanfang Yu, Qijie Wang, Mikhail Kats, Jonathan Fan, and Federico Capasso (Harvard)
Suraj Khamma, Lianhe Li, A. Giles Davies, and Edmund Linfield (Leeds)

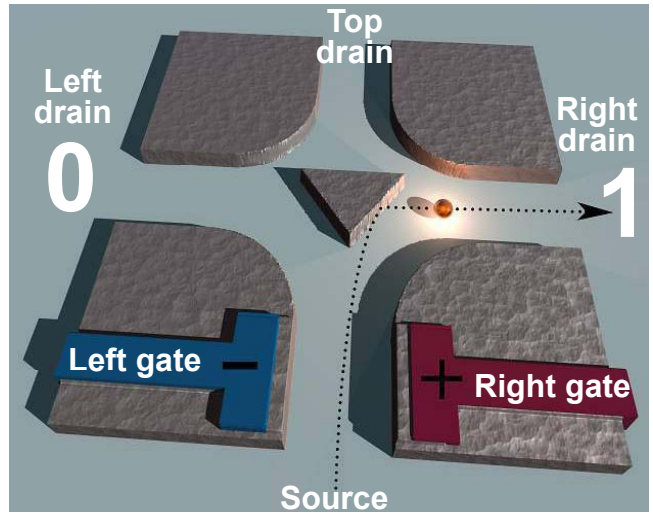
Work performed at the Harvard Center for Nanoscale Systems (CNS).

Ballistic Deflector Transistor

BDT is a novel device that is based upon an electron steering and a ballistic deflection effect. The layout of BDT can be described as a highway intersection, with the triangle shaped deflector sitting in the middle of the intersection. As an electron approaches the intersection from the “south,” it passes through an electric field that causes the particle’s ballistic trajectory to shift ever so slightly. Depending on the field’s polarity, the electron can be made to hit the median so it gets diverted either to “east” or “west.” Electrons flowing to the east would register as a logical "1", while the west registers a "0“ logic in absence of electrons. This binary numeral system of 1s and 0s can be used like in all modern computers and digital electronic circuitry with logic gates operating at ultra high frequencies.

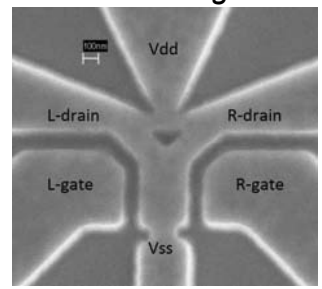
Vikas Kaushal, Ignacio Iñiguez-de-la-Torre and Martin Margala, UMASS Lowell.

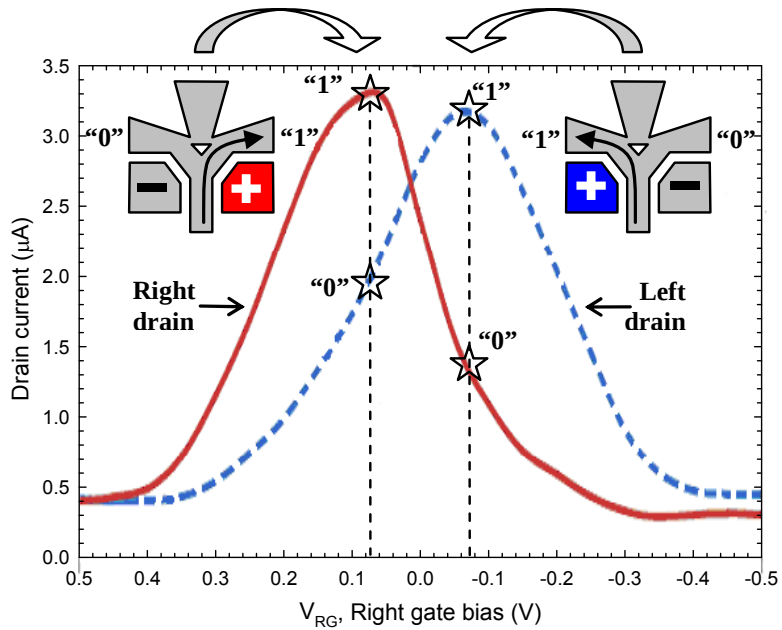
Work performed at the Harvard Center for Nanoscale Systems (CNS).



Artistic conception of the BDT and its operation

SEM image

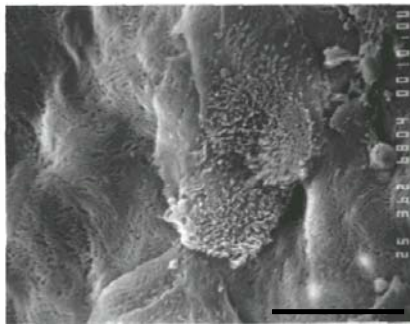




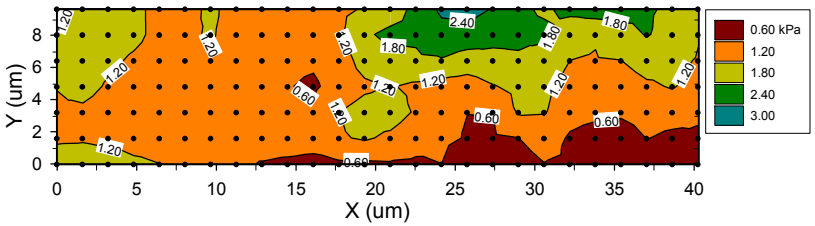
Typical transfer characteristic

Surface Morphology and Stiffness of the Pleura at Micron Scale

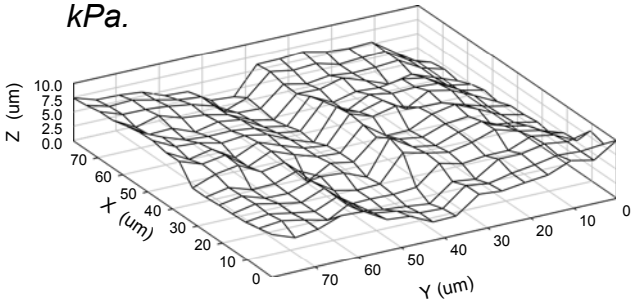
The purpose of the current study is to access the physics of respiratory sliding motion between the lung and chest wall. The stiffness and surface profile of the rat chest wall is studied to support the elastohydrodynamic hypothesis on the lubrication mechanism. The atomic force microscopy (AFM) at CNS was used to probe the parietal pleural surface of rat chest wall in a fluid environment. Modified spherical probes minimized nonlinear deformation of the tissue, avoiding damage. Combined with the capability of low force detection, the AFM allows measurement of the in vitro roughness of the pleural surface in the absence of pre-stress or respiratory motion.



Scanning EM of the mesothelial surface of rat pleura.



Stiffness map of the rat parietal pleura. Average stiffness ranges 0.38-0.94 kPa.



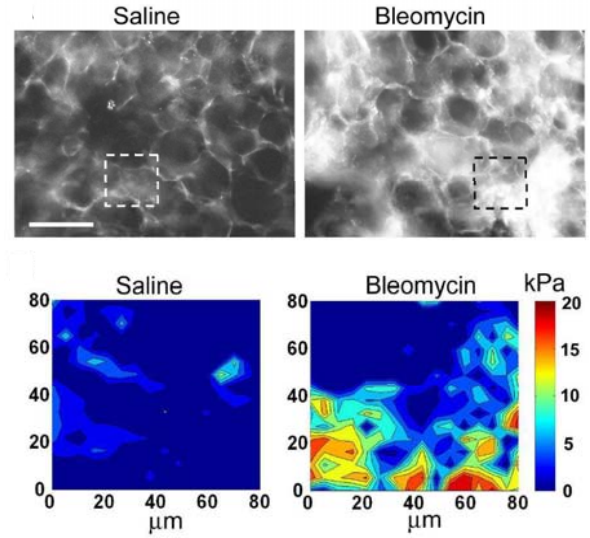
Surface profile of the pleura.

Jae Hun Kim, Stephen H. Loring, James P. Butler, Beth Israel Deaconess Medical Center and Harvard Medical School

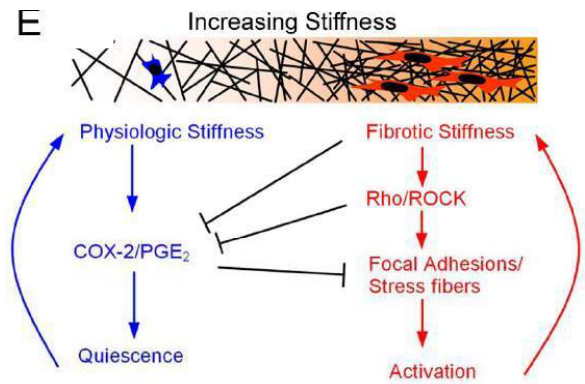
Work performed at the Harvard Center for Nanoscale Systems (CNS).

Lung Fibrosis Matrix Stiffness Project

The purpose of the Lung Fibrosis Matrix Stiffness Project is to investigate the role matrix stiffening plays in the progression of lung fibrosis. Atomic force microscopy microindentation is used to measure the elastic modulus of fresh lung tissue from a murine model of pulmonary fibrosis. Synthetic hydrogel culture systems are then designed to replicate the stiffness of normal and fibrotic tissue, and used to study fibroblast biology within these physiologically relevant mechanical environments.



Lung tissue from normal (saline) and fibrotic (bleomycin) mice, and corresponding stiffness maps.



Lung Epithelium – PGE_2

Cell culture studies reveal two mutually antagonistic feedback loops that control fibroblast activation status, with switching regulated by matrix stiffness.

Daniel Tschumperlin, Justin Mih, Fei Liu, Harvard School of Public Health.

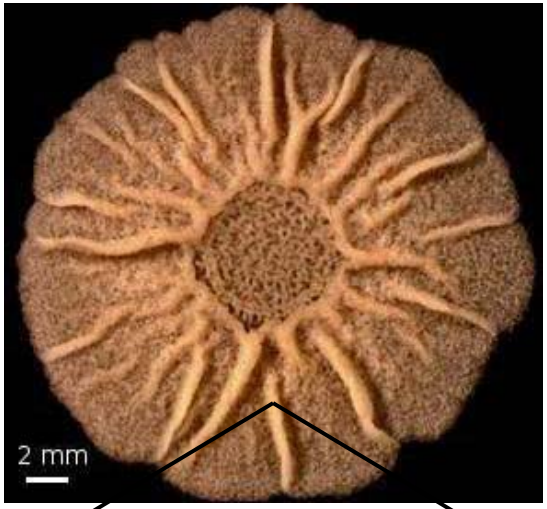
Work performed at the Harvard Center Nanoscale Systems (CNS).

Characterization of Extracellular Matrix Components Extracted from Bacteria

Bacteria form complex, structure communities called biofilms in response to environmental cues . A common feature of biofilms is the formation of an extracellular matrix that holds the cells together. It is composed of polysaccharides, proteins, and nucleic acids and helps maintain the structural integrity of biofilms.

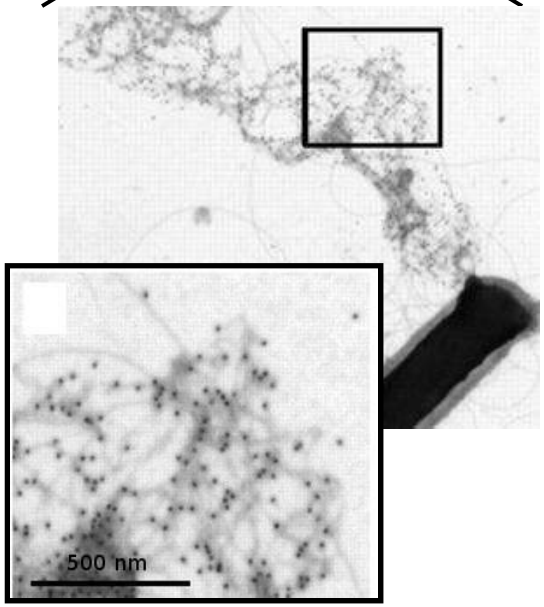
The purpose of this Project is to understand how the different components of the matrix assemble to give the final structure of the colony (see top figure).

Using a Veeco Asylum SPM at the CNS, we extend previous work on the protein component that has been shown to form amyloid fibers. (see electron micrographs in middle and bottom pictures).



A colony of the spore forming bactrium,

Bacillus subtilis



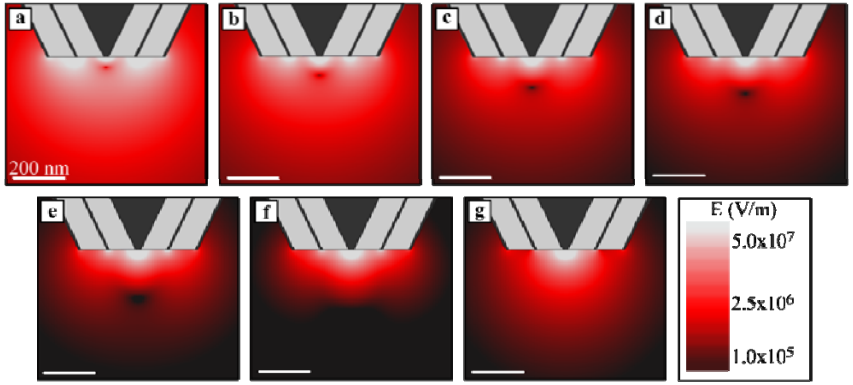
A single cell secreting prrotein fibers. Electron micrographs of negatively stained, immunogold labeled samples from pellicles after 24 h of incubation.

Liraz Chai, Diego Romero and Roberto Kolter, Harvard Medical School, Microbiology and Molecular Genetics.

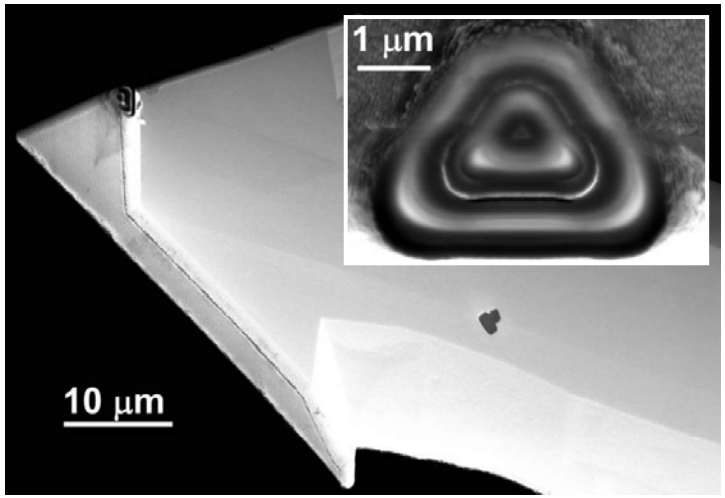
Work performed at the Harvard Center for Nanoscale Systems (CNS).

Triaxial AFM Probes for Nanoassembly

We have created atomic force microscope (AFM) probes with three coaxial electrodes at their tip. By applying specific voltages to the three electrodes, a zero in the electric field will be formed displaced from the surface of the probe. Objects less polarizable than the medium will be pushed into field zero with negative dielectrophoresis (nDEP). Trapped objects may then be positioned by the AFM. It is necessary to use a non-contact method to trap nanoscale particles because otherwise they will become irreversibly stuck by adhesion forces.



By adjusting the voltages on a triaxial AFM probe, it is possible to create a movable zero in the electric field. This zero may be used as a nDEP trap to manipulate nanoscale objects.



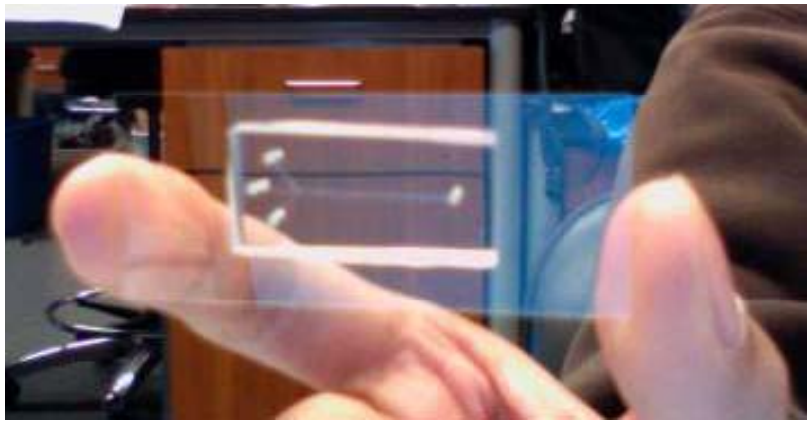
SEM image of a finished triaxial AFM probe. The inset shows the nanofabricated insulating and conducting layers at the tip.

Keith A. Brown and Robert M. Westervelt, Harvard University School of Engineering and Applied Science

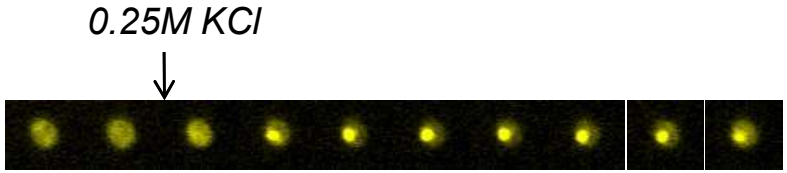
Work performed at the Harvard Center for Nanoscale Systems (CNS).

Signal Processing in Single Live Cells

The purpose of the project is to understand how information about intensity and identify of environmental signals are encoded and transmitted inside a cell and eventually decoded to generate specific gene expression. To precisely and dynamically control the environments that single cells are exposed to, we fabricated a microfluidics chip using soft-lithographic techniques at the Center for Nanoscale Systems. We then immobilize live cells inside this microfluidics chip, change the extracellular environments and use fluorescence microscope to monitor activity changes of signaling molecules inside live cells.



A microfluidics chip fabricated at the Center for Nanoscale Systems.



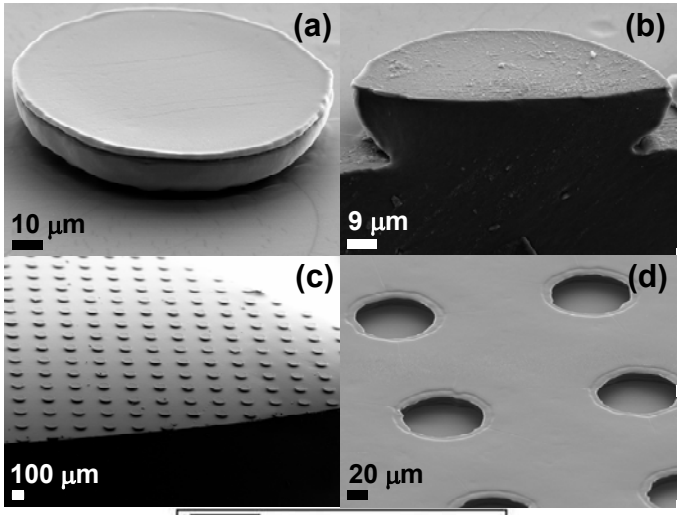
Monitoring translocation of a fluorescent signaling protein into nucleus inside a live yeast cell in response to osmotic stress.

Nan Hao and Erin O'Shea
Howard Hughes Medical Institute
Harvard University FAS Center for Systems Biology
Departments of Molecular and Cellular Biology and Chemistry and Chemical Biology

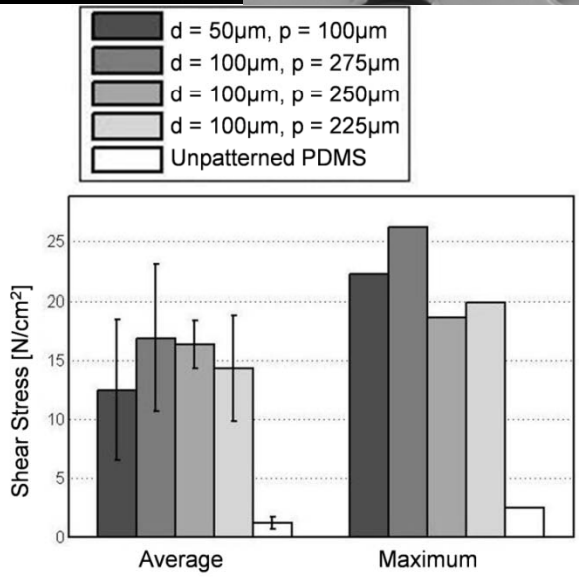
Work performed at the Harvard Center for Nanoscale Systems (CNS).

Shear-mode Contact Splitting for Enhanced Interfacial Bonding in Elastomers

Under the MRSEC program, we have developed a synthetic dry adhesive via micro-texturing of an elastomer film. The fabrication of the microstructures is achieved by standard photolithography processes. In testing the microstructures, it was found that patterning the surface of a PDMS film with hemispherically shaped microscale pillars (aspect ratio = 0.2) enhances shear adhesion to a rigid substrate by an order of magnitude when compared to untextured control films.



SEM images of the microstructure, the cross –section, a fibrillar array, and the SU-8 mold from which the microstructures were fabricated.



Shear adhesive strength of varying fibrillar diameters and pitches (center-to-center distance between structures)

Rebecca Kramer, Carmel Majidi and Robert Wood
SEAS, Harvard University
Work performed at the Harvard Center for Nanoscale Systems (CNS).

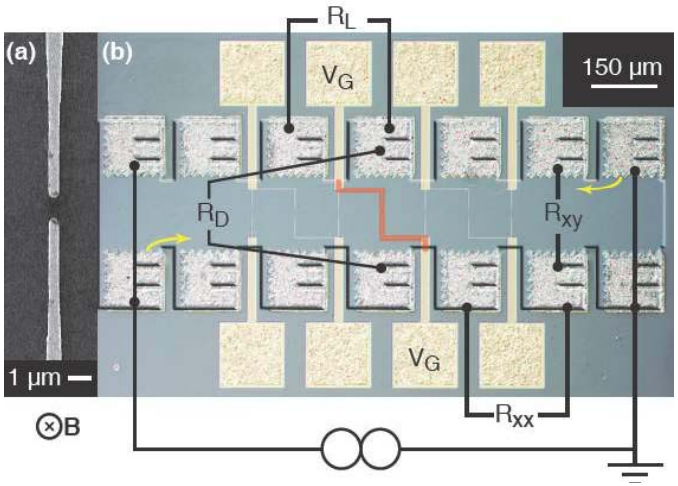
Supported in part by NSF MRSEC, grant #: DMR-0820484.

Quasiparticle Tunneling and Interference in the FQHE Regime

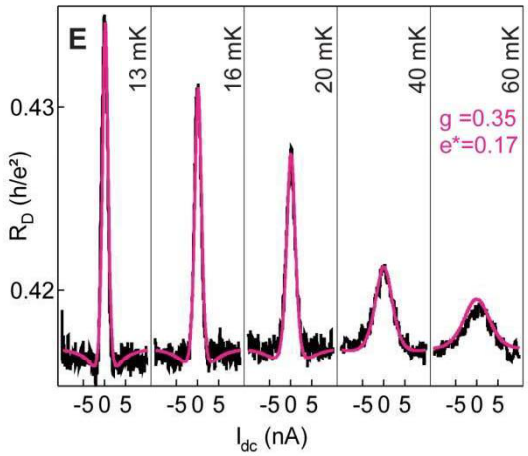
The fractional quantum Hall effect (FQHE) arises in two-dimensional electron systems under a strong perpendicular magnetic field and demonstrates interesting nonclassical phenomena, including chiral current-carrying edge channels. To better understand the FQHE we study tunneling of quasiparticles across quantum point contacts (QPCs), allowing us to measure the quasiparticle charge and their interaction strength. In addition, measurements of quasiparticle interference are planned in order to search for nonabelian statistics among other interesting physics.

Measurements are performed on GaAs/AlGaAs heterostructures with ohmic contacts and surface deposited split-gates partially fabricated at the Harvard CNS facilities.

X. Lin, C. Dillard, M. Kastner, MIT.
Work performed at the Harvard Center for Nanoscale Systems (CNS).



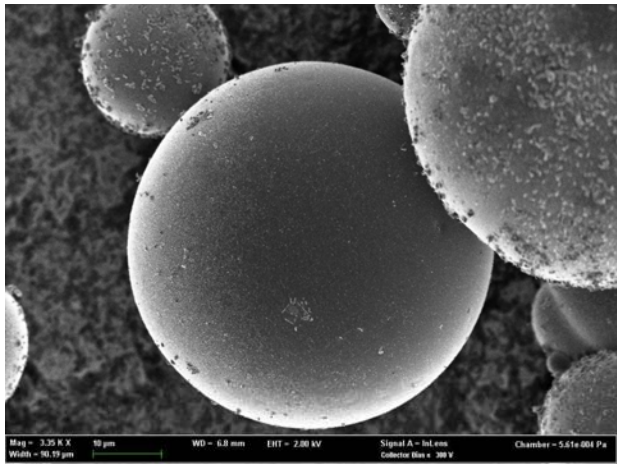
(a) SEM picture of a quantum point contact (QPC) fabricated with surface deposited split-gates. (b) Optical false-color image of the type of device studied. Yellow arrows indicate current flow and red lines highlight the region of the split gates.



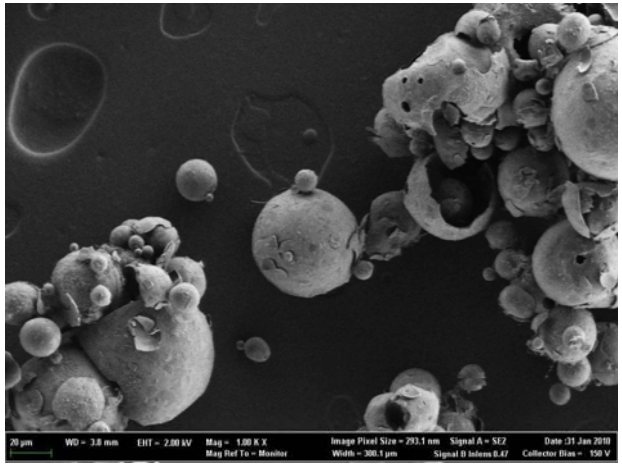
Tunneling conductance across a QPC at filling factor 5/2. Fits to data give values for the quasiparticle charge e and interaction parameter g.*

SiC-CMB Development

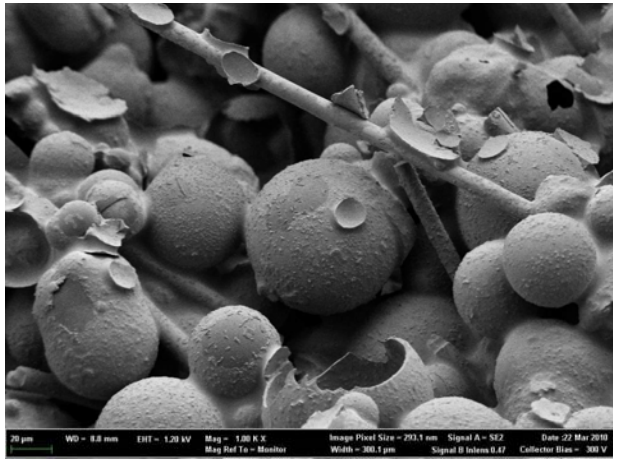
Trelleborg Offshore, in conjunction with other industrial partners, are developing a nanometer-scale silicon carbide (SiC) coating for our hollow carbon microsphere (CMB) product line. This material is expected to play a significant role in the next generation of ablative heat shields for aerospace applications, especially heat shield applications involving high aeroshear loading. Use of the CNS facilities is an invaluable resource for characterization of our coating development efforts.



TECMB-45 commercially available hollow carbon microspheres



SiC coated CMBs



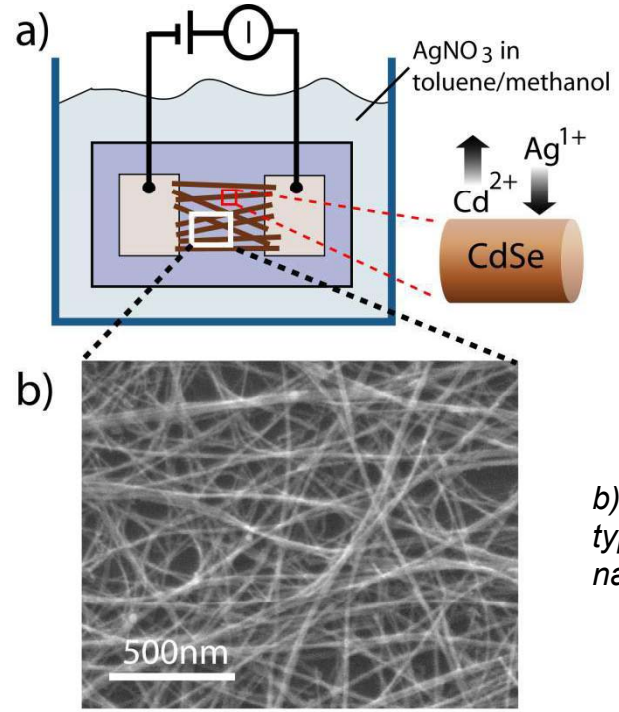
Ablator prepared using SiC coated CMBs

Dr. Kipp B. Carlisle, Staff Scientist, Trelleborg Offshore US – Boston

Work performed at the Harvard Center for Nanoscale Systems (CNS).

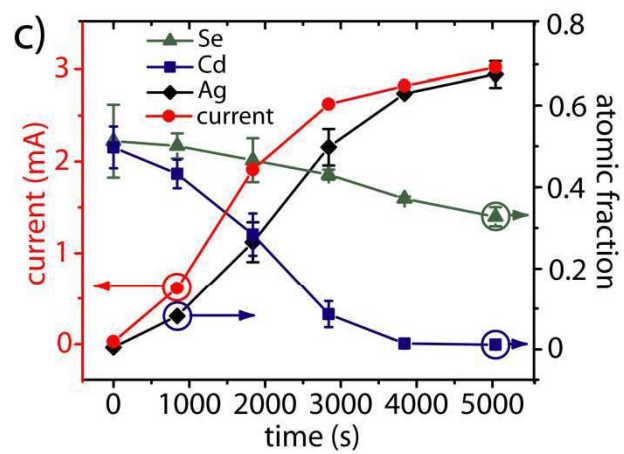
In Situ Electrical Monitoring of Cation Exchange in Nanowires

Controlling the extent of cation exchange reactions is a promising route for tuning the material composition and properties of nanostructures. Here we demonstrate how measuring the conductivity of nanowires during cation exchange can be used to monitor the transition from CdSe to Ag_2Se, in situ. In addition, by imaging the same wire mat region before and after complete cation exchange, we find that the shape and morphology of the nanowires are completely preserved.



a) Schematic of the setup used to monitor the conductivity of nanowires contacted between two electrodes in solution.

b) SEM image of a typical CdSe nanowire mat.



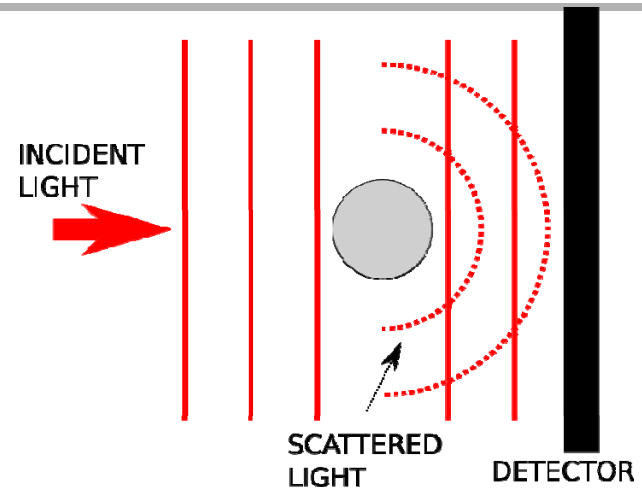
c) Current through the nanowire mat at a bias of 100 mV (left axis) and elemental composition of the nanowire mat (right axis) as a function of time during cation exchange from CdSe to Ag_2Se.

August Dorn,* Peter M. Allen, Daniel K. Harris, and Moungi G. Bawendi, Department of Chemistry, MIT

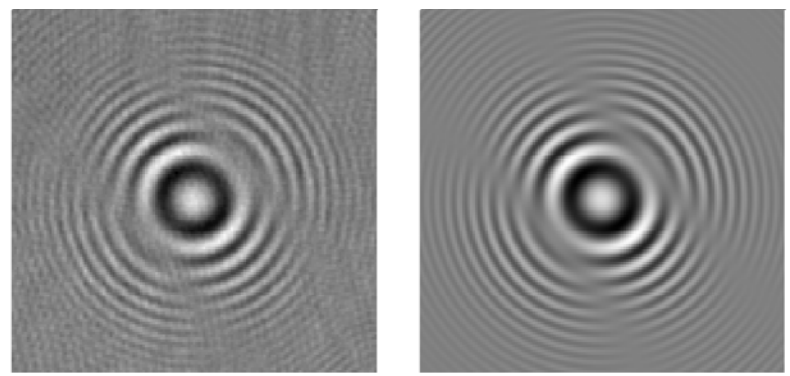
Work performed at MIT and Harvard Center for Nanoscale Systems (CNS). To be published in Nano Letters.

Analyzing Holograms of Colloidal Particles

Using the fast 3D imaging capabilities of digital holographic microscopy, we study interactions in colloidal systems to facilitate the self-assembly of novel materials from colloids. We utilize the NNIN/C cluster to analyze holograms formed by single spheres and clusters of spheres in terms of exact electromagnetic scattering theory, which allows us to measure the 3D position of colloidal particles with nanometer precision, from a single 2D hologram.



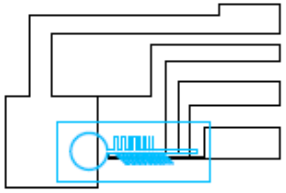
Schematic diagram of hologram formation. A CMOS camera records the interference pattern formed by light scattered by a colloidal particle and an incident laser beam.



(Left) Experimentally recorded hologram of a cluster of 2 1-µm polystyrene spheres resulting from a depletion attraction. (Right) Best-fit hologram computed using NNIN/C cluster.

Jerome Fung and Vinothan N. Manoharan,
Department of Physics and School of Engineering and Applied Sciences, Harvard University.

Work performed at the Harvard Center for Nanoscale Systems (CNS).



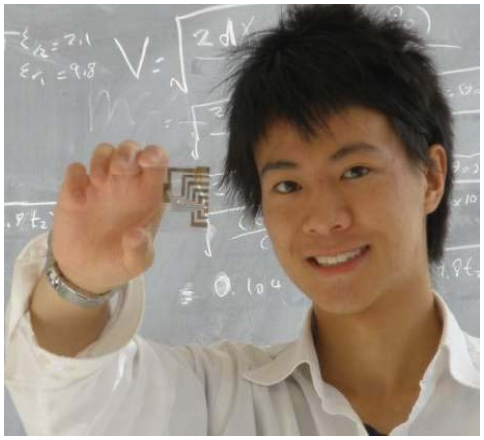
Microfluidic Biosensor

A means for biosensors to manipulate fluid using electrowetting has been developed, where actuation is achieved by selectively inducing electric fields in certain portions of the fluid through applying a voltage via patterned electrodes. The ability to manipulate small volumes of liquid without the need for moving parts makes electrowetting a promising fluid transport mechanism that will improve the robustness and efficiency of biosensors.

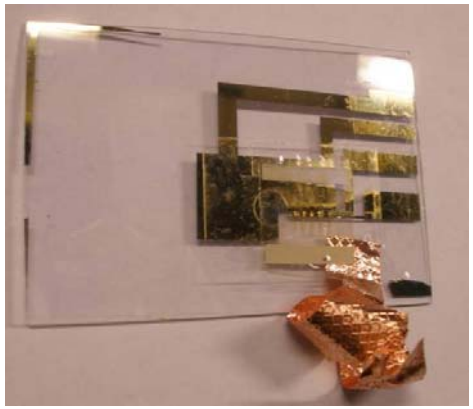
The biosensor can be completely submerged and is able to extract ambient fluid on command. The fluid is then actuated into a single long channel from which small droplets will be pinched off and directed into separate branching channels leading to sites where bioassays will be conducted. All operations were accomplished with a square wave of less than 17V p-p.

Jonathan Yam[1], Alex Nemiroski[2], Robert M. Westervelt[2]
[1]University of Toronto, [2]Harvard University (SEAS)
NSEC NSF PHY-0646094, University of Toronto ESROP Fellowship

Devices fabricated at the Harvard Center for Nanoscale Systems (CNS).



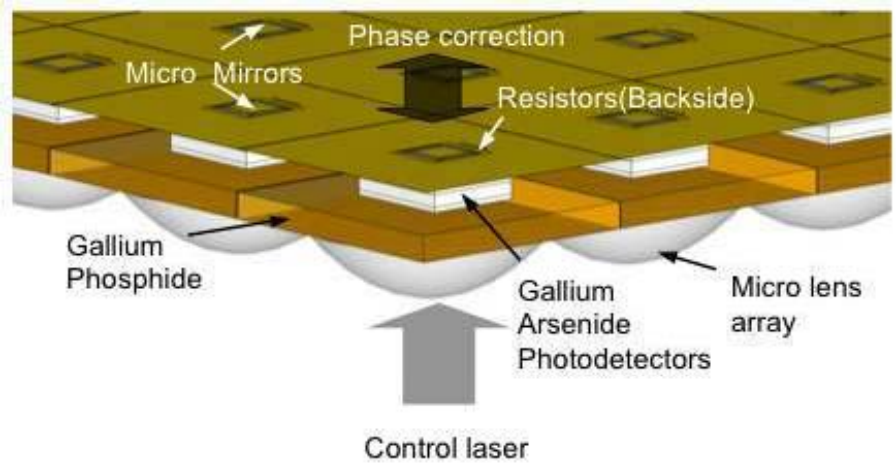
Shows small scale of microfluidic device.



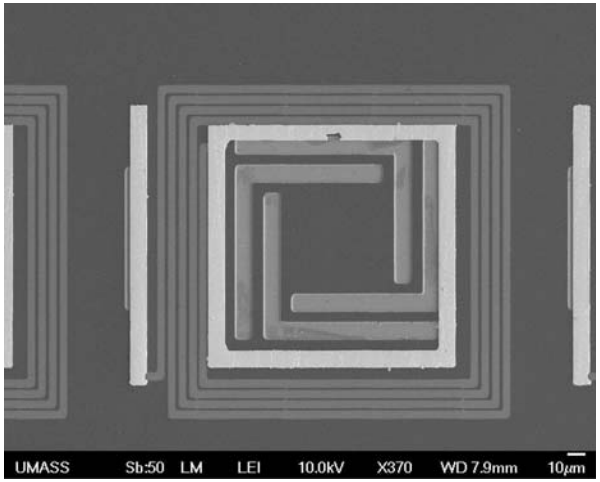
Close-up of fluid transport device.

Optically Controlled MEMS

The goal of this project was to demonstrate a new technique for optically addressing and actuating large arrays of micromirrors requiring just a single voltage bias. In these devices an optical signal focused on an element's photodiode through a transparent substrate changed the ratio of the voltage across a load resistor allowing the capacitor to charge which in turn changed the position of a cascaded micro-mirror. Control signals as low as 100 microwatts caused the mirror to move sufficiently to change the phase of a reflected signal by half a wavelength, thereby providing a phase change to the reflected beam at that element. The immediate motivation for the device here was adaptive optics, but the idea may be extended to other MEMS based devices applications such as tip/tilt optical switches and micro fluidics.



3-D Schematic of the 900 pixel Optically Controlled (OC) MEMS



Integrated Tantalum Nitride (TaN) thin film resistors around a Silicon Nitride (Si_3N_4) mirror

Vaibhav Mathur,William D.Goodhue from UMass Lowell and Bahareh Haji-Saeed, Jed Khoury from Air Force Research Lab

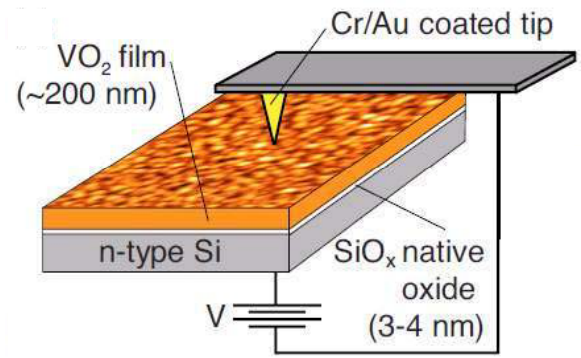
Work performed at the Harvard Center for Nanoscale Systems (CNS).

Appl. Phys. Lett. 96,211103(2010)

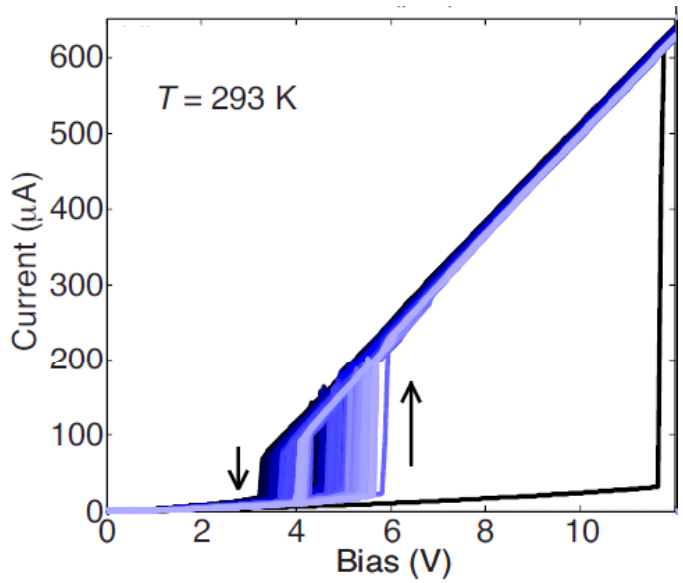
Nanoscale Resistance Switching in VO_2

VO_2 displays an insulator-to-metal transition with useful properties such as fast 80 fs switching time, high resistivity ratio up to 10^5, large change in optical reflectance, and tunability near room temperature. Proposed applications include bolometers, memristors, tunable-frequency metamaterials, and data storage. Here, we demonstrate the first controlled local phase switching of a VO_2 film using a biased conducting atomic force microscope tip. Our imaging technique opens up the possibility for an understanding of the microscopic mechanism of phase transition in VO_2 as well as its potential relevance to solid state devices.

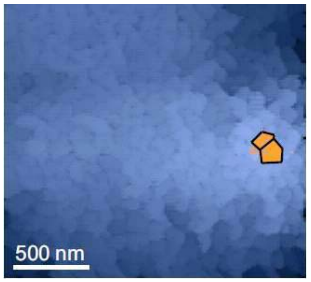
Jennifer Hoffman and Shriram Ramanathan,
Harvard Physics Department and SEAS. Work performed at the Harvard Center for Nanoscale Systems (CNS).



A conducting atomic force microscope tip is used to apply a local voltage to a VO_2 film.



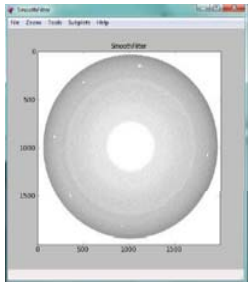
After application of an initial "training" voltage ~12V, the transition vollows a repeatable hysteresis loop.



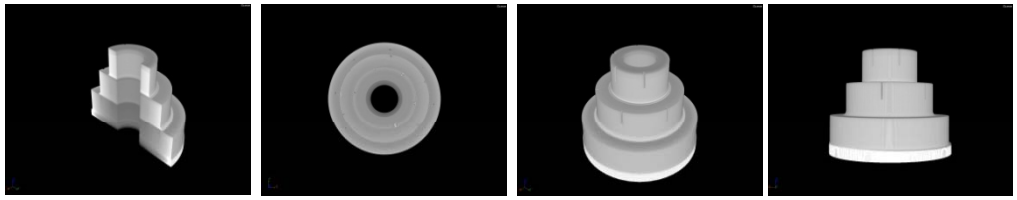
An image of the current flow with a fixed 3.45 V applied to the tip shows the insulator-to-metal transition seeded at 2 grains of the film.

Life Extension of Structural Components via an Improved NDT Methodology

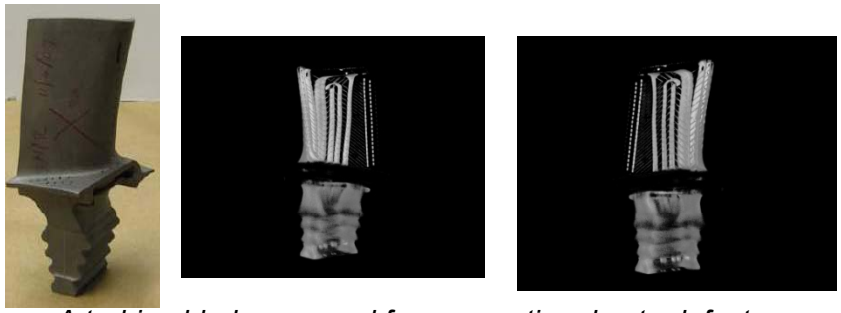
The purpose of the Improved NDT Methodology is to decrease the *minimum detectable flaw size* while increasing the "**NDT process"** sensitivity and reliability for structural components, by using advanced NDT processes which utilize digital technology. The methodology takes a systems approach to NDT, and the incorporation of multiple NDT techniques (with overlapping defect inspection capabilities) in a redundant manner has resulted in improved NDT reliability. A comparison between the 3D-CT and other radiographic NDT processes was made, and the inspection data was incorporated into image analysis and probability of detection (POD) software to quantify the benefit of the advanced techniques and the effect of various sources of inspection "noise" on POD capability. The goal is to reliably extend the time in operation for structural components at or near the end of their originally intended design lives without increasing the risk of catastrophic structural failure.



A "Wedding Cake" specimen manufactured from 6061 Al-alloy material with various flat bottom hole (FBH) and side drilled hole (SDH) synthetic defects laser drilled into it, and image analysis software optimization.



Various perspective and segmented cutaway views of the wedding cake sample. An increased amount of "noise" is apparent near the bored out center hole region.



A turbine blade removed from operation due to defects introduced during a service weld-repair process, and front/back 3D-CT views of the reconstructed blade.

Brian P. Hohmann and Prof. T.W. Eagar, MIT Dept. of Materials Science and Engineering.
Work performed at the Harvard Center for Nanoscale Systems (CNS).

Photonic Crystal Nanobeam Lasers

Objective: Low-threshold photonic crystal lasers operating at room temperature based on high *Q*/*V* nanobeam cavities. We also reported a very large spontaneous emission factor ($\beta \sim 0.97$).

Device and Fabrication

- *High Q nanobeam cavities with sub-wavelength photon confinement*
- *Quaternary InGaAs/InAlGaAs compressively-stained quantum wells*
- *E-beam lithography + RIE etching + HCl wet etching*

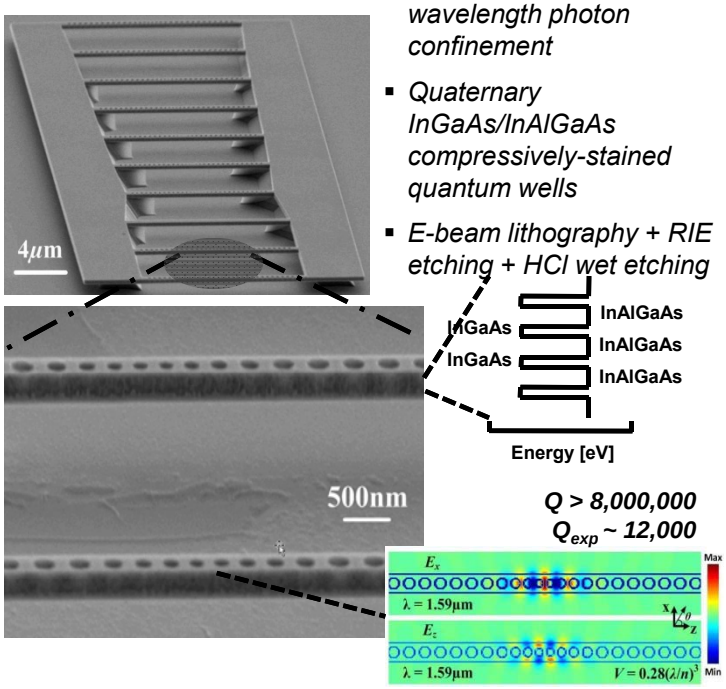
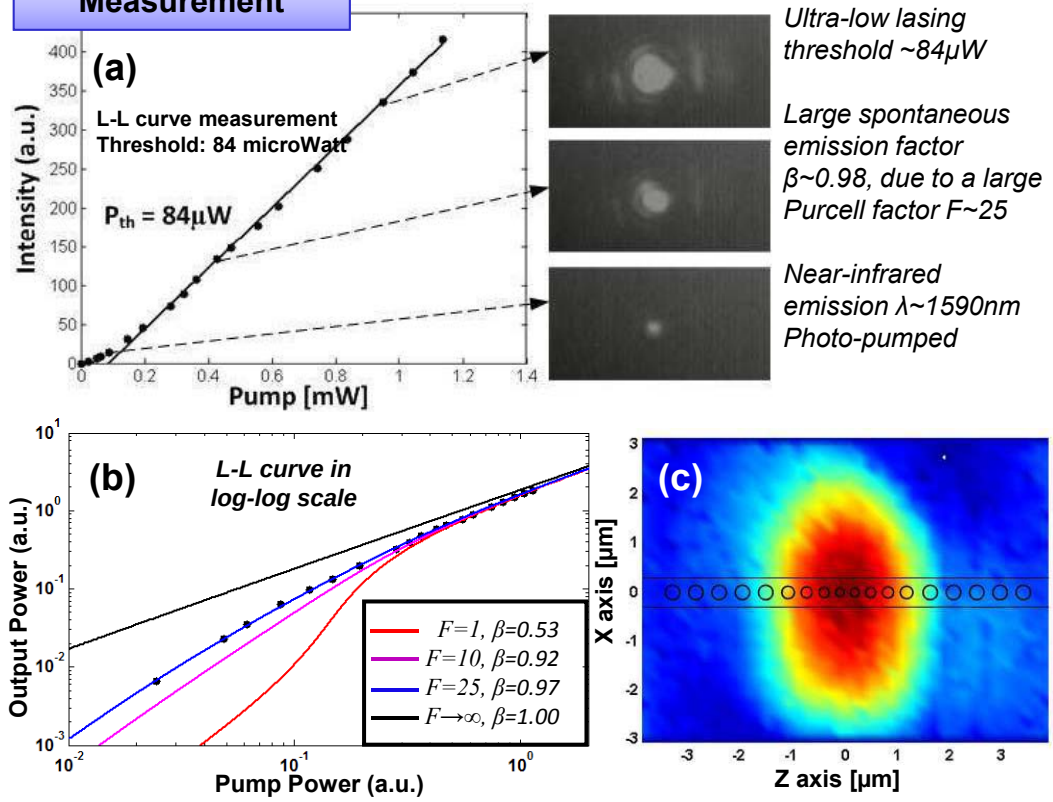


Fig. 1. SEM images of the laser devices with illustrations of the quantum wells embedded within the beam and the photon cavity mode profile.

Measurement



Ultra-low lasing threshold ~84μW

Large spontaneous emission factor β~0.98, due to a large Purcell factor F~25

Near-infrared emission λ~1590nm Photo-pumped

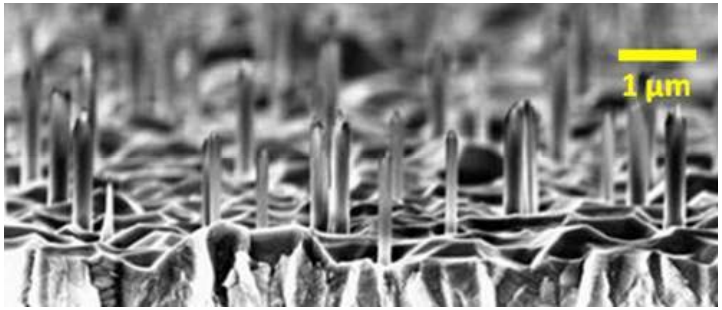
Fig. 2 (a)(b) L-L curve measurement in linear and log-log scale. (c) Lasing power as a function of pump beam position.

Contributors: Yinan Zhang, Mughees Khan, Yong Huang, Jae-Hyun Ryou, Parag Deotare, Russell Dupuis, and Marko Loncar, Harvard University and Georgia Institute of Technology.

Work performed at the Harvard Center for Nanoscale Systems (CNS).

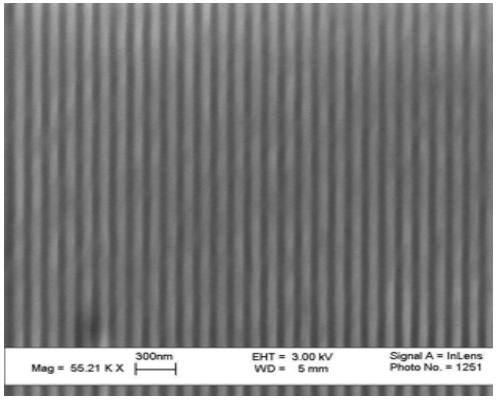
Diamond Nanowires for UV Detection

Diamond nanowires are useful for a number of different applications, due to the unique properties of diamond, including wide bandgap and extreme hardness and thermal conductivity. By etching diamond films laterally or vertically, nanowires can be produced in a parallel array or in random positions. After suitable contacts are made, the nanowires can be used as UV sensors, high-speed high-power FETs, field emission sources or other devices.



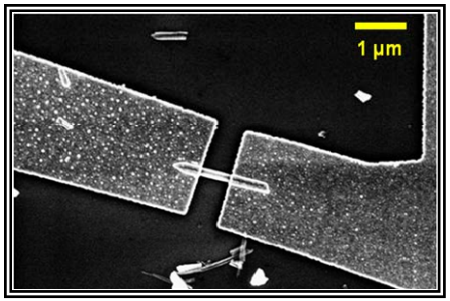
Vertically-etched diamond nanowires

Laterally-etched array of diamond nanowires



Steven Palefsky, Chih-Hsun Hsu, Hongsik Park and Jimmy Xu, Brown University

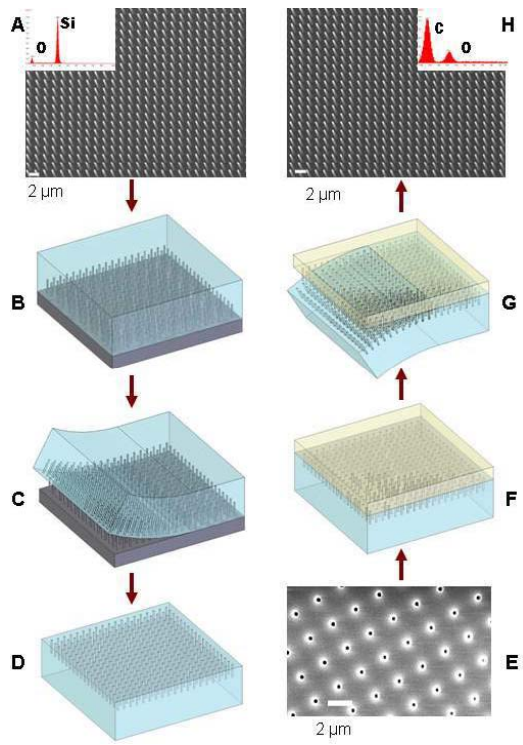
Work performed at the Harvard Center for Nanoscale Systems (CNS).



Single diamond nanowire device with metal contacts

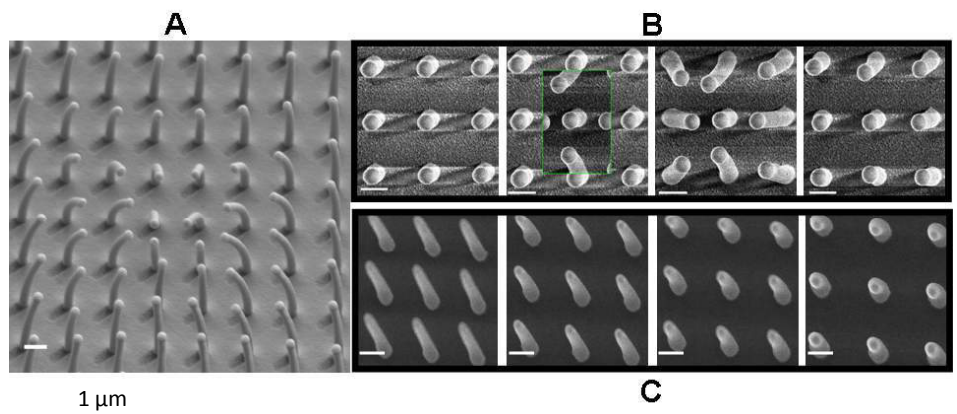
Fabrication of Bioinspired Actuated Nanostructures with Broad Applications

We have produced versatile high-aspect-ratio nanostructured surfaces inspired by the echinoderm skin, gecko foot, and superficial neuromasts of fish. For this purpose, we have developed a soft-lithographic method that allows the one-to-many replication of nanostructures in arbitrary materials, cross-sections, orientations, and symmetries. The resulting bioinspired surfaces enable multifunctional behaviors that include superhydrophobicity, actuation, and sensing. Using CNS's FE-SEM, we have already demonstrated a remote and reversible actuation method via controlled electron beam application.



(Left) Our soft-lithography process for creating nanostructured surfaces with high-aspect-ratio features. EDS insets (CNS) show different compositions of identical structures.

(below) FE-SEM images showing reversible electron beam-actuated epoxy nanoposts, operating as arrays of actuators.



B. Pokroy, A.K Epstein, M.C.M. Persson-Gulda, and J. Aizenberg, Harvard School of Engineering and Applied Sciences, *Adv. Mater.* 2009, *21*, 463–469.

Work performed at the Harvard Center for Nanoscale Systems (CNS).

Building Chiral Colloidal Clusters

Enantiomers are pairs of structures that are non-superimposable mirror images of each other (Figure 1). Fu and Powers, researchers at Brown University, have a theory which implies that enantiomeric mixtures can be separated by applying shear to the mixture. We are building chiral colloidal clusters consisting of four different sized particles to be used by Fu and Powers to verify their theory. If successful, this method of separating enantiomers may be used to separate larger organic compounds and proteins.

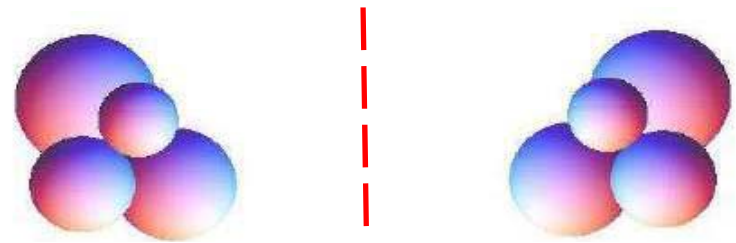


Figure 1: Enantiomers

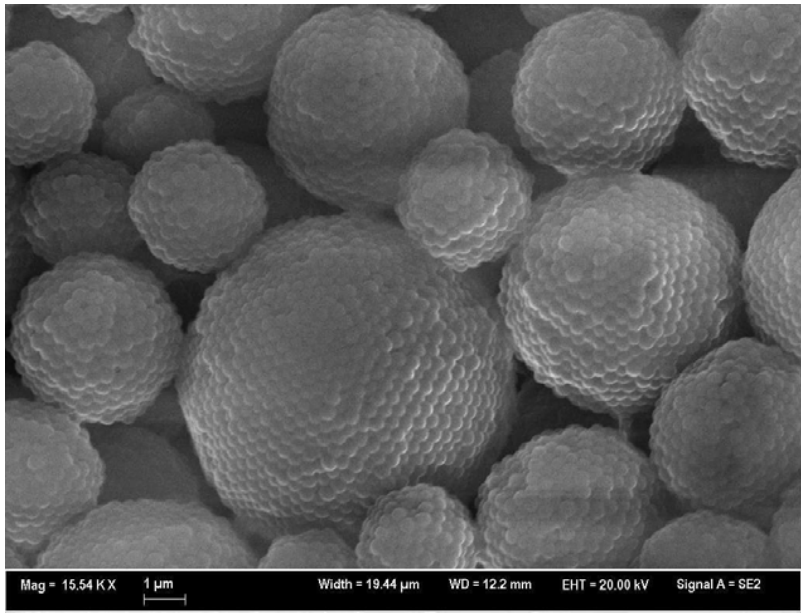


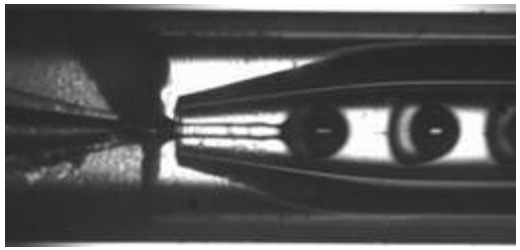
Figure 2: SEM image of colloidal clusters

Suhare Adam1, James Wilking2, David A. Weitz2
Houston Baptist University1, Harvard University2
NSF DMR-0649199

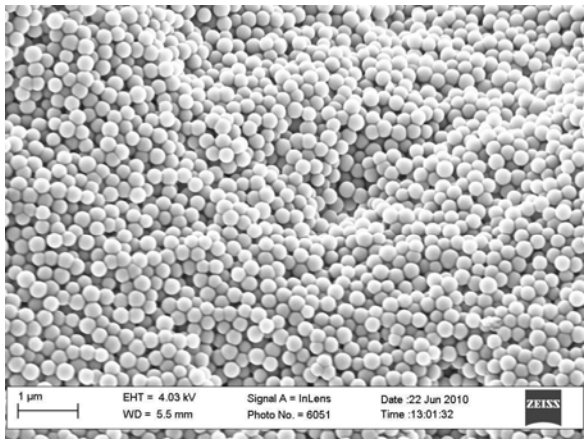
Work performed at the Harvard Center for Nanoscale Systems (CNS).

Stable, Controllable Nanoparticle-Shelled Microbubbles

Gas filled microbubbles are used in medicine as drug delivery devices as well as ultrasound contrast agents (UCAs). They are excellent UCAs because they readily expand and contract due to pressure changes in ultrasound waves, thereby generating reflective waves that enhance imaging contrast. The current methods of fabrication lack control over bubble size and shell thicknesses, which result in uneven signal outputs. To overcome these limitations, we used glass capillary microfluidics to produce bubbles with modifiable diameters and shell thicknesses by simple adjustments in device geometry and flow rates. Our key approach to stabilization was the use of nanoparticles which strongly adsorb at the interface of liquid and air. We produced monodisperse bubbles using an air-in-oil-in-water double emulsion template in which nanoparticles were dispersed in a volatile organic solvent as the oil phase. Upon evaporation, the oil suspension formed a shell of packed nanoparticles surrounding the gas bubble. However, we found that the bubbles were unstable. We hypothesize that this is due to low surface tension in our organic solvent, and in the future plan on using more viscous oils to aide in bubble fabrication. Once the issue of solvent viscosity is solved, we will have developed a set of techniques that enables us to fabricate stable, monodisperse microbubbles that function as customizable UCAs.



Microfluidic fabrication of liquid microbubbles. This device allows us to have precise control over bubble dimensions.



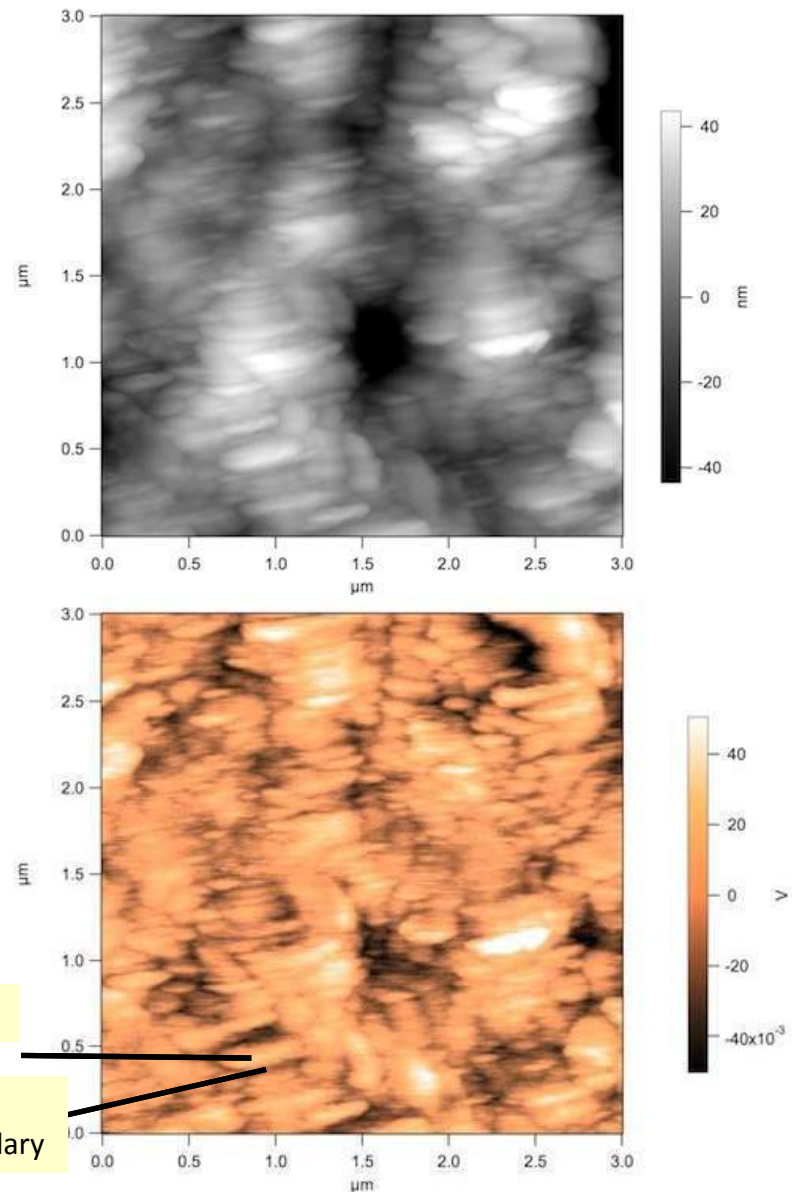
Scanning electron microscope image of monodisperse SiO_2 nanoparticles. These can be used to create hollow shells for many applications, such as drug delivery.

Beth Ann Lopez[1], Wynter Duncanson[2], David Weitz[2], [1]The University of New Mexico, [2]Harvard University
NSF PREM, DMR-0611616
Work performed at the Harvard Center for Nanoscale Systems (CNS).

Controlling Nanoscale Electronic Variability in ZnO:Al Transparent Conducting Films

Aluminum-doped zinc oxide (ZnO:Al) is becoming an increasingly important material for use in solar cells. We have used a technique known as Kelvin force microscopy to study variation in the work function (a materials property that is critical in many electronic applications) of ZnO:Al. We have seen that the work function varies significantly on and off grain boundaries, which supports a model to explain how electrons travel through the material. Our results also demonstrate how we can tune the work function by altering the growth conditions of the film and by applying certain post-processing treatments.

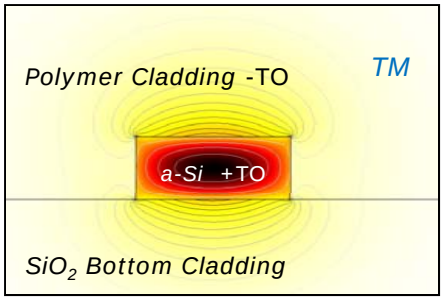
Image: 3x3 μm^2 scans of the height (top) and change in work function (bottom) of a ZnO:Al film. The top scan clearly shows where the grains and grain boundaries are located, and the bottom scan indicates that changes in the work function correspond to the granularity of the material. The displayed potential varies inversely with the surface work function (higher potential = lower work function).



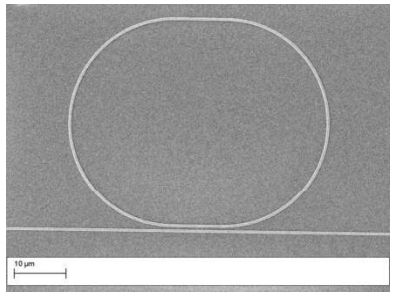
Ruby Lee, Rafael Jaramillo, Shriram Ramanathan, Harvard University, NSF ECCS-0821565
Work performed at the Harvard Center for Nanoscale Systems (CNS).

Athermal Photonics Circuit on a Si platform

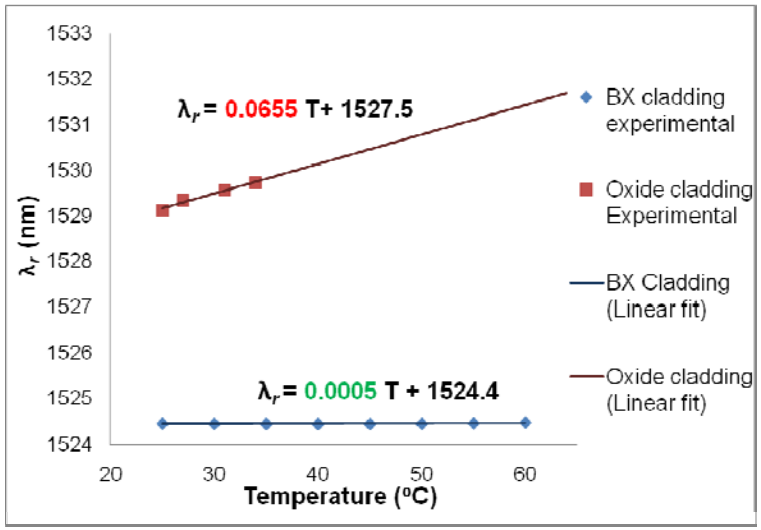
The motivation for this work comes from an increasing demand for on-chip electronic-photonic integration based on a Si platform. However local and global temperature excursions due to on-chip electronics prove problematic for Si based photonic devices due to their high thermo-optic coefficient (TO). This proves crucial in applications such as wavelength division multiplexing (WDM) and high resolution spectroscopy where TO index variations result in temperature dependent resonant wavelength shift (TDWS) thereby limiting its resolution. This project focuses on a passive solution wherein an a-Si (deposited at the Harvard CNS facility) waveguide with a positive TO is compensated by a polymer clad that has a negative TO thereby resulting in athermal behavior



Athermal design rule involving expansion of the mode into the cladding and compensation of +TO effects from the core by the -TO effects from the cladding



An example of a prototype design that shows the top view of an unclad a-Si ring with a racetrack configuration and a bus waveguide



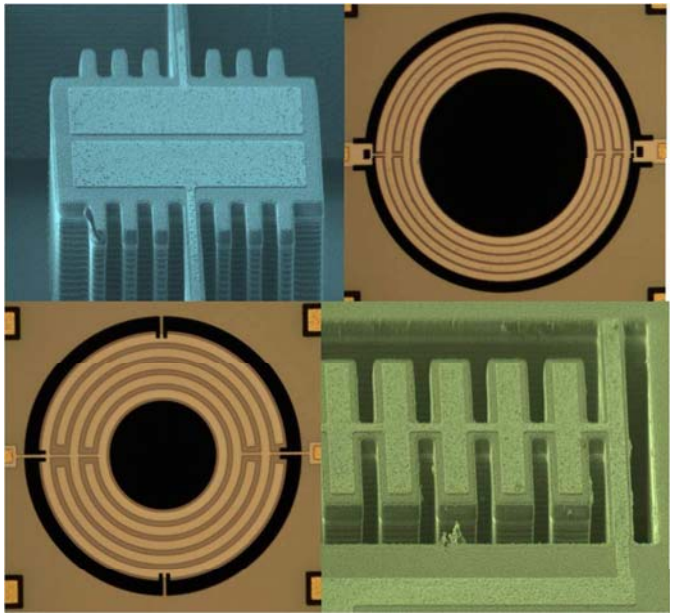
Demonstration of a working prototype performance that shows near complete TO compensation with a polymer (BX) clad where the TDWS comes down from 65.5 pm/K for an oxide clad to 0.5 pm/K for a polymer (BX) clad

Vivek Raghunathan, Jurgen Michel and Lionel C Kimerling, MIT

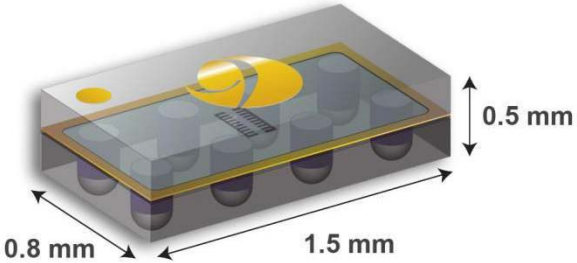
Work performed at the Harvard Center for Nanoscale Systems (CNS).

TCMO: Temperature Compensated MEMS Oscillator Project

The TCMO™ is a new generation of high stability reference clocks that is based on Micro-Electro-Mechanical resonator technology, developed by Sand 9. Oscillator clocks are used as frequency references in every wireless transciever system, such as the cellular phone. Prototype silicon-based resonators with high quality factors and low phase noise serve as the frequency selecting element in the TCMO. Development of the new technology has been performed in part at the CNS nano-fabrication facility through basic silicon lithography, micromachining, metrology and testing.



Silicon-based RF micro-resonator designs.

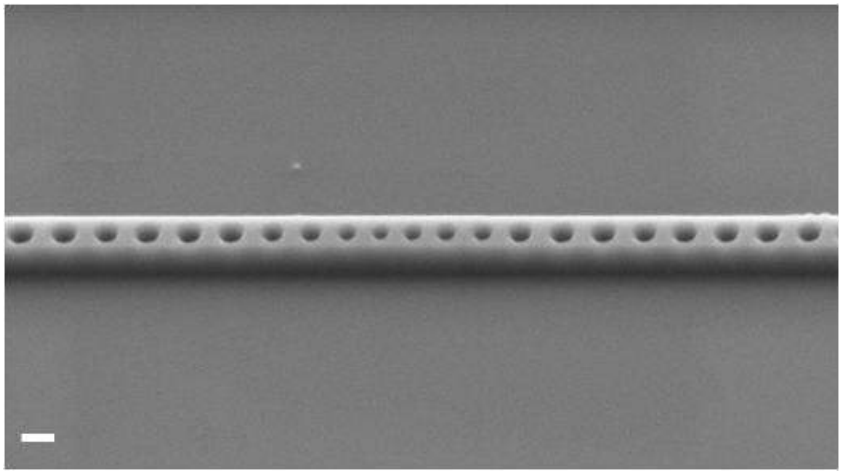


Model TCMO chip-scale package with embedded micro-resonator and control circuits.

Sand 9, Cambridge MA
Work performed at the Harvard Center for Nanoscale Systems (CNS).

Visible Nanophotonics with TiO_2 Thin Films

The purpose of this project is to create a passive photonics platform for the visible wavelengths based on titanium dioxide (TiO_2) thin films. The development of such an architecture is relevant given the availability of various robust quantum emitters in the visible, including fluorescent dyes, colloidal quantum dots, and the nitrogen-vacancy (NV) center in diamond. For instance, waveguides and resonators are critical elements in the triggering, manipulation, and extraction of single photons from an emitter. We have fabricated waveguides, microresonators, and nanobeam photonic crystals using electron beam lithography, electron beam evaporation, and reactive ion etching. The resulting structures are intended for optical probing via coupling to diamond nanocrystals containing single NV centers.



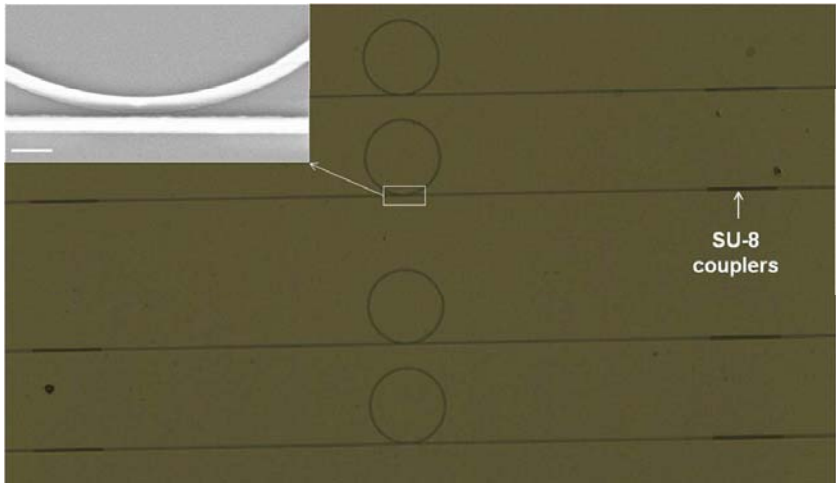
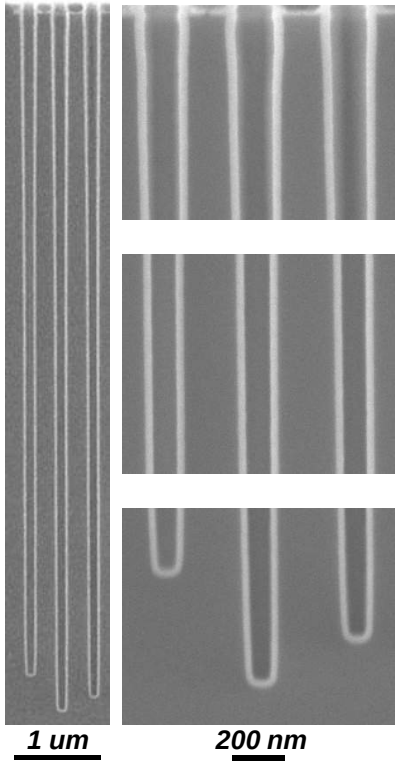


Figure Captions: (Top Right) Nanobeam photonic crystal cavity fabricated in a sputtered TiO_2 thin film deposited on a silicon wafer. The Si substrate can be selectively wet-etched to create a suspending nanobeam. The scale bar corresponds to 200nm. (Bottom Right) Elements of a quantum circuit comprising of TiO_2. micro-rings coupled to TiO_2 waveguides on a SiO_2/Si wafer. SU-8 couplers have been added to deliver light into and out of the circuit. The scale bar in the inset corresponds to 1μm.

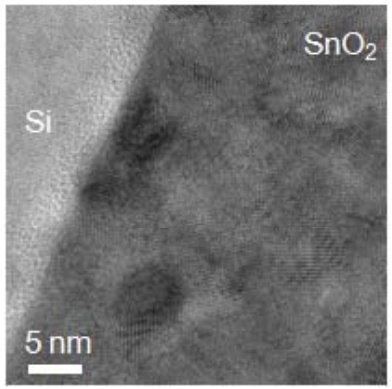
Lončar Group, Harvard University (in collaboration with the Bawendi (MIT), Bulovic (MIT), and Mazur (Harvard) groups). Work performed at the Harvard Center for Nanoscale Systems (CNS).

Low Temperature ALD of SnO_2 Project

The purpose of the Low Temperature Atomic Layer Deposition of SnO_2 Project is to fabricate highly pure, conductive and transparent SnO_2 thin films at lower temperature than conventional ALD range (>200 ^oC). The combination of a newly synthesized Sn precursor, N^2,N^3-di-*tert*-butyl-butane-2,3-diamido-tin(II), and hydrogen peroxide enables the film growth at substrate temperature as low as 50 ^oC. This successful low temperature growth of conductive nanocrystalline SnO_2 films by ALD allows it to be exploited in transparent electrodes for displays, organic light emitting diodes, solar cells, conductive and protective coatings on plastic, microchannel electron multiplier plates, or as a semiconductor layer in transparent transistors.



Cross-sectional SEM of holes with aspect ratio 50:1 coated by ALD SnO_2.



Cross-sectional high-resolution TEM image of the nanocrystalline SnO_2 film.

Jaeyeong Heo, Adam S. Hock, and Roy G. Gordon, Harvard University.

Work performed at The Center for Nanoscale Systems (CNS) at the Harvard, a member of the NNIN.

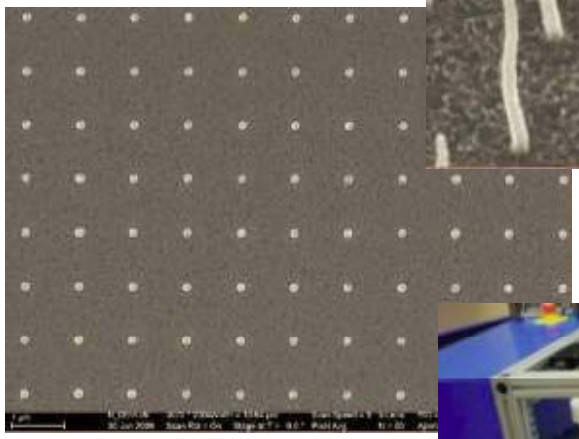
Georgia Tech

Biohazard Water Analyzer and Detector using Carbon Nanofiber Arrays

Early Warning is a developer of Biohazard Analyzers that directly measure the total and viable cell concentrations of individual species of bacteria, viruses and protozoa parasites.

NASA's biosensor works when a single strand of nucleic acid in a target solution comes into contact with a matching strand of nucleic acid attached to the end of an ultra-conductive carbon nanofiber. The matching strands form a double helix that generates an electrical signal which is used to determine the presence of specific microorganisms in the sample. Because of their tiny size, millions of carbon nanofibers can fit on a single biosensor chip allowing identification of very low cell counts. Early Warning has also developed its own intellectual property pertaining to electrochemical biosensing devices, detecting multiple organisms at the same time, detecting molecules over a wide range of concentrations, and mass fabrication methods.

Resulting carbon nanofiber grown from Ni catalyst



130 nanometer diameter Ni catalyst

Early Warning Biohazard Analyzer system

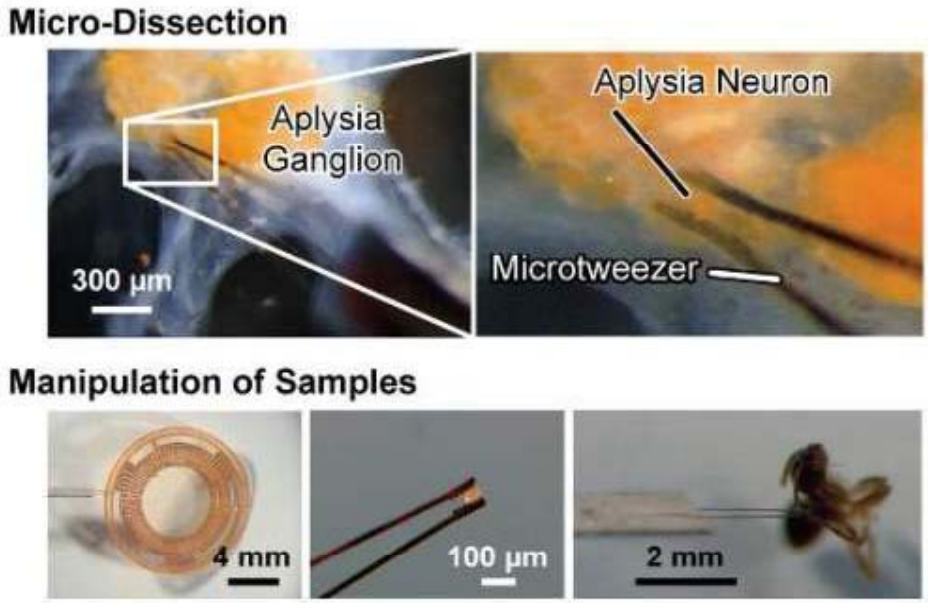
Devin Brown, Georgia Tech, Bruce Gale, University of Utah, Alan Cassell, NASA Ames Research Center, Neil Gordon, Early Warning Inc.
Work performed at Ga Tech NRC.

NanoGrip Technologies: Mechanically Actuated Microtools for Micromanipulation

NanoGrip Technologies, Atlanta, offers a series of microscale manipulation tools that eliminate the need for electrostatic or electrothermal forces to provide gripping strength.

The NG70xx series is ideally suited for applications that require long-lasting tips and high-resolution control for grasping, manipulating and excising microscale objects. Among specific applications are MEMS micro-assembly, fiber optic positioning, stiction release, acute cellular manipulations, microdissection and microscopy sample positioning.

The series features nine tip styles, including square, serrated and piercing tips. Other features include microfabricated Ni metal tips, 500nm resolution tip control, a grasping range from 0mm to 1mm, and a temperature operating range from -40ºC to 100ºC.



Application space for mechanically actuated microtools includes

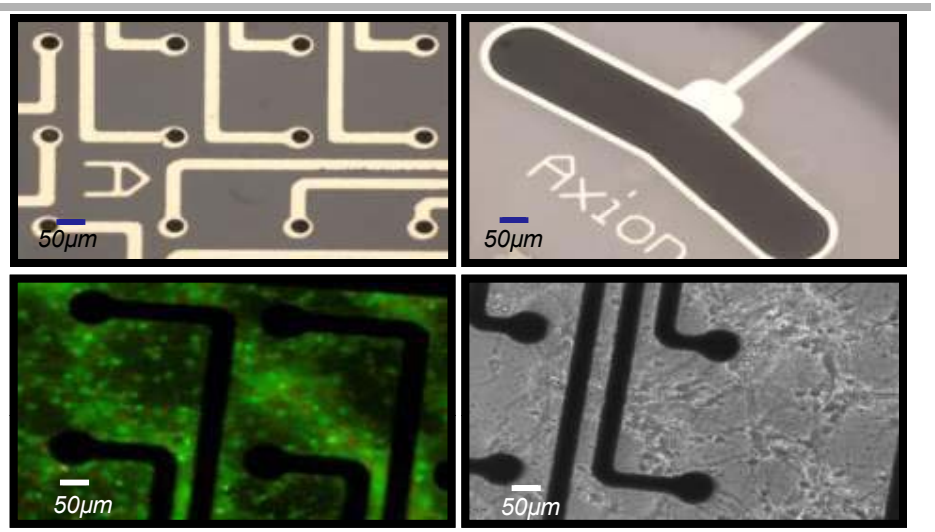
- ***Microdissections, microsurgery***
- ***MEMS/NEMS manipulation,***
- ***MEMS release***
- ***Optical crystal manipulation, assembly***
- ***Mechanical characterization, assembly***

Brock Wester, James Ross, Swami Rajaraman, Mark Allen
NanoGrip Technologies, Atlanta, GA
Work performed at Ga Tech NRC.

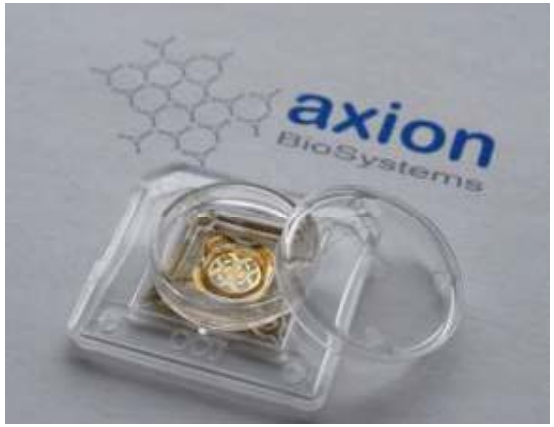
Axion BioSystems: Microelectrode Array Systems for Electrophysiology

Axion Biosystems has developed the next generation multi-electrode array (MEA) technology to provide unprecedented access to cellular information at a reasonable cost.

Axion Biosystems' proprietary technology addresses two challenges that have existed in the cellular analysis field. First, we have eliminated the long-lasting stimulation artifacts from the electrophysiological tissue response, enabling simultaneous stimulation and recording. Second, we have created fabrication methods for low-cost microelectrode arrays. The combination of these developments allows for high throughput cell-based assays and superior electro-active tissue diagnostics.



Optical micrographs of Axion 2-D MEA (top) and cultures of neurons growing on the MEAs (bottom)



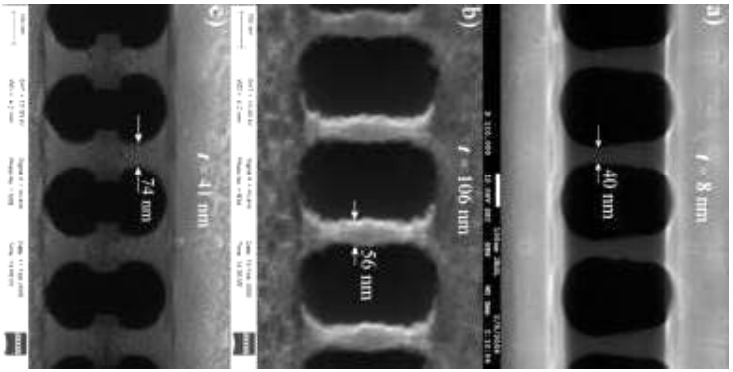
Application space for Microelectrode Arrays includes

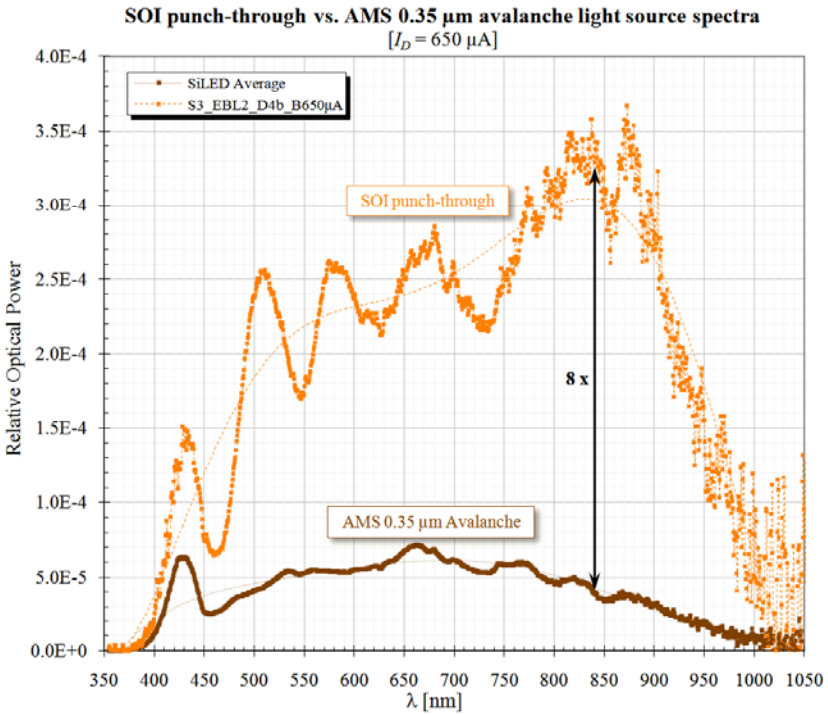
- ***In-vitro neuronal cultures***
- ***Brain slice analysis***
- ***In-vitro cardiac cells***
- ***Drug discovery***
- ***Toxicity screening***

Swami Rajaraman, James Ross, Edgar Brown, Mark Allen
Axion BioSystems, Atlanta, GA
Work performed at Ga Tech NRC.

Design and Manufacture of Nanometer-scale SOI Light Sources

THE monolithic integration of silicon light emitting devices (Si-LEDs), for the formation of all-silicon optoelectronic systems, is in growing. Any proposed solution requiring a change of the present very large scale integration (VLSI) fabrication routine, as well as deviating from the standard low-voltage IC operation (5 V or less), will be rejected by the chip manufacturers, which are reluctant to alter their well-established strict processing procedures. Here, it is demonstrated that, by utilizing conventional VLSI design rules, 1) Si-LEDs can be fabricated in present technology, using the same masks which include the other Si CMOS/BiCMOS components. This yields full Si-LED/Si circuits integration, on the same chip, without any modifications to the standard VLSI fabrication processing and Materials, and 2) Low-voltage operation is achieved, by fabricating Si-LEDs composed of heavily doped n p junctions, operating at a reverse bias of 4.25 V. Optical radiation could be readily detected and measured at reverse currents of less than 1 mA. Accordingly, the power consumption levels are 1 mW to 10 mW, i.e., comparable to the power consumption of Si output driving circuits integrated within the same chip. This voltage compatibility enables the operation of entire Si-LEDs/CMOS-BiCMOS integrated optoelectronic VLSI chips, using a single power supply. This is unlike avalanche Si-LEDs, which require high voltage and high power consumption.



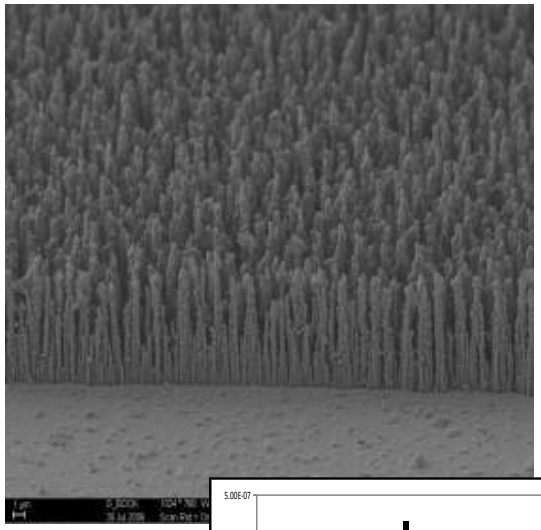


A. W. Bogalecki, M. du Plessis and P. J. Venter
Carl and Emily Fuchs Institute for Microelectronics
University of Pretoria, South Africa
Work performed at Ga Tech NRC

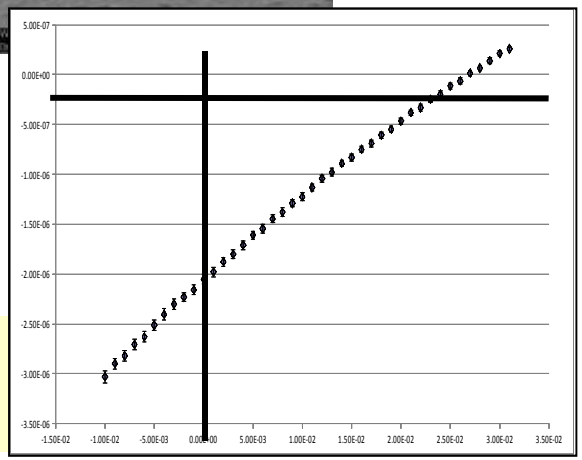
3-Dimensional CNT/Silicon Based PV Cell

3D solar cells capture photons from sunlight using an array of miniature “tower” structures that resemble high-rise buildings in a city street grid. The cells could find near-term applications for powering spacecraft, and by enabling efficiency improvements in photovoltaic coating materials, could also change the way solar cells are designed for a broad range of applications.

The goal is to harvest every last photon that is available to the cells. By capturing more of the light in the 3D structures, much smaller photovoltaic arrays can be used. On a satellite or other spacecraft, that would mean less weight and less space taken up with the PV system.



CNTs coated with trilayer of n-Si, i-Si and p-Si



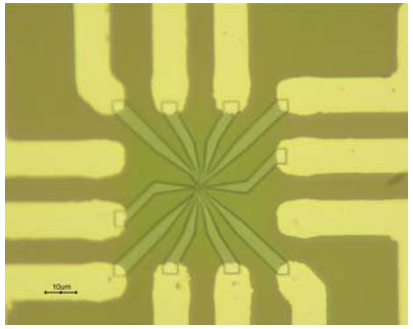
3-D CNT Solar Cell is demonstrated capable of generating its own power (I-V curve passes through quadrant IV)

Phillip Bonhomme, University of Louisiana, Lafayette (2009 SURE Student)
Jud Ready, Greg Book, Georgia Tech
Work performed at Ga Tech NRC

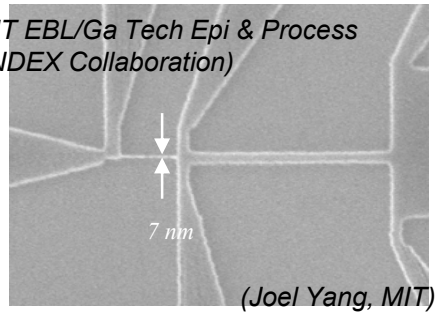
Graphene Process/Device Integration for Post-CMOS Electronics

Epitaxial graphene on silicon carbide (EG) is has demonstrated its importance for fundamental graphene research and its applications potential. Continuous layers can be grown over SiC wafer-size surfaces, thereby allowing large scale patterning by conventional lithographic methods. Recently discovered multilayer epitaxial graphene (MEG) shows large electronic mobilities, with values exceeding 250,000 cm2/Vs at room temperature. Due to the rotational stacking, the layers are effectively decoupled and their properties are similar to a single graphene sheet. A major challenge is to develop electrostatic gating schemes to control the charge density of the material without significantly affecting the carrier mobilities of the pristine material. We show that epitaxial graphene grown on both Si-terminated and C-terminated faces can be gated by electrostatic gates patterned on top of the graphene. We further show that significant gating can be achieved in an all graphene, side-gated structure. This is a particularly promising scheme that potentially overcomes the detrimental effect of gate dielectrics on the graphene layer.

Epitaxial Graphene Process Development

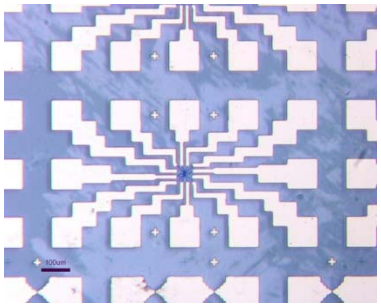


MIT EBL/Ga Tech Epi & Process (INDEX Collaboration)



(Joel Yang, MIT)

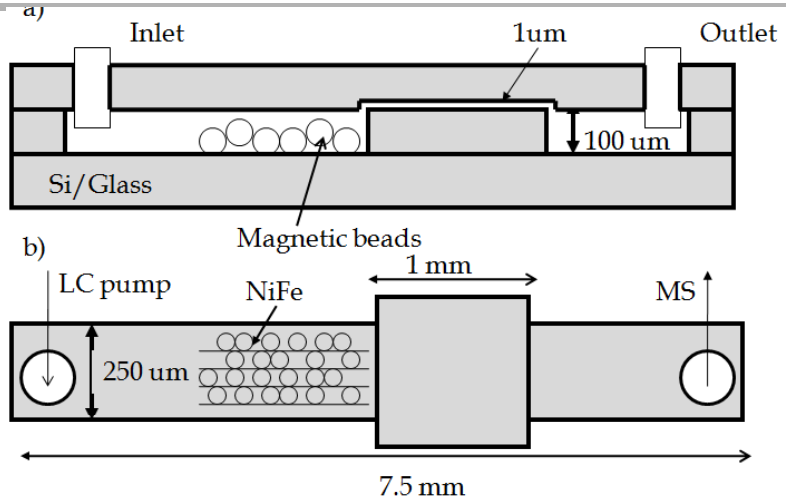
Top-gated Graphene FETs



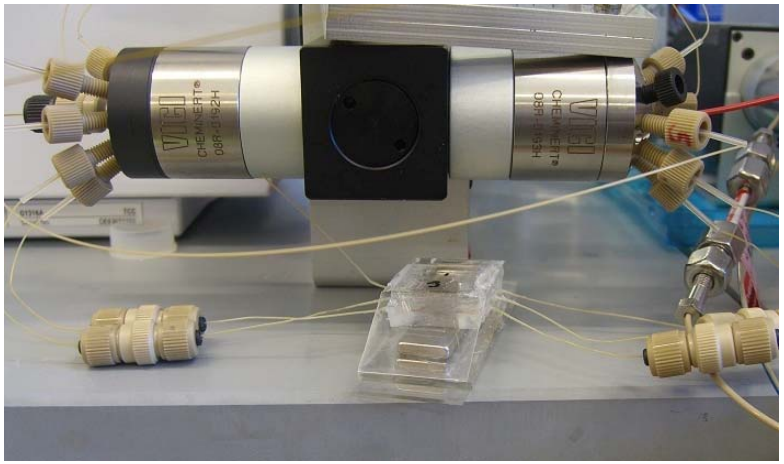
Jeff J. Peterson, *Intel Assignee to INDEX*
Work performed at Ga Tech NRC

Microfluidic Assay for Determination of Protein Toxins

Anthrax lethal factor (LF) caused by infection with *Bacillus anthracis* (a spore forming Gram-positive bacterium) and protein toxins such as botulinum neurotoxin and ricin are likely agents of bioterrorism. In the US bioterrorism attacks of 2001, pulmonary anthrax had 45% fatality rate despite aggressive treatment and supportive care. Developing rapid, specific, and sensitive screening assay, which can be used in case of national emergency, is a high priority for Centers for Disease Control and Prevention. In this work, a coupled microfluidic enzyme reactor mass spectrometry platform for the detection of protein toxins was developed. The lethal toxin is a complex protective antigen, which localizes the toxin to the cell receptor and lethal factor (LF). We have demonstrated the applicability of a microfluidic reactor for the capture and concentration of enzyme reaction solid-phase. The reaction solid-phase consists of anti-LF monoclonal antibodies immobilized on magnetic protein G beads for the capture of LF. The captured LF, on exposure to optimized peptide substrate, hydrolyzes into two smaller peptide products. These cleavage products were then analyzed by mass spectrometer coupled to the microfluidic reactor. This resulted in efficient sample preparation, high sensitivity, larger reaction sites, less reagents consumption and shorter analysis time. We have showed here reproducible detection of anthrax lethal factor in concentration range of 40 to 0.5 ng/mL with a detection limit of 1 ng/mL. The enzymatic reaction and the analysis were performed in less than 15 minutes, indicating a rapid diagnostic tool for early anthrax prognosis.



Microfluidic enzyme reactor (a) cross-sectional view, (b) overview with beads trapped in microchannel



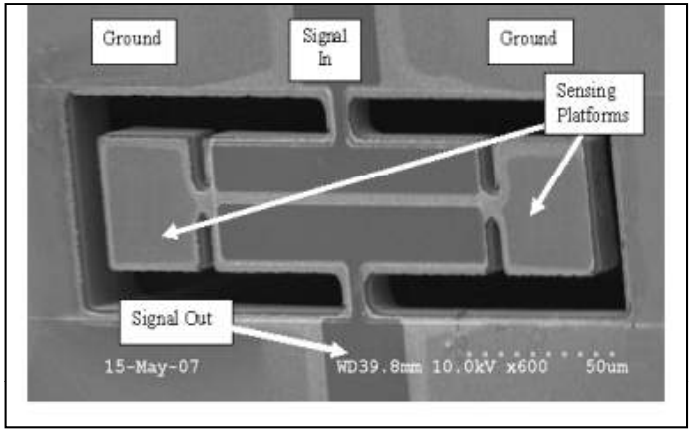
PDMS based Microfluidic enzyme reactor connected to 10 port valve, to continuously collect products onto a HPLC column for MS/MS analysis

Susan Kuklenyik and John Barr, Center for Disease Control and Prevention, Atlanta, GA
Work performed at Georgia Tech Nanotechnology Research Center

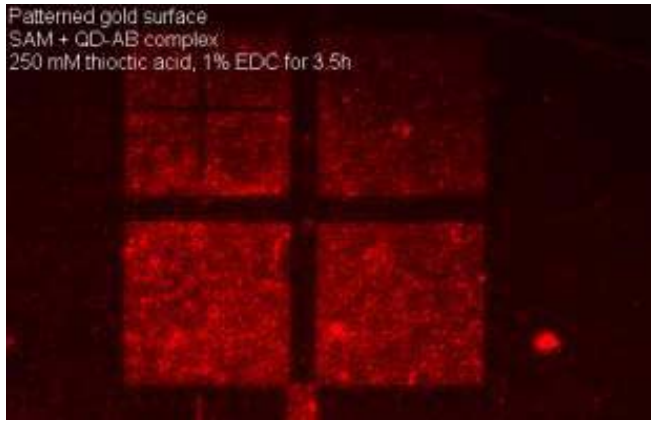
Detection of Cancer Biomarkers on Microfluidic Resonant Mass Device

Innovative techniques for ultrasensitive and early detection of biologically relevant cancer molecules are of vital importance for clinical management. This project seeks to address these challenges in cancer diagnosis by developing a prototype label-free Micro-Electro-Mechanical- System (MEMS)-based resonant mass sensor with integrated microfluidics. The integrated microfluidic resonant mass sensors exhibits two orders of magnitude greater sensitivity compared to conventional Quartz Crystal Microbalance (QCM) towards ovarian cancer biomarkers (such as CA125) directly from minimally processed serum samples. Furthermore, the microfluidic platform will enable high throughput and multiplexed detection with drastically reduced analysis time and reagent cost.

In this work ZnO micromechanical resonators packaged in a poly(dimethylsiloxane) (PDMS) microfluidic platform was developed. The piezoelectric resonators have a featured resonant frequency determined by the design and structure of the device. Application of an external force (from the mass of the adsorbed target molecule) on the ZnO piezoelectric film induces a shift in this resonant frequency and magnitude of shift is a function of external mass adsorbed. Based on this principle, resonant mass sensors can be used to detect concentration of target molecules or biomarkers. In our preliminary studies, the applicability of the ZnO-based piezoelectric resonator as a label-free biosensor was demonstrated using nM concentrations of TNF-α. Change of 9.7 KHz and 33.6 KHz for 100 nM of anti-TNF-α (control and target respectively) were observed.



ZnO micromechanical resonant mass sensor with two annexing sensing platforms



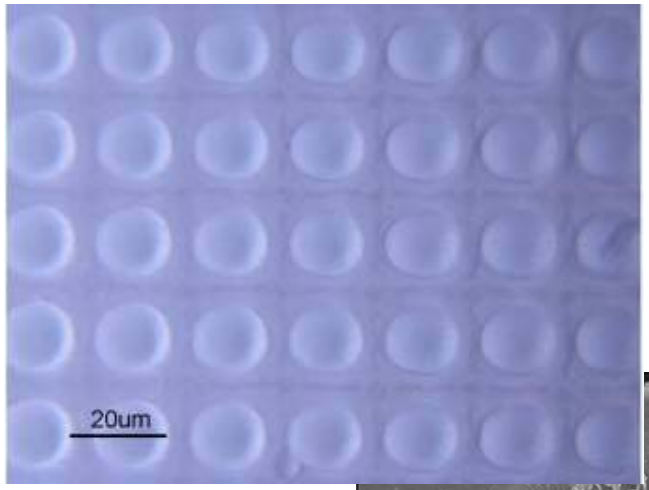
Surface functionalization cross-validated using Quantum dots

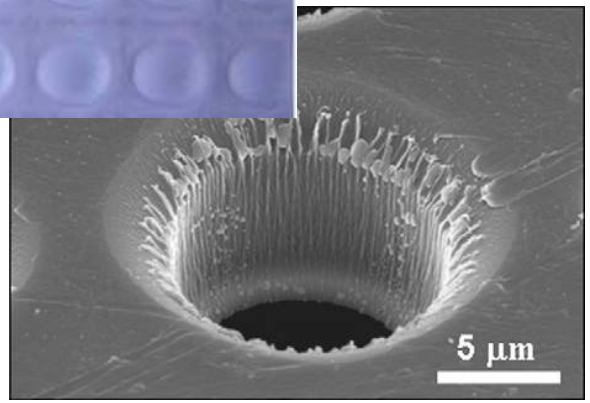
S. Aravamudhan, F. Ayazi, S. Nie, Center for Cancer Nanotechnology Excellence, Emory University

Work performed at Georgia Tech Nanotechnology Research Center

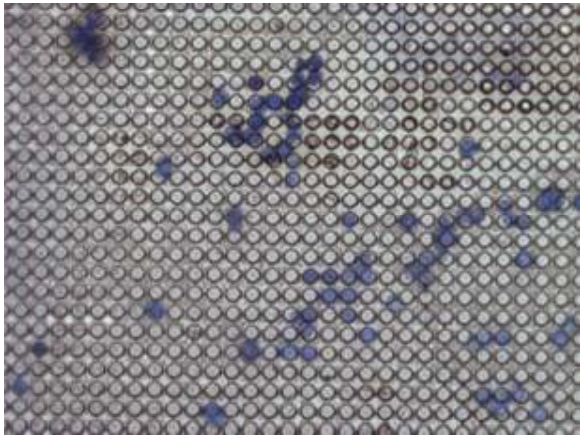
Isolation of Circulating Tumor Cells (CTCs) in Whole Blood

CTCs are cancer cells that has detached from a solid tumor lesion (epithelial origin) and enter the peripheral blood circulation. They provide significant prognostic information on cancer metastasis. As few as five CTCs in about 7.5 mL of whole blood is clinically significant. In this work, parylene microfilters were fabricated for selective capture of CTCs, at a later stage cell lysis and genomic analysis could be performed on these captured CTCs. The filter design is based on the size difference between CTCs (about 20-22 µm) and normal human blood cells (about 5-9 µm).





Representative image of the micropore from the published paper, Zheng et al. J Chromatogr. A 1162 (2007)



Stained CTCs captured on parylene microfilters

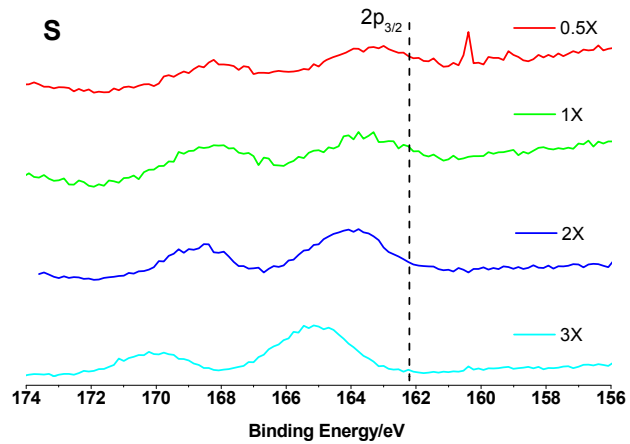
Ram Datar, Richard Cote, Department of Pathology, University of Miami Miller School of Medicine, FL

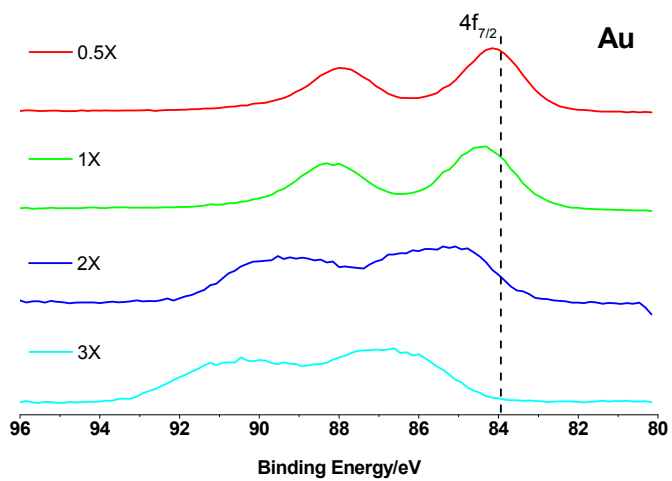
Work performed at Georgia Tech Nanotechnology Research Center

Study Au-S interactions using X-ray Photoemission Spectroscopy (XPS)

The project targets to elucidate the impacts of interfacial bond structures on the physiochemical properties of Au nanoclusters and Au nanoparticles. With tailored energetics and composition/structure at atomic scale, the dithiol-Au nanoclusters are designed for **energy technology and biomedical applications**. The XPS results reveal the charge transfer between Au and S atoms (charge states). The binding energy (BE) is found shifted to higher energy, confirming our hypothesis and experimental design. As a powerful surface chemical analysis technique, XPS helps to study the chemical nature of the gold core, the binding energy of the Au and S, hence to probe the Au-S bond structures of these clusters and have a better understanding of their properties. The results have been published as listed below.

Zhenghua Tang and Gangli Wang School of Chemistry, Georgia State University, Atlanta, GA*
Work performed at Georgia Tech Nanotechnology Research Center

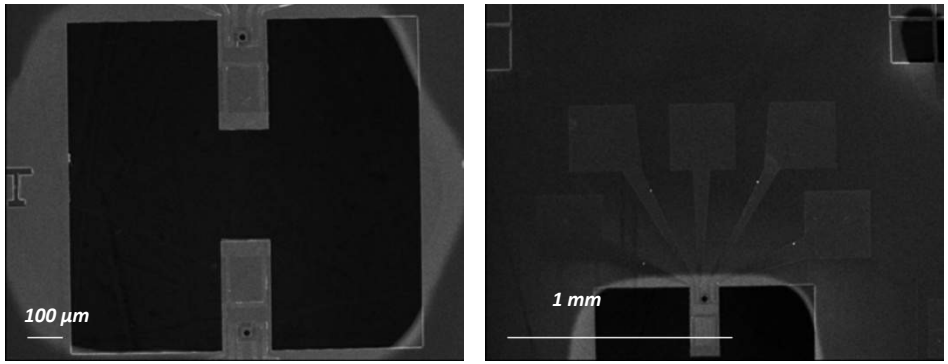




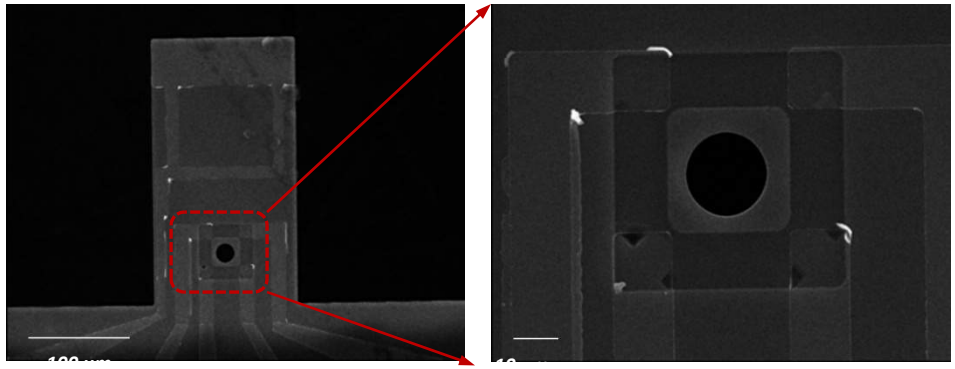
Work published in the Journal of the American Chemical Society ***2010, 132 (10), 3367-3374***

Fabrication of Si Piezoresistive µCantilevers

The goal of this project is the fabrication of Si microcantilevers with embedded piezoresistors forming a wheatstone bridge. The microcantilevers will be used as integrated potentiometric chemical sensors. The devices were constructed from 4 inch SOI (Si on insulator) wafers with thick Si substrate (400 µm) and a 2 µm thick top layer of Si. The process flow consists of p-type piezoresistor formation, etching of the cantilever top outline, formation of the ohmic contacts and annealing, deposition of the bonding pads, and release of the cantilever from the backside. TLM patterns were fabricated and characterized to measure sheet resistance and contact resistance, and the piezoresistors forming the wheatstone bridge were measured. Further characterization is currently underway.



SEM images of a pocket with two released cantilevers (left) and a released cantilever with four bonding pads and one tip biasing pad (right).

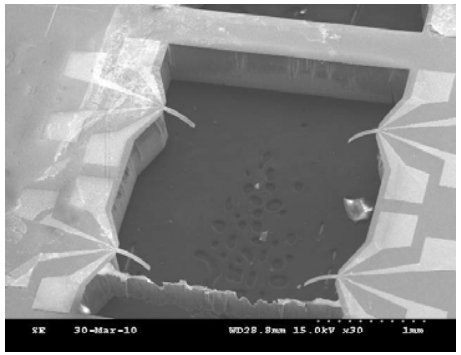


SEM images of a released cantilever (left) and the embedded piezoresistors (right).

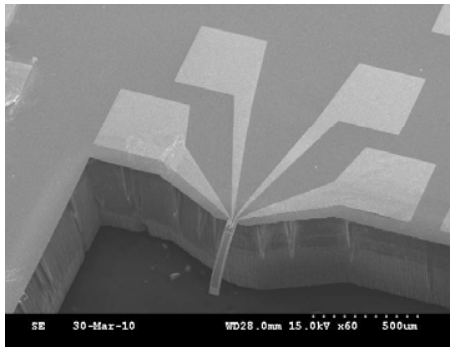
Jie Liu and Goutam Koley, Univ. of South Carolina
Work performed at the Georgia Tech Nanotechnology Research Center

Fabrication of AlGaN/GaN HFET Embedded µCantilevers

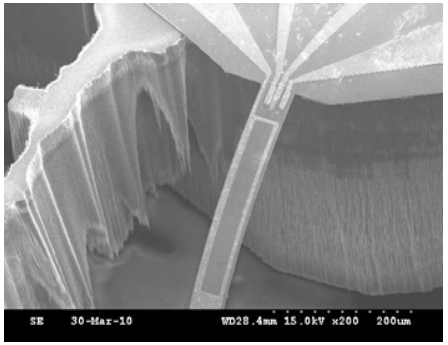
This project is designed to fabricate GaN microcantilevers with an AlGaN/GaN heterostructure field effect transistor (HFET) embedded at the base of the cantilever. The cantilevers will be used as potentiometric sensors for molecular detection. The fabrication begins with AlGaN/GaN layers (GaN: 2.1µm, AlGaN:17 nm) grown on a 500 µm thick Si substrate. The process continues with mesa etching of the AlGaN, etching of the cantilever (GaN) top outline, formation of source-drain ohmic contacts and rapid thermal annealing. Gate Schottky contacts are then deposited along with bonding pads and finally through wafer backside Bosch Si etching to release the cantilevers. TLM pads were fabricated and characterized to measure the sheet resistance. HFET devices were fabricated and the ID-VD and ID-VG were measured..



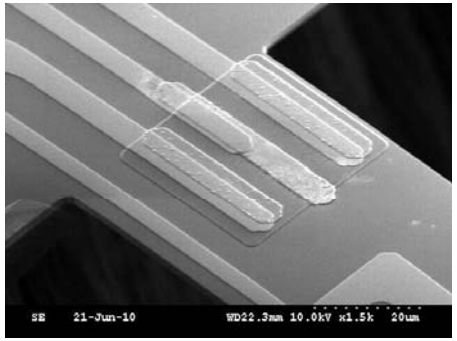
SEM micrograph of one of the pockets accommodating 4 released cantilevers.



SEM micrograph of a released cantilever with source, drain and gate contact pads. An additional metal pad is used for cantilever tip biasing



SEM micrograph of a released cantilever. Vertically etched Si surface can be seen.



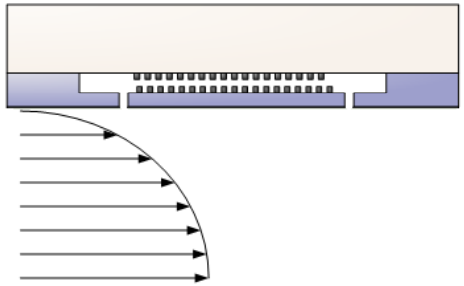
SEM micrograph a MESA (height: 0.2µm) showing source, gate, and drain contacts.

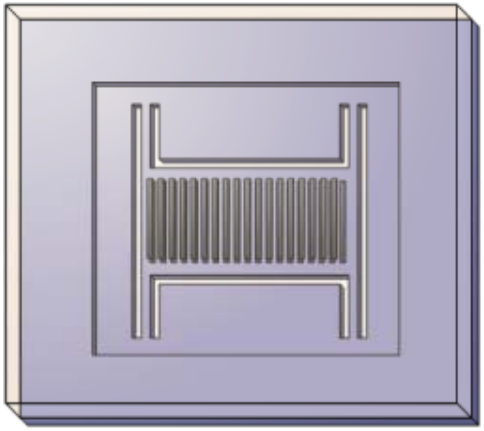
Muhammad Qazi and Goutam Koley, Univ. of South Carolina
Work performed at the Georgia Tech Nanotechnology Research Center

Nanofabrication of an Optical Moiré Shear Stress Sensor

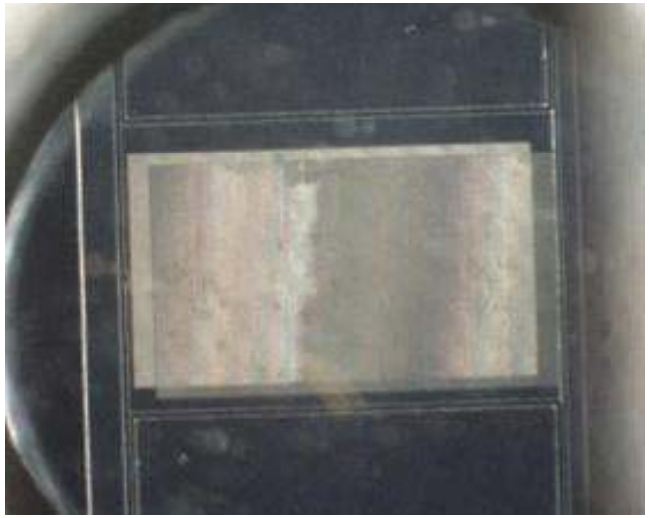
Moiré fringe patterns are placed between the silicon floating element structure and the Pyrex base structure for optical transduction. Rigid alignment of the aluminum gratings between the Pyrex and SOI layer is critical and is achieved using an anodic bond. The floating element is then released using a backside DRIE process.

Cross section of a floating element shear stress sensor in a flow





Top view of a floating element Moiré shear stress sensor



Photograph of a nanofabricated Moiré shear stress sensor in a test package

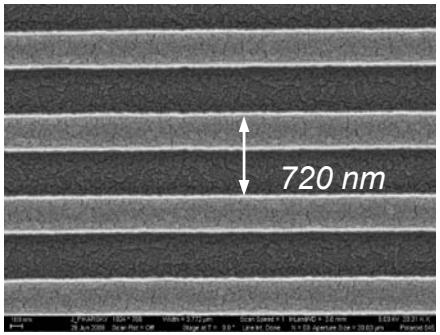
Tai-An Chen, Vijay Chandrasekharan, David Arnold, Mark Sheplak, University of Florida

Work performed at the Georgia Tech Nanotechnology Research Center

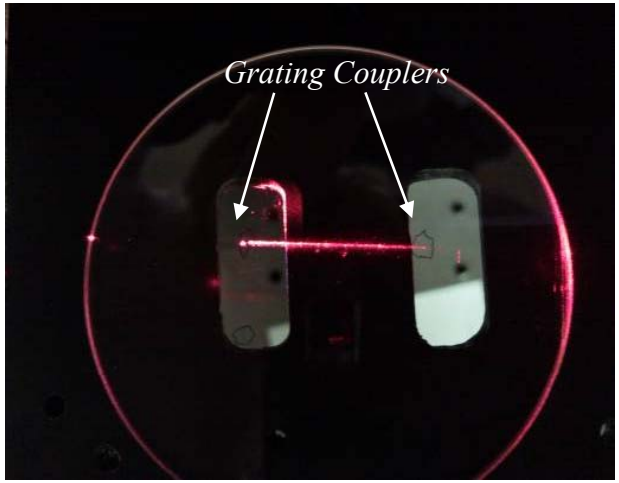
Grating Coupler Fabrication for Interferometric Waveguide Sensors

Fabrication of grating couplers for optical waveguides poses a challenge, as the line width of the gratings is only 360 nm. Previously, we showed that nano-imprint lithography can provide a solution to this problem, with the ability to replicate 3-D patterns inexpensively at nanometer resolution. Using standard and grayscale electron-beam lithography, imprint templates for both square and blazed gratings were successfully fabricated. The patterns were then transferred to a UV-curable photoresist that was used as an etch mask for plasma etching of the grating structures in a quartz substrate. More recently, additional work in this area was performed to determine if the UV-curable polymer (a proprietary compound from Micro Resist Technology GmbH) can be used directly as the substrate for the grating couplers and waveguide deposition, thus eliminating the plasma etching process.

Successful transfer of the pattern into the UV curable polymer was achieved. After deposition of the silicon nitride waveguide, testing of the completed structure was done using a HeNe laser (633 nm) with illumination from below and through the quartz substrate. Qualitative evidence so far indicates that devices made using this process provide a viable alternative to the standard fabrication methods.



SEM images of grating patterns in mr-UVCur06

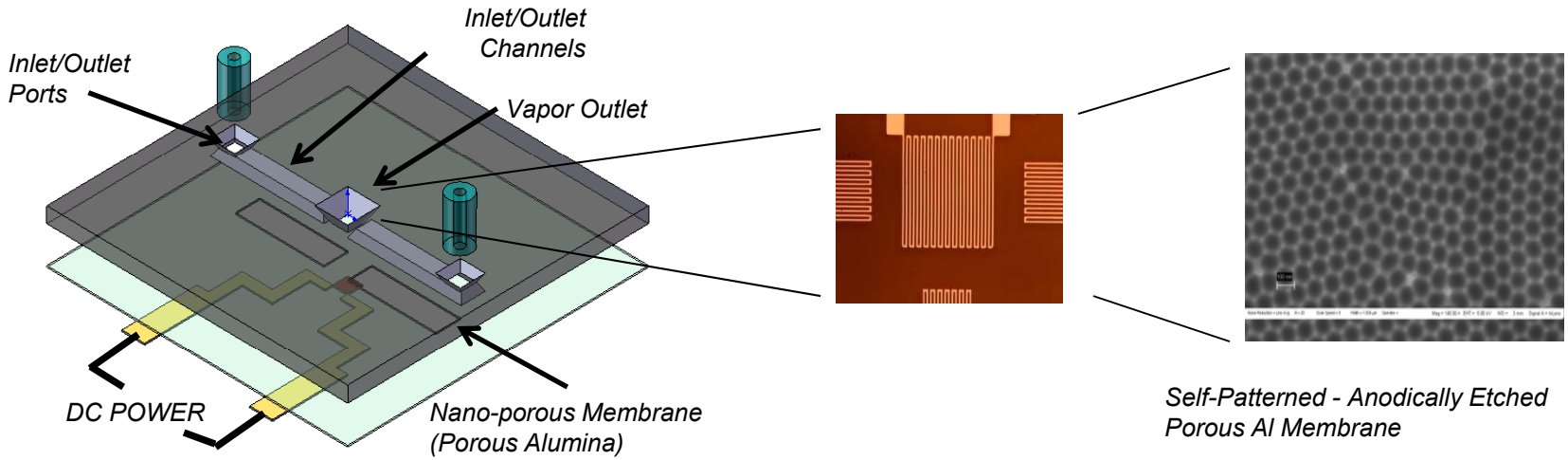


Optical image of the completed grating coupled waveguide showing coupling of the laser and waveguiding.

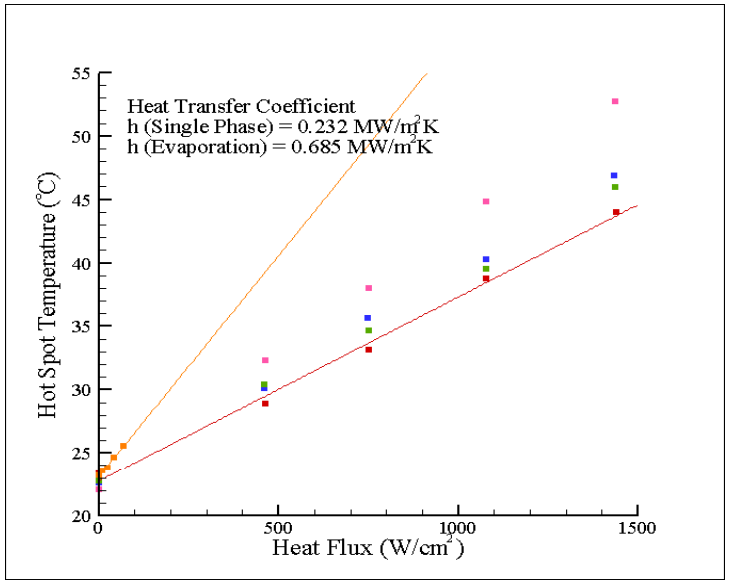
Edgar Gary (REU), Florida International University, Janet Cobb-Sullivan and David Gottfried, Georgia Tech

Work performed at the Georgia Tech Nanotechnology Research Center

Perspiration NanoPatch for Electronics Cooling



Heat removal is a limiting factor in maximum power density in high performance IC's. This work demonstrates the use of porous membranes to provide localized 2-phase cooling for hotspots and dissipate extremely large heat fluxes. These nanoporous perspiration patches demonstate heat removal exceeds 500 W/cm^2 and heat transfer coefficient exceeds 450,000 W/m^{2}K. The method developed to make these structures is compatible with CMOS fabrication.



Student: Narayanan, S., PI's:Fedorov, A., and Joshi, Y.,- ME, Georgia Tech
Work performed at the Georgia Tech Nanotechnology Research Center

New Complementary Memristor Technology Allows both Inhibitory and Excitatory Synapses

This work demonstrates the first complementary memristors (both n-type and p-type) and the first analog memristor. The n-type material exhibits inhibitory response (increasing resistance with time/voltage) and the p-type material exhibits excitatory response (decreasing resistance with time/voltage). In principle, this complementary memory technology can fully implement neuron/synapse brain function. Rapid lithium ion movement facilitates fast switching and allows macroscopic devices for reduced cost development.

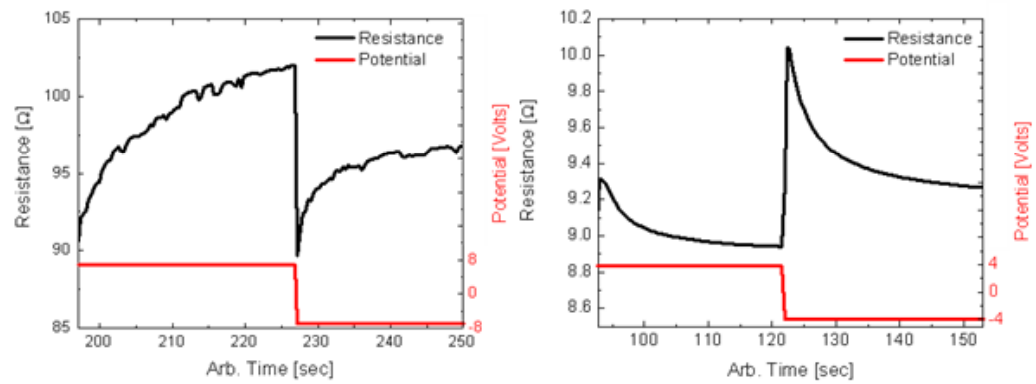


Figure 1) N-type (left) and p-type (right) Response of 40 um $LiNbO_2$ memristor to a voltage step input.

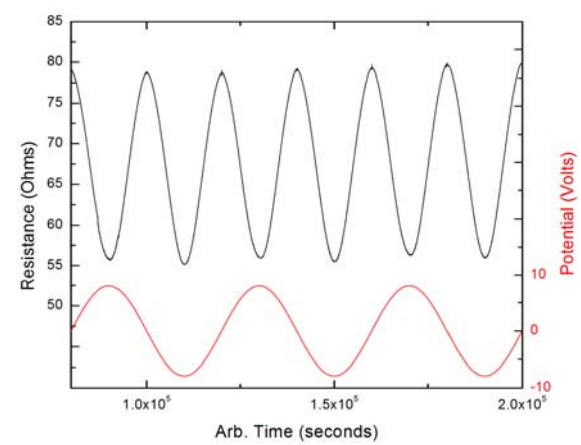
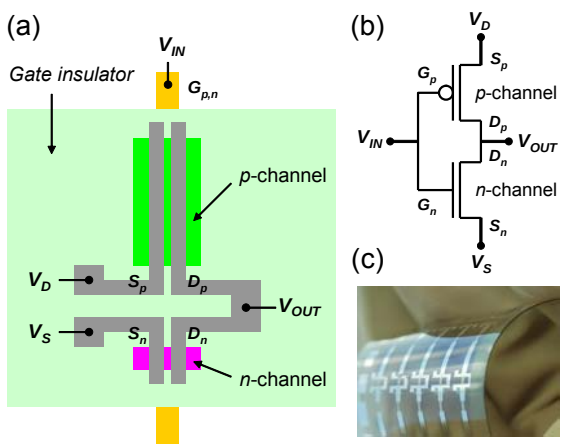


Figure 2) Response of $LiNbO_2$ memristor to a sinusoidal input voltage displays memristance effect at a large range of voltages, proving analog operation.

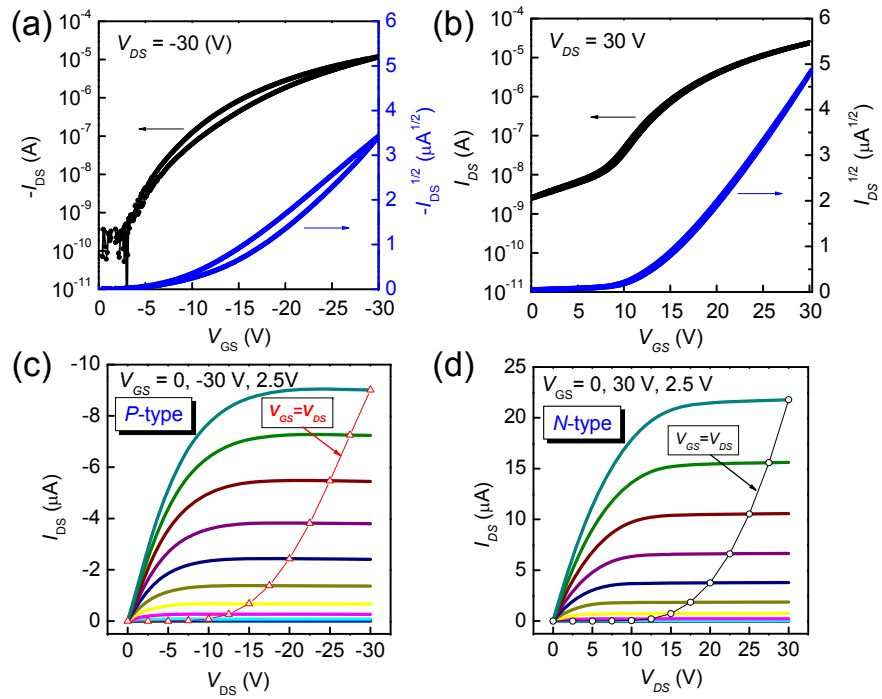
Dr. Alan Doolittle and Students- ECE, Ga Tech
<u>Acknowledgments:</u> This work was funded under an ONR basic science grant monitored by Dr. Daniel Green
Work performed at the Georgia Tech Nanotechnology Research Center

Organic-Inorganic Hybrid Complementary Inverters on Flexible PES Substrates with High Gain

High gain organic-inorganic hybrid complementary inverters were fabricated on flexible PES substrates. The p-channel semiconductor was formed from pentacene and showed a mobility of 0.13 cm^2/Vs. The n-channel semiconductor was formed from a-InGaZnO and showed a mobility of 3.8 cm^2/Vs. The device architecture included a patterned bottom gate (dielectric Si_3N_4) and Au electrodes on top. This structure provides a new method to find the switching threshold voltage and the optimum supply voltage of complementary inverters. It also demonstrates a new method for creating hybrid complementary inverters



Inverter Layout (above), Inverter Schematic (upper right), Finished Device (lower right)



Inverter Electrical Characteristics

Center on Materials & Devices for Information Technology Research
An NSF Science & Technology Center, DMR-0120967

Students: Kim, J. B.; Fuentes-Hernandez, C.; Kim, S. -J.; Choi, S., PI Kippelen, B. - Center for Organic Photonics and Electronics (COPE), Georgia Tech
Work performed at the Georgia Tech Nanotechnology Research Center

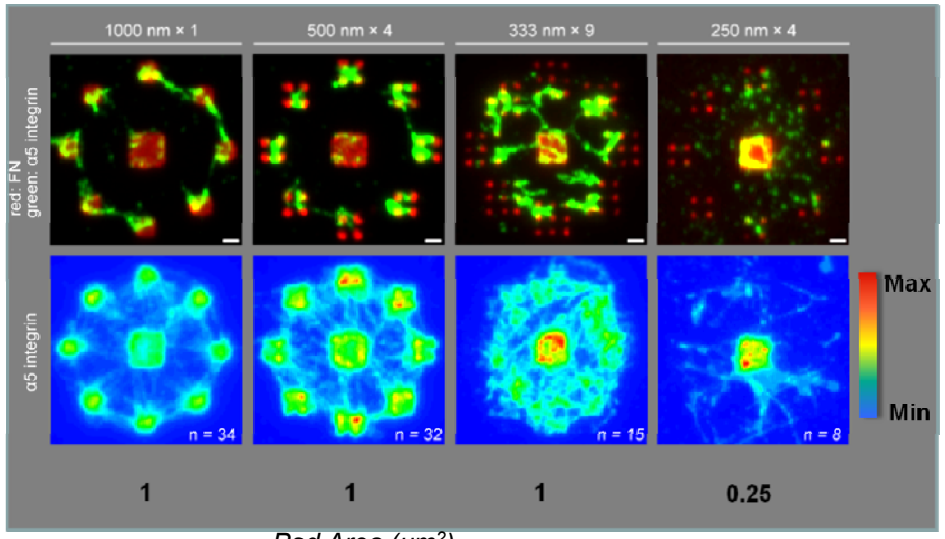
Nanoscale Geometry of the Adhesive Interface Regulates Integrin Recruitment and Adhesive Force

Bio-inspired surfaces, including micropatterned substrates, are engineered to control cell adhesion in order to direct signaling and cell function. Biomolecular surfaces have been engineered to target specific adhesion receptors to modulate cell signaling and differentiation. These biomolecular strategies are applicable to the development of 3D hybrid scaffolds for enhanced tissue reconstruction,"smart" biomaterials, and cell growth supports.

Integrin Binding

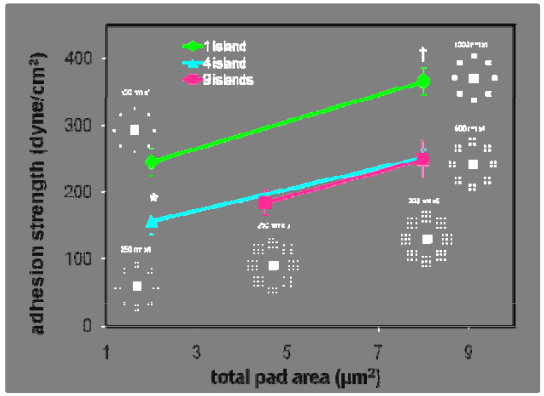
One cell / pattern

"Heat Map" Stacked Average



Pad Area (μm²)

Cell Adhesive Force

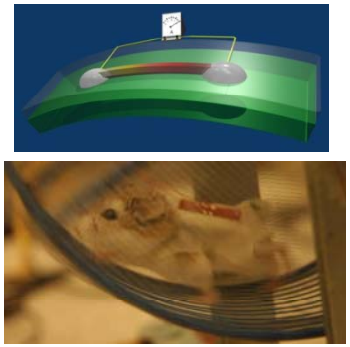


Student: Sean Coyer, PI: Andrés J. García- ME, Georgia Tech
Funded by NIH R01-GM065918
Work performed at the Georgia Tech Nanotechnology Research Center

Nanogenerator (NG): Science, Engineering, Technology and Applications

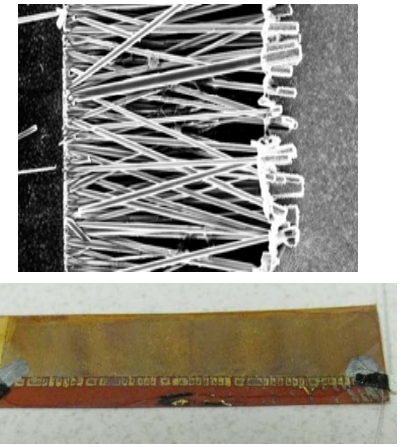
Energy harvesting is critical to achieve independent and sustainable operations of nanodevices, aiming at building self-powered nanosystems. Taking the forms of irregular air flow/vibration, ultrasonic waves, body movement, and hydraulic pressure, mechanical energy is ubiquitously available in our living environment. The mechanical-electric energy conversion has been demonstrated using piezoelectric cantilever working at its resonating mode. In the example to the right, the generated electric energy was effectively stored by utilizing capacitors, and it was successfully used to light up a commercial light-emitting diode (LED).

Lateral and packaged NG

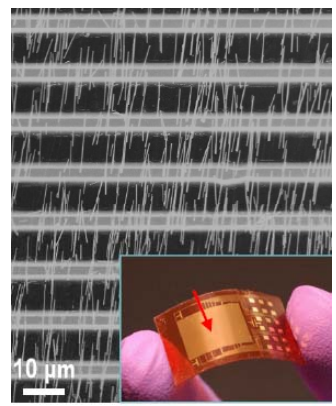


Nature Nanotech., 4 (2009) 34
Nano Letters, 9 (2009) 1201

Powering nanodevices

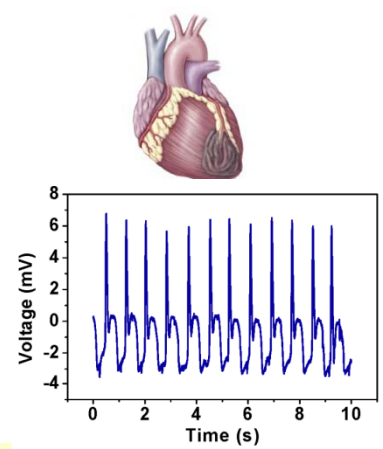


Lighting up a LED



Nano Letts., online

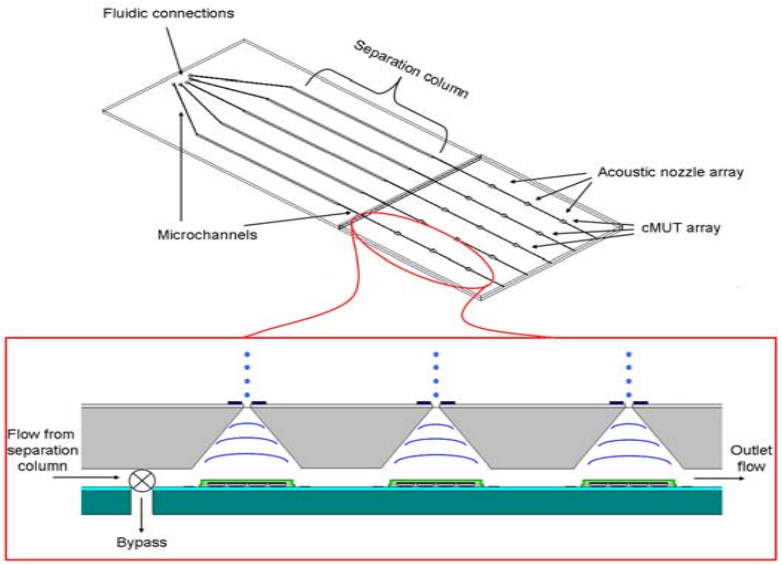
In-vivo nanogenerator

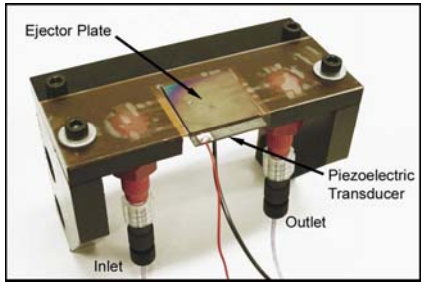


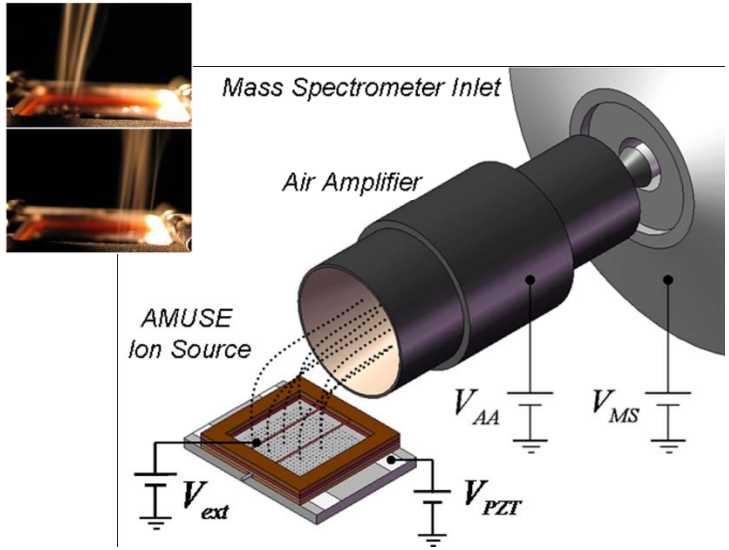
Adv. Mater. 22 (2010) 2534

ZL Wang's group- MSE, Georgia Tech
Work performed at the Georgia Tech Nanotechnology Research Center

Array of Micromachined UltraSonic Electropsrays (AMUSE)



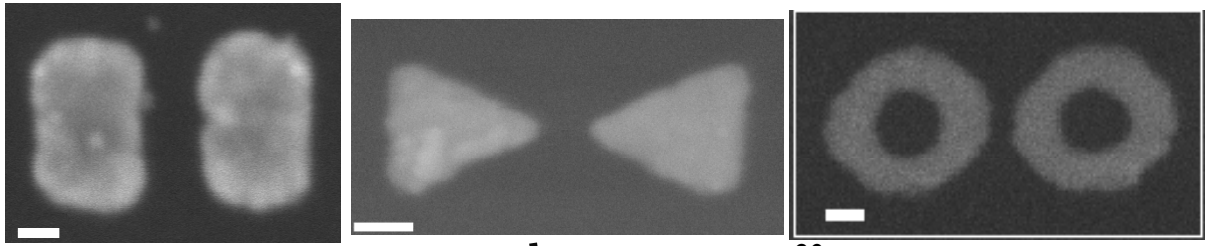




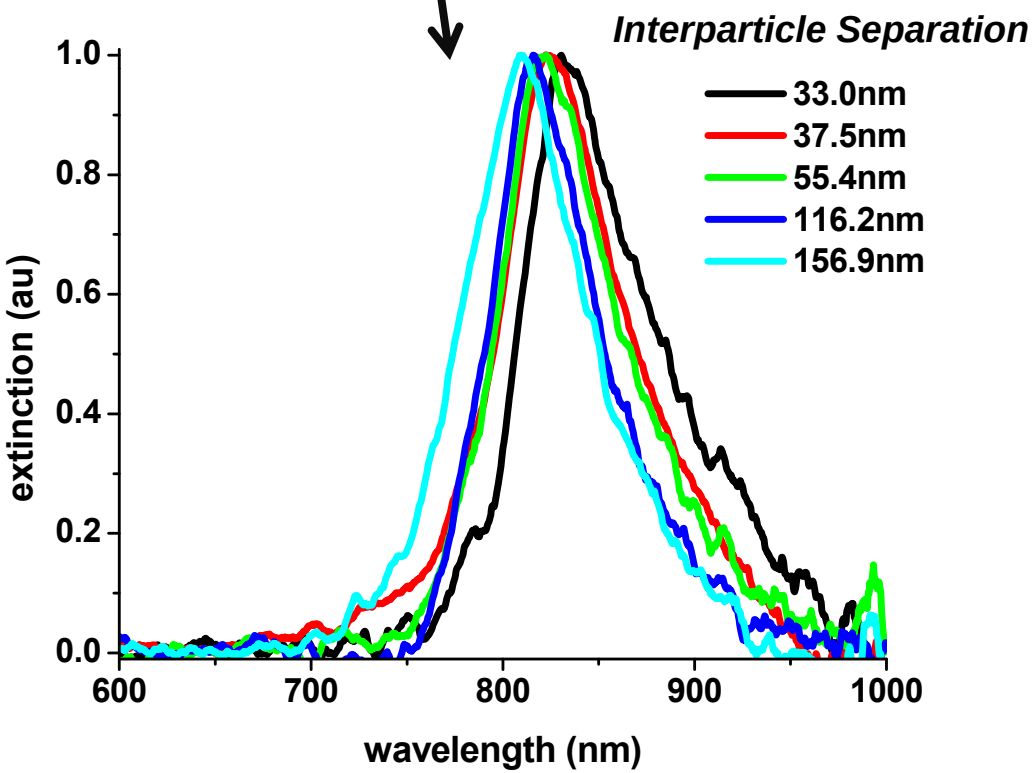
This work used a MEMS-enabled technology for mass spectrometric detection of complex biomolecules. Using hardware-enabled multiplexing and interfacing with multiple LC streams it demonstrated on-line high throughput and off-line operation with ultra small sample volumes.

Andrei Federov , Georgia Tech, In Collaboration: Prof. Degertekin (GT ME), Prof. Fernandez (GT Chem) and Prof. Muddiman (NCSU Chem)
Work performed at the Georgia Tech Nanotechnology Research Center

Studying the Properties of Assembled Nanoparticles of Different Shapes



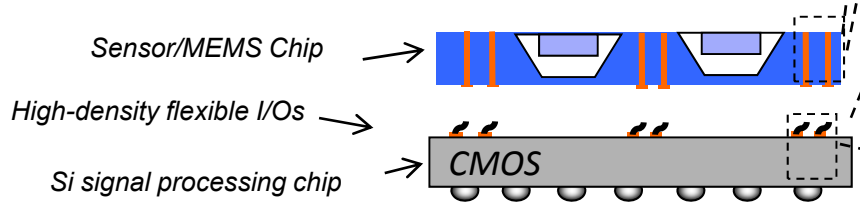
Arrays of nanorods, nanoprisms and nanorings were fabricated on the JEOL JBX-9300FS EBL system. The optical properties of the various systems were then investigated spectroscopically.
The plot shows the extinction spectra for nanoprisms at five different tip-to-tip interparticle separations. As the distance between the particles decreases, the peak redshifts. This indicates that the optical properties of ensembles of metallic nanoparticles depends on their individual shapes and sizes as well their particle separation.

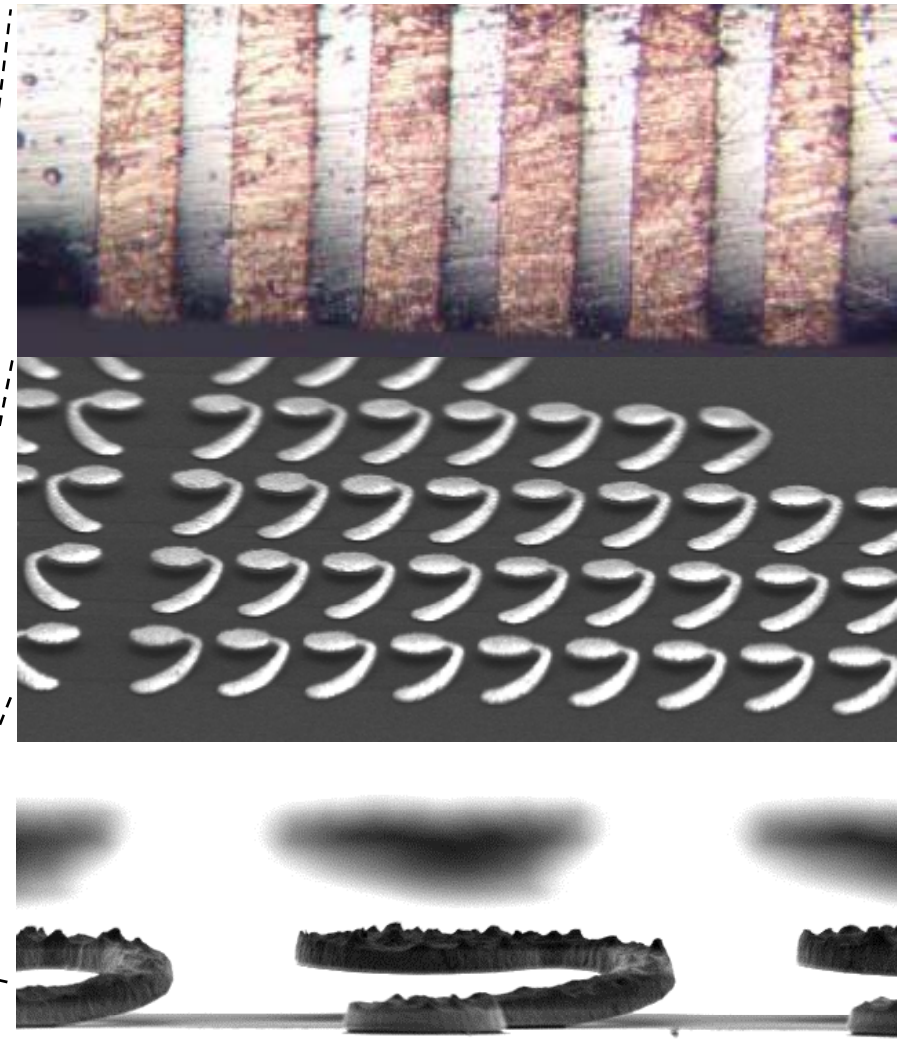


Student: Rachel Givens, PI: Mostafa El-Sayed-Chemistry, Georgia Tech
Work performed at the Georgia Tech Nanotechnology Research Center

Heterogeneous 3D Integration

3D integration of arbitrary MEMS/sensors with a state-of-the-art CMOS is increasingly important for the monolithic fabrication of complex microsystems. MEMS/Sensors are very sensitive to thermomechanical stress and flexible I/Os allow stress-free area-array vertical interconnections between dissimilar chips. This work demonstrated the fabrication and assembly of flexible I/O with 20μm+ vertical range of motion. Flexible I/Os also enable temporary interconnections between chips; contaminated sensors can now be disposed while reusing the CMOS chip. Through-Silicon Via (TSV) allows sensors to be exposed to the environment. A new TSV process that can be fabricated in thick (500μm) MEMS/sensor wafers has also been demonstrated.





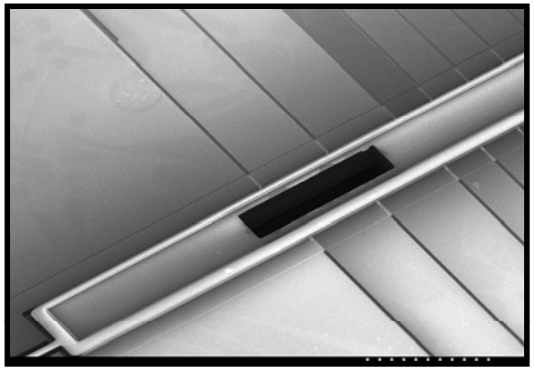
H. S. Yang et al., ECTC 2010, IITC 2010

Student: H. S. Yang, PI: M. A. Bakir –ECE, Georgia Tech
Work performed at the Georgia Tech Nanotechnology Research Center

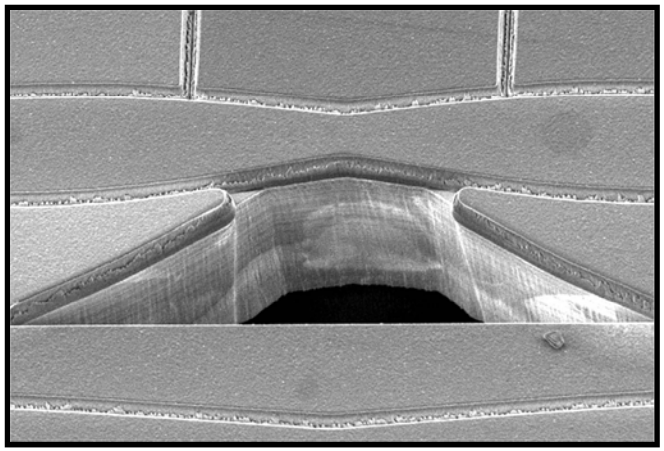
Scalable Multiplexed Ion Trap Fabrication

The purpose of this project is to design, fabricate and test scalable planar ion traps for quantum computing applications. To day two generations of ion traps have been successfully fabricated at the Nanotechnology Research Center. $^{40}Ca^{+}$ ions have been trapped and shuttled up to 600 um and Long ion lifetimes (> 1 hr) and low heating rates measured. Static ion crystals of up to 5 ions have been loaded. Future work will include the fabricate of next generation design capable of 50 ion crystals. Additionally, traps with integrated micromirrors for enhanced collection efficiency will be fabricated and tested.

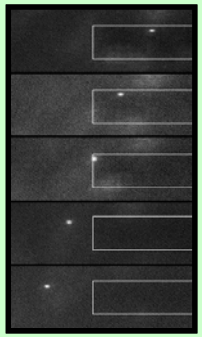
First Generation Ion Trap



Second Generation Ion Trap



Single Ion Trapping and Transport

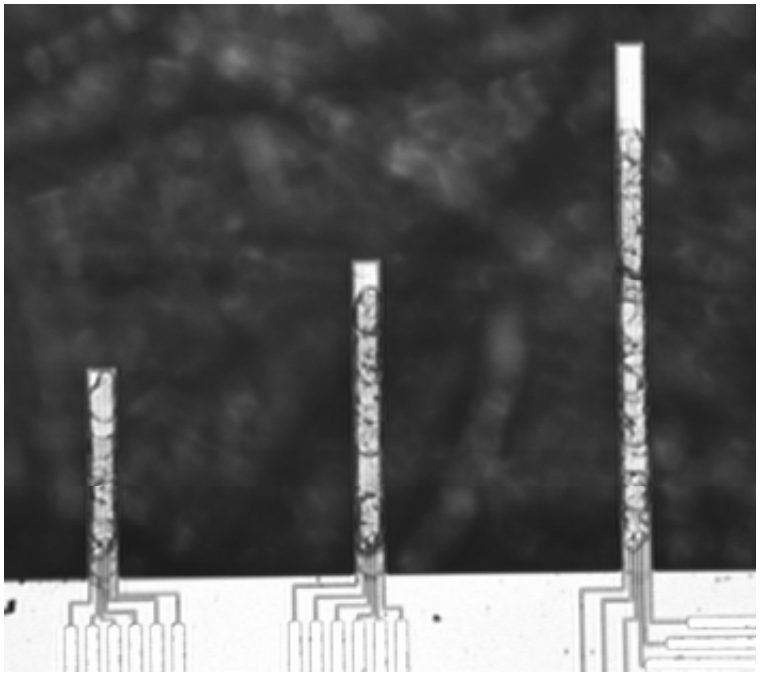


Ion Crystals

T. Merrill, CS Pais, H. Hayden, C. Volin, D. Denison, D. Faircloth, A. Harter, D. Slusher, J. Amini, D. Geddis. K. Martin- Georgia Tech
Work performed at the Georgia Tech Nanotechnology Research Center

Polymer Deposition of Sensing Layers on Micromachined Cantilever Sensors

Mass-sensitive chemical sensors typically utilize surface functionalization techniques to capture a specific analyte from an ambient liquid or gas. An ideal surface functionalization technique would allow the sensing devices to capture the desired analyte preferentially, even in the presence of other undesired analytes. The goal of this effort was the localized deposition of polymer sensing layers onto micromachined cantilever sensors for biochemical sensing. The polymer chosen for this project was polyethylene-co-propylene (EPCO), dissolved initially in a toluene solvent. Through careful manipulation of the jetting control parameters available on the Jetlab II, droplets of EPCO solution with 47 pL of volume were realized. Droplets of these volumes resulted in printed dots that were 51 µm wide after drying. Once droplet formation and deposition were established and characterized, the use of several script files automated the process so that arrays of microcantilevers were coated with 1.7 µm thick layers of EPCO polymer .

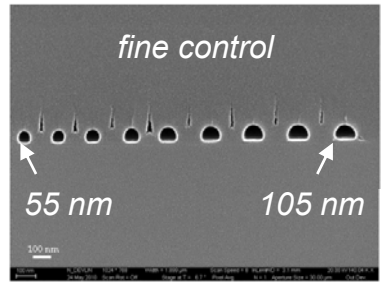


45 µm wide silicon cantilevers coated with EPCO

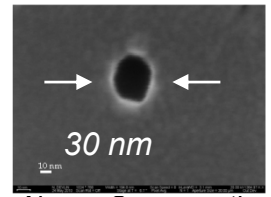
Student: C. Carron, PI: O. Brand- ECE, Georgia Tech
Work performed at the Georgia Tech Nanotechnology Research Center

Fabricating Nanofluidic Devices from Polynorbornene Exposed by Electron Beam Lithography

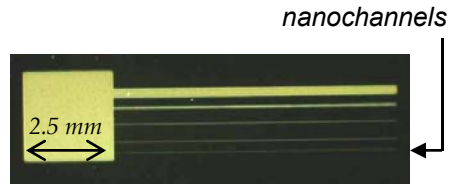
Nanofluidic devices are needed for lab-on-a-chip applications, especially where reagents are valuable. Most nanofluidic devices require both large basins (like storage vessels) and small channels. Creating μm- or mm- sized features and small nanochannels on the same chip is complex. In this research, Unity® 4671E, a decomposable polynorbornene resist, is patterned with electron beam lithography to create both mm and nm sized features at the same time. The low base dose of this resist (10 μC/cm^2), makes this a feasible process with relatively short exposure times. The patterns were then coated with a top layer (4 μm thick of either titanium or silicon dioxide) and the polynorbornene decomposes in a furnace, diffusing through the top layer without any access ports, leaving behind a nanofluidic device.



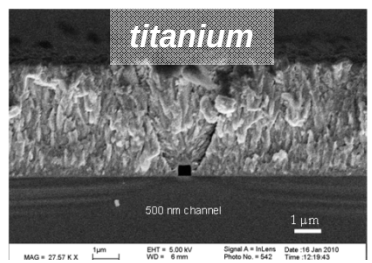
Cross-section view of channels from 55 nm to 105 nm decomposed through 4 μm of oxide



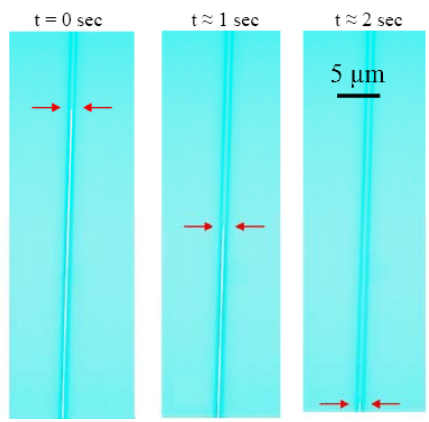
Above: Cross-section view of a 30 nm channel



Top down image of the fluidic device fabricated, large 2.5 mm basin and nanochannels



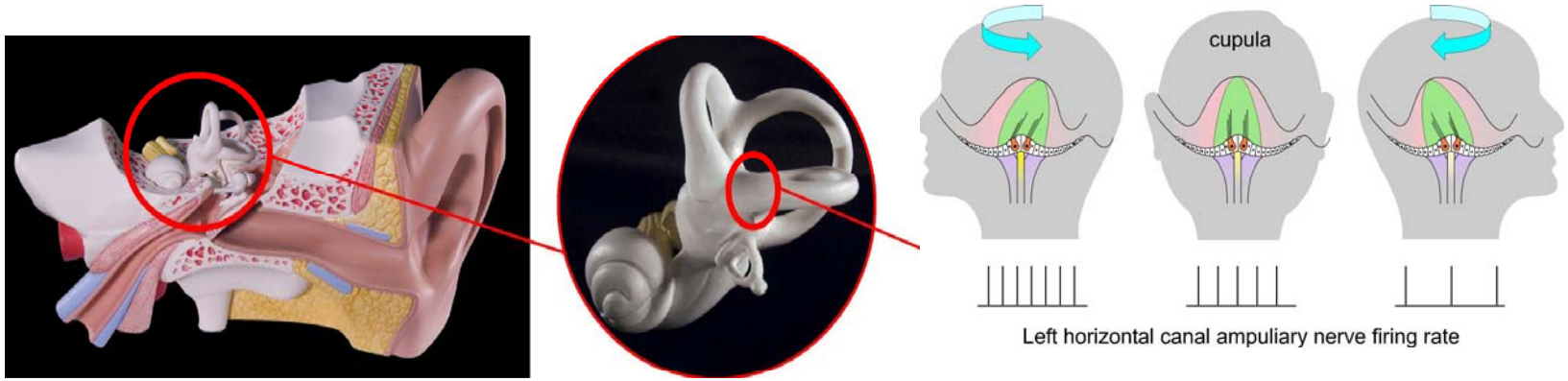
Cross-section view of a 500 nm channel decomposed through 4 μm of titanium



Left to Right: Water flowing through a 1 μm channel. The water is flowing from the top of the picture to the bottom.

Student: Nicole R. Devlin, PI: Devin K. Brown-NRC, Georgia Tech
Work performed at the Georgia Tech Nanotechnology Research Center

Biomimetic Angular Rotation Sensor for a Vestibular Prosthesis



Over 35% of US adults aged 40 years and older (69 million Americans) had a vestibular dysfunction (2001-2004). Falls are the leading cause of fatal and non-fatal injuries for persons age > 65 years. This work seeks to develop prostheses that provide electrical stimulation to overcome bilateral vestibular hypofunction. Input to these prostheses consists of three angular rotation sensors located in the inner ear shown above.

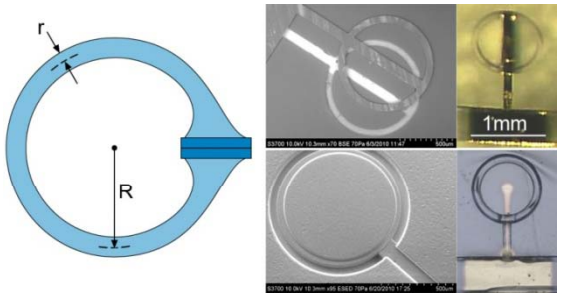
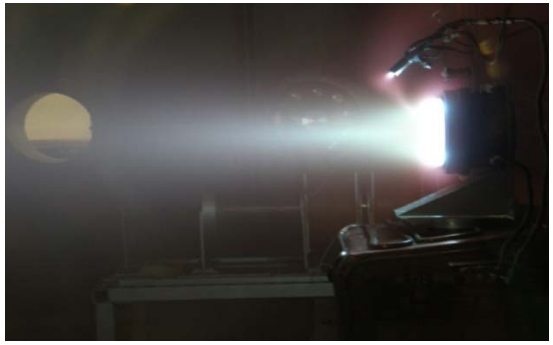


Figure. Left: *Illustration of the MEMS-cupula and the SCC-torus. The sensor's axis of rotation is out of the page. The MEMS-cupula bisects the SCC-torus and deflects in response to angular acceleration induced fluid motion. The radius of curvature (R) and the lumen radius (r) are indicated.* ***Center****: Scanning electron micrographs of the SU-molds used to define the respective reference (top) and sense (bottom) electrodes of the MEMS-cupula.* ***Right****: Photographs of the fabricated MEMS-cupula electrodes. A released sense electrode (top) is shown. The bottom picture illustrates an unreleased reference electrode. The metallization on the bottom of each structure enables signal transfer. The total structure is formed by mating the reference with the sense electrode that has a "lip" and a groove for aligning and eventually sealing the two.*

Students: M. McClain, H. Toreyin, J. Falcone, S. Datta Roy, PI: P. Bhatti- BioSystems Interface Lab, ECE, Georgia Tech
Work performed at the Georgia Tech Nanotechnology Research Center

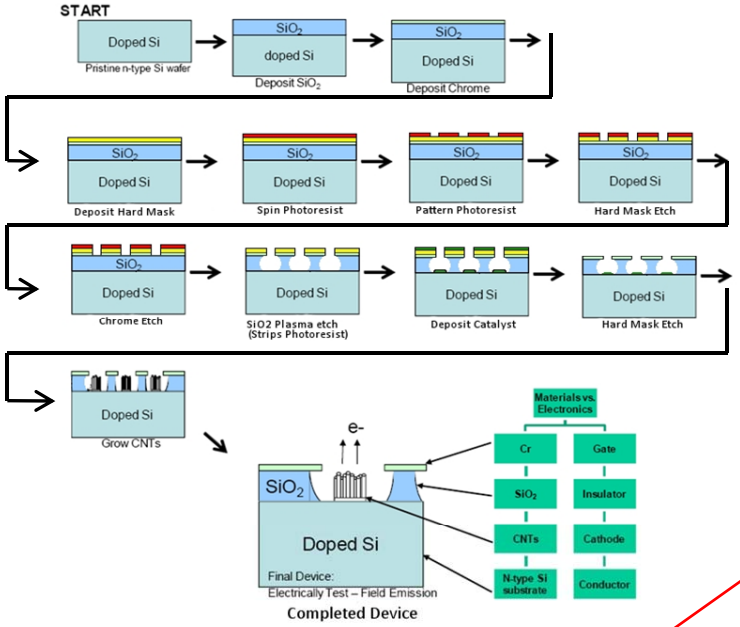
Carbon Nanotube-Based Spindt Cathodes for Hall Effect Thrusters

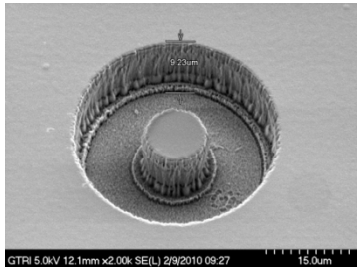
High specific impulse, high thrust efficiency, and high thrust density makes Hall thrusters appealing for a number of Earth-orbit space missions. Carbon nanotube electrode arrays offer 10% fuel saving, longer mission lifetime, a higher level of reliability and redundancy, and low power field emission extraction of electrons.

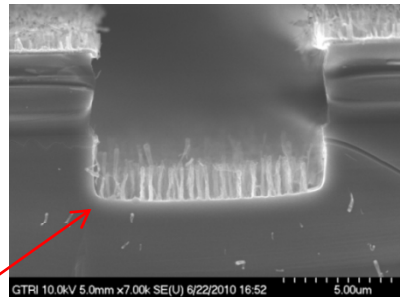


Hall Thruster Under Test

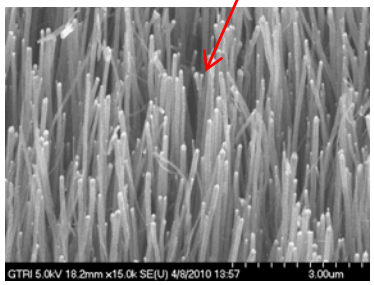
Fabrication Process Flow







Carbon Nanotubes

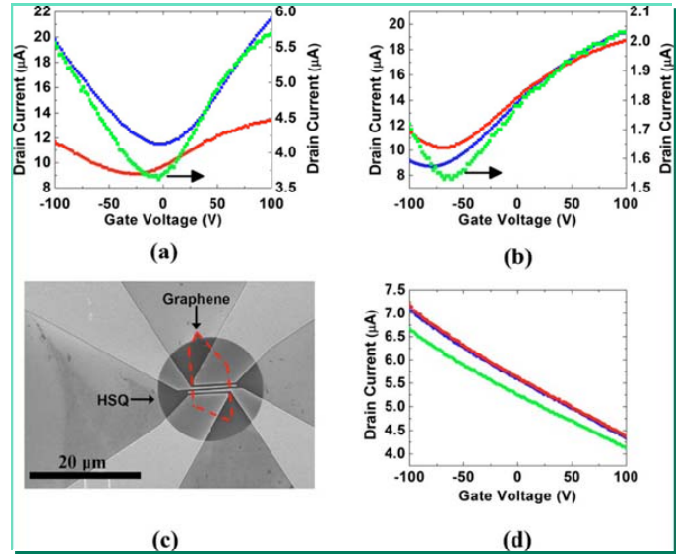


DARPA Funding:
- *HR0011-07-C-0056*
- *HR0011-09-C-0142*

Dr J. Ready –GTRI, Prof. M. Walker – AE, Georgia Tech
Work performed at the Georgia Tech Nanotechnology Research Center

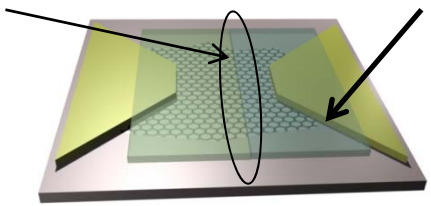
Graphene p-n Junction

This work demonstrated the formation of graphene p-n junctions in a single lithography step, using hydrogen silsesquioxane patterned on graphene. Both electron and hole doping was achieved through control of the polymer cross-linking process. This dual-doping is attributed to the mismatch in bond strength of the Si–H and Si–O bonds in the film as well as out-gassing of hydrogen with increasing cross-linking. High spatial resolution, allowing for production of novel nano-scale devices using graphene; these novel devices will result in orders of magnitude savings in power while operating at a higher frequency than traditional Silicon CMOS devices.

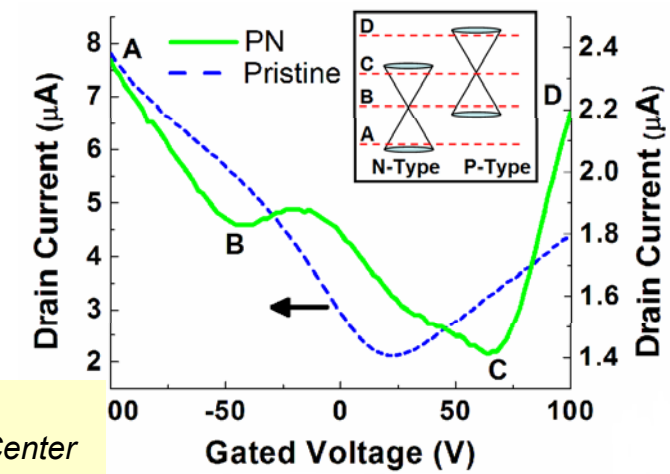


Nanoscale PN junction in Graphene

p-n junction



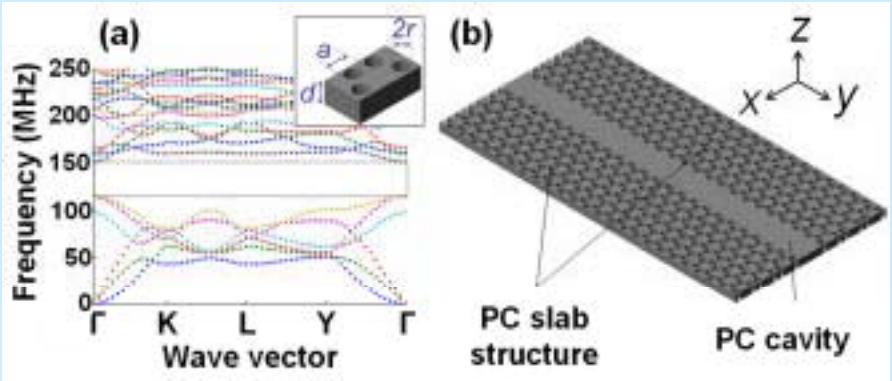
Graphene Nanowire



Student: K. Brenner, PI: R. Murali- Georgia Tech
Work performed at the Georgia Tech Nanotechnology Research Center

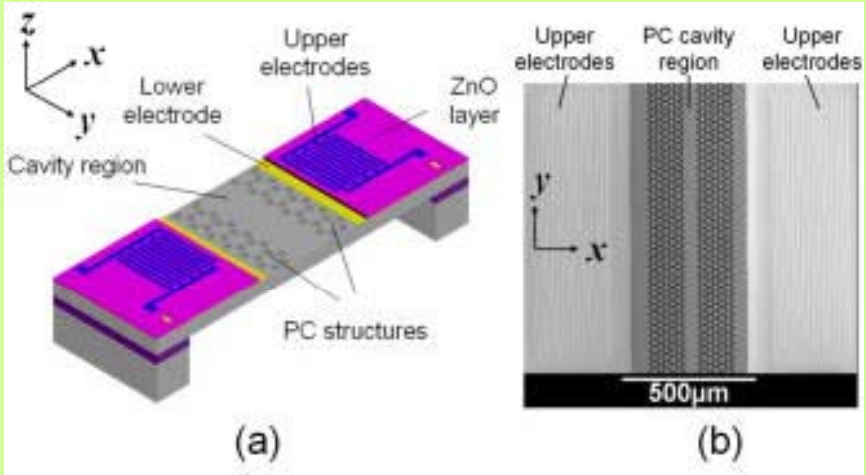
Phononic Mechanical Oscillator

Structures with periodic variations in their mechanical properties named phononic crystals PCs have unique frequency characteristics which cannot be achieved using conventional bulk materials. PCs support the existence of phononic band gaps PBGs that are frequency bands in which mechanical energy cannot propagate through the structure. PCs with PBGs can be used to filter, confine, or guide mechanical energy and hence are useful for a variety of applications including wireless communications and sensing.



(Left) The band structure of a hexagonal lattice PC of circular holes in Si slab with r=6.4 m, a=15 m, and d=15 m. A unit cell of the structure is shown in the inset. r, a, and d represent the holes radius, the distance between the two closest holes, and the slab thickness, respectively.

(Rigth) Schematic of the designed PC slab resonator in which a cavity is made in the PC structure by removing four rows one period of holes from the PC structure.



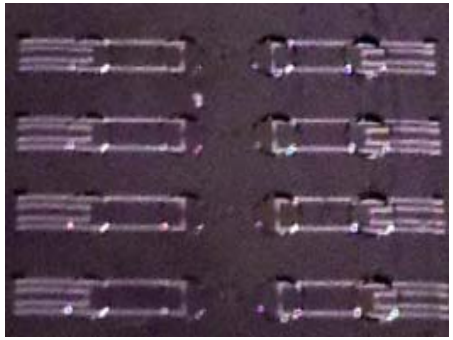
(Left) Schematic of the PC slab resonator structure with excitation and receiving transducers on its two sides. In this schematic, the cavity region is surrounded by four rows of holes one period of the PC on each side.

(Right) Top SEM image of a fabricated PC slab resonator with the transducer electrodes on each side. The cavity region is surrounded by 12 rows three periods of holes on each side.

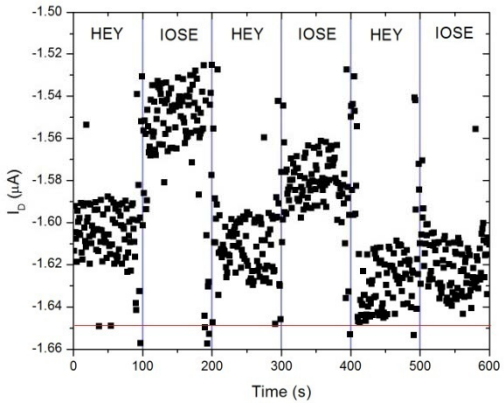
Students: M. Saeed, E. A. Ali, PIs: W. D. Hunt, A. Adibis- ECE, - Georgia Tech
Work performed at the Georgia Tech Nanotechnology Research Center

Electronic Microplate with Silicon Nanowire Sensors

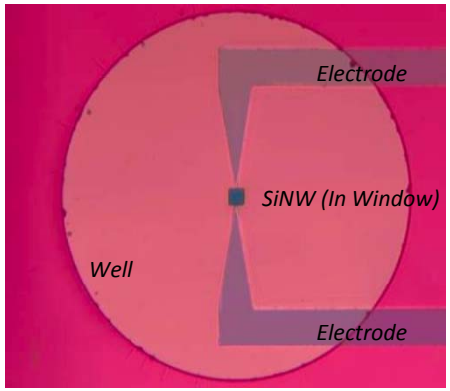
The objective of this research was to develop a label-free monlithically integrated electronic sensing platform to replace the conventional microplate. Critical to this goal was using a fabrication method that was a fully CMOS compatible top-down process. The sensor front end is base from silicon nanowires fabricated on a silicon substrate. This highly adaptable, integrated sensor platform will enable exciting new detection methods for cancer markers, gene expression, and a host of other emerging aspects of personalized medicine. Shown below is the change in current through an array of nanowires as they are exposed to healthy and cancerous cells.



Completed 1cm^2 4x4 array



Testing of healthy (IOSE) to cancerous (HEY) cells



Completed Well

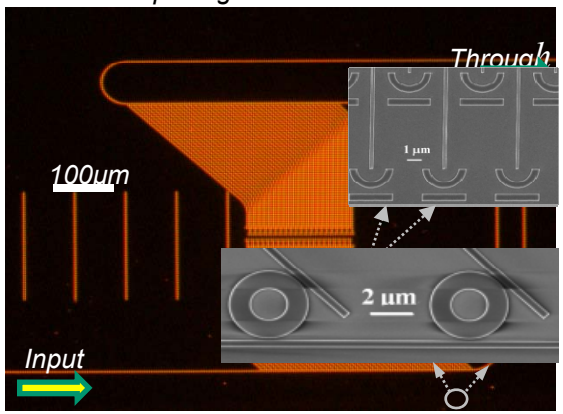
Student: R. Ravindran, Pis: Dr. M.S. Bakir, Dr. J. F. McDonald, and Dr. J. D. Meindl, Georgia Tech
Work performed at the Georgia Tech Nanotechnology Research Center

Microdonut On-chip Spectrometer

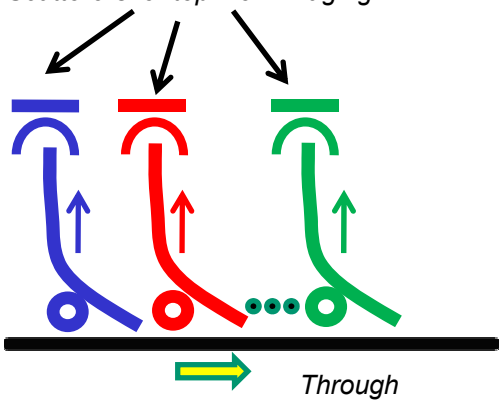
Properties such as high Q, small mode volume and the compatibility of planar travelling-wave-resonator (TWR) structures with planar CMOS fabrication and post-fabrication have promised the potential for large scale integration of optical and electronic elements on a silicon-on-insulator (SOI) platform. A systematic approach to the engineering of waveguide-resonator coupling for optimum phase matching and field-overlap was used to achieve critical coupling and strong over-critical coupling for microring, micro racetrack and microdisk resonators on silicon-on-insulator (SOI) platform. The impact of the waveguide-resonator dimensions, their spacing and interaction length on the strength of the coupling were investigated. It was shown that by optimization of the dimension of the waveguide-resonator structure, the coupling strength can be engineered to be insensitive to fabrication errors. Based on our optimization techniques, critical coupling to low Q (~ 10^4) resonators as well as ultra-high Q (~ 10^5) resonators is experimentally demonstrated.

Students: X. Zhixuan, M. Soltani, Q. Li, M. Chamanzar, S. Yegnanaravanan, B. Momeni, A. Eftekhar, PI: A. Adibi-ECE, Georgia Tech
Work performed at the Georgia Tech Nanotechnology Research Center

Large scale array of 84 microdonuts
Inner radius – fixed at 0.95 µm
Outer radius – 1.950 to 2.033 µm, step – 1nm
Resonance Spacing ~ 0.6 nm



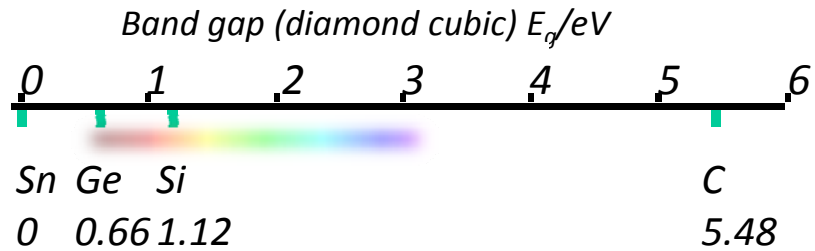
Scatterers for top-view imaging

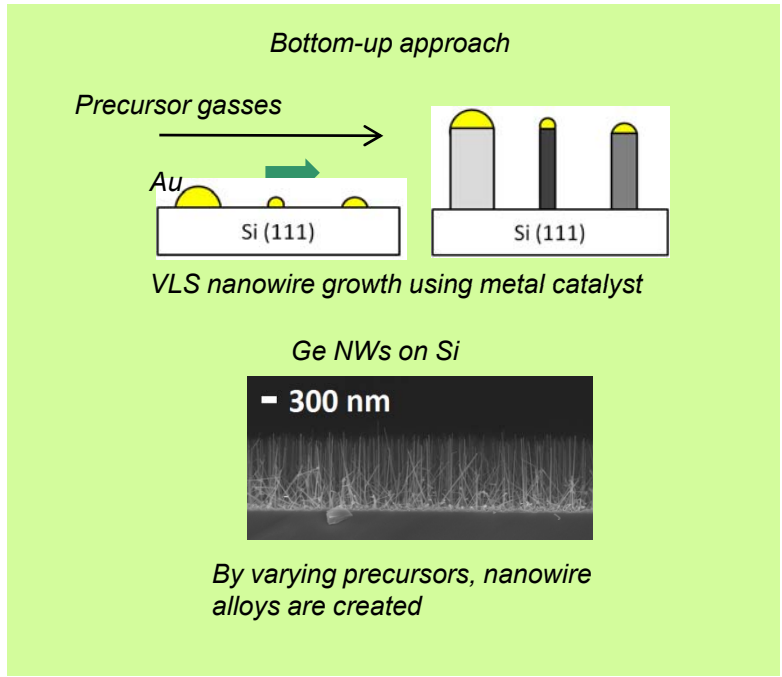


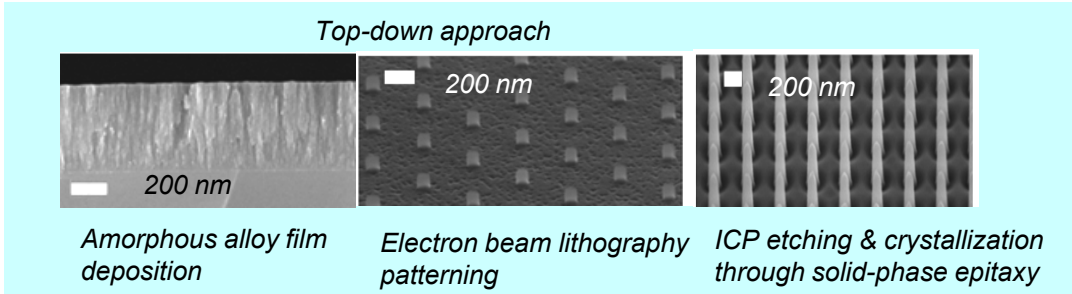
Each resonator corresponds to its own resonance wavelength

Novel Group IV Semiconductor Nanowire Alloys for Next Generation Solar Energy Conversion

In the area of photovoltaics, alloy and heterostructure nanowires are under investigation to achieve energy conversion efficiencies in excess of the Shockley-Queisser limit. Band-gap engineering group IV alloys in strain-relaxed nanostructures opens the doorway to efficiently harvesting light across the entire solar spectrum with earth-abundant and non-toxic materials. Many of the properties inherent to the nanowire geometry, such as quantum confinement and strain relaxation, offer exciting opportunities to create novel solar harvesting materials to realize this goal. Group-IV elements and their alloys are a particular focus in this work because they are earth-abundant, non-toxic, and may permit band gap engineering throughout the solar spectrum. In addition, these materials offer the advantages of bottoms-up over top-down nanowire growth methods.





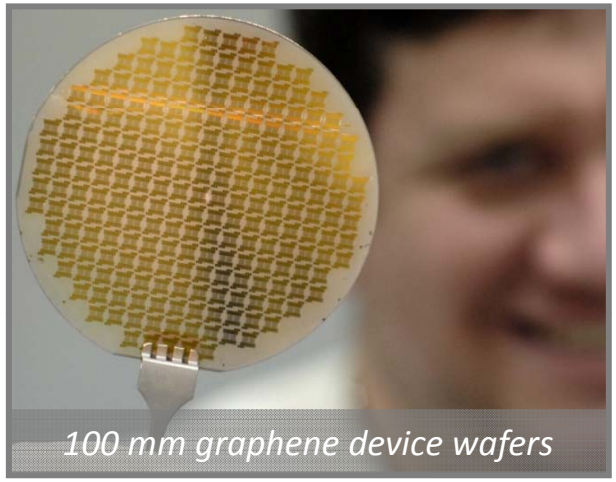


Student: I. Musin, PI: M. Filler - ChemE, Georgia Tech
Work performed at the Georgia Tech Nanotechnology Research Center

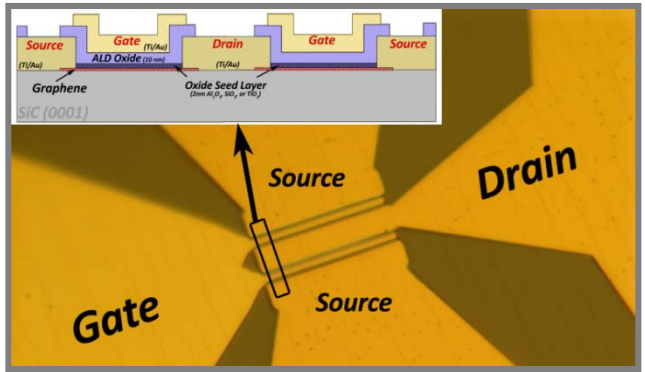
Penn State University

Ultra-Large Area Graphene for RF Applications

Joshua Robinson and David Snyder, Electro-Optics Center, Freeport, PA 16229



100 mm graphene device wafers



RF graphene transistors

With its remarkable properties, graphene is being studied worldwide for electronics, displays, solar cells, sensors, and hydrogen storage. It has the potential to enable terahertz computing at processor speeds 1,000 times faster than silicon.

Researchers in the Pennsylvania Electro-Optics Center have produced the world's first RF graphene transistors on 100mm diameter epitaxial graphene wafers, a key milestone in the development of graphene for next generation high frequency electronic devices.

This achievement has put the Center in a leading position for the synthesis of ultra-large graphene and graphene-based devices.

*J. A. Robinson *et al.*, "Epitaxial Graphene Materials Integration: Effects of Dielectric Overlayers on Structural and Electronic Properties," *ACS Nano* 4 (5), 2667 (2010).

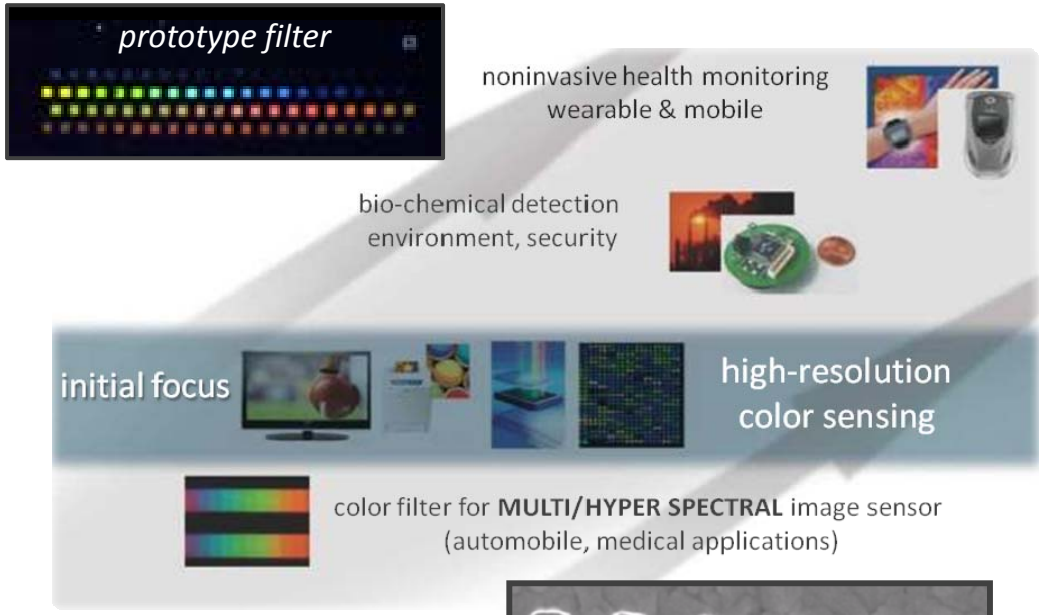
Work performed at Penn State Nanofabrication Laboratory

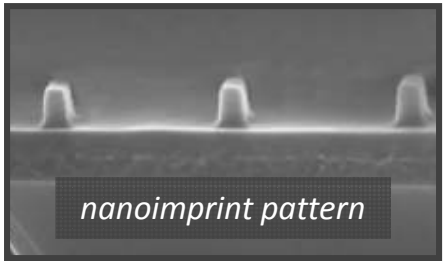
World's first RF graphene transistors on 100mm diameter epitaxial graphene wafers, a key milestone for next generation high frequency electronic devices.

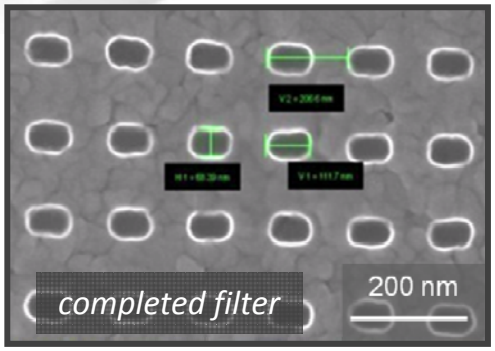
Spectrum Sensor™ Chip using Nanoimprint

nanoλ

Min Kyu Song, Byunghee Lee, and Bill Choi, NanoLambda Inc, Pittsburgh, PA.







The Penn State NNIN Site was used to demonstrate a nanoplasmonic filter array device technology that is being integrated into an inexpensive, portable on-chip spectrometer for high resolution color sensing, non-invasive health monitoring, bio-chemical detection.

The nanoimprint process that was developed in the NNIN is currently being transferred to pilot line production where the cost and yield of the filter manufacturing process is being analyzed for specific customer applications.

Work performed at Penn State Nanofabrication Laboratory

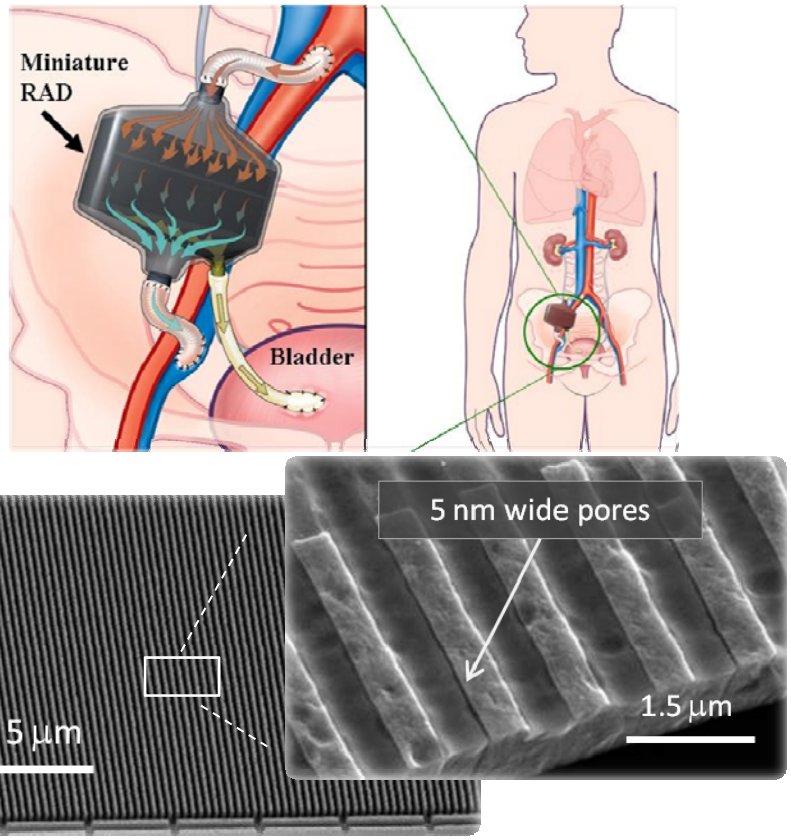
NNIN
www.nnin.org
Nanoscale Science, Engineering & Technology

Nanoimprint-based manufacturing is enabling a cutting edge, low cost nanoplasmonic filter technology with projected revenues of > $90M by 2012.

Nanoporous Hemofilter

Cleveland Clinic H-Cubed, Inc.

S. Roy, University of California, San Francisco, CA, K. Goldman, H-Cubed, Inc., A. Fleischman, Cleveland Clinic Foundation, Cleveland, OH.



The Penn State NNIN Site was used to prototype a miniature nanoporous poly-Si membrane hemofilter, a key component for artificial kidneys. The envisioned renal assist device (RAD) is composed of a passive hemofilter and an active renal tubule cell bioreactor that together form a self-regulating implantable system.

RAD filters with 5 nm wide pores were fabricated by precise Si oxidation and sacrificial oxide removal, while the pore density was determined by nanolithography. Membranes with 4000 lines/mm are currently being characterized for nanofiltration and mechanical robustness.

Work performed at Penn State Nanofabrication Laboratory

NNIN www.nnin.org Nanoscale Science, Engineering & Technology

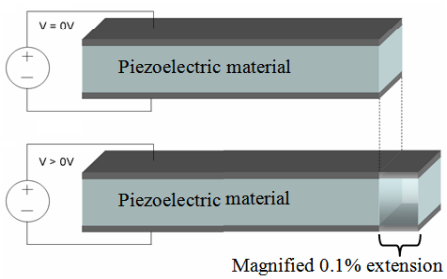
Renal assist devices that integrate ultra-dense nanoporous membranes will benefit over 400,000 US patients suffering from kidney failure each year.

Solid-State Muscles for Microrobots

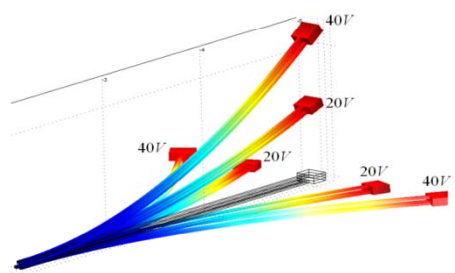
PURDUE UNIVERSITY

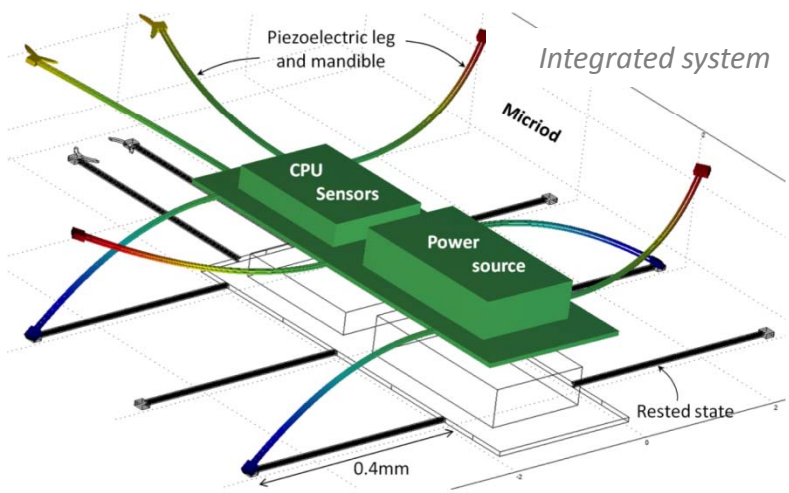
Fengyuan Li and Jason V. Clark, Purdue University, Discovery Park, IN

One PZT fiber



Triplet of PZT fibers





The micro-robot has a solid state construct. No joints or gears to jam or wear out.

The PSU NNIN site is being used for the fabrication of Microids, which are microrobots with insect-like dexterity.

The pioneering developments of this research are expected to lead to the following microrobotic capabilities:

- Walk and jump in various directions.
- Traverse harsh terrains such as sand.
- Pick up, carry, and place micro-loads.
- Withstand large impacts or accelerations.
- Walk and jump upside down if flipped over.
- Recharge using vibrational energy-scavenging.

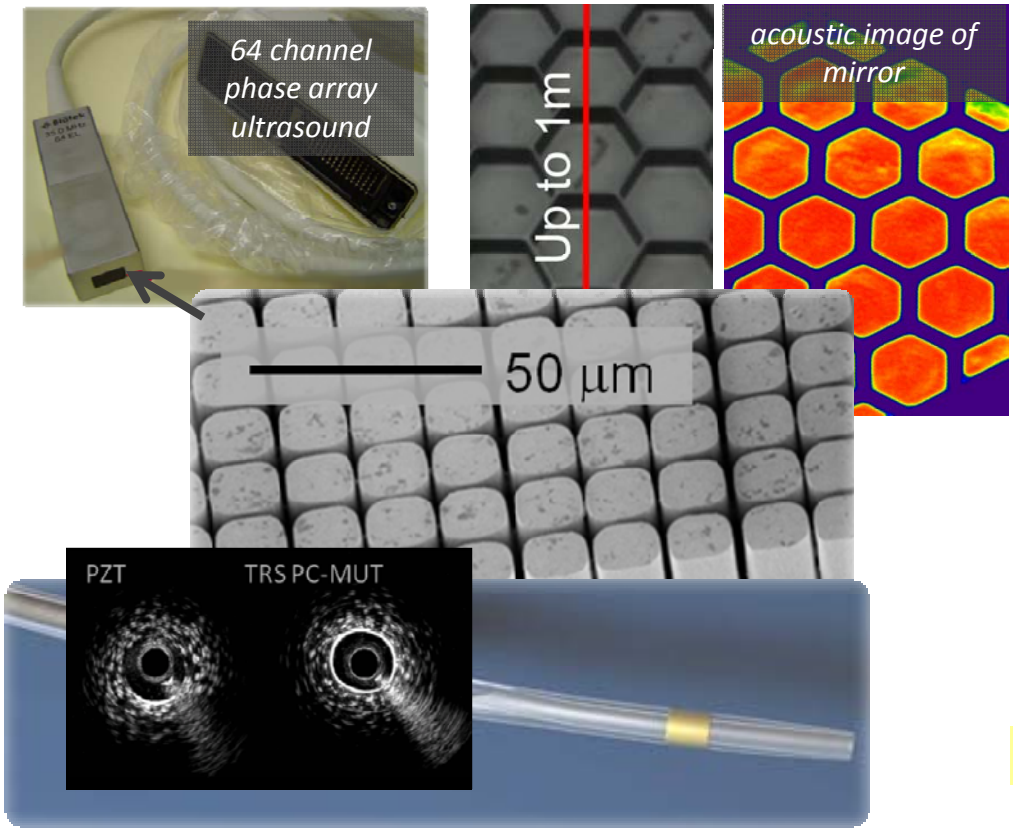
Work performed at Penn State Nanofabrication Laboratory

NNIN www.nnin.org Nanoscale Science, Engineering & Technology

By integrating PZT actuators, a power source, and a CPU, we expect to develop the first all-terrain autonomous microrobots.

High-Frequency Ultrasound

X. Jiang, K. Snook, and W. Hackenberger, TRS Technologies, Inc., State College, PA.
R. Liu and X. Geng, Blatek, Inc., State College, PA.



The PSU NNIN site is being used for micromachining bulk piezoelectrics to fabricate micron-scale high-aspect ratio 2-2 and 1-3 PMN-PT single crystal/epoxy composites for high frequency ultrasound transducers used for medical imaging and industrial non-destructive evaluation.

For the first time, a 64-channel, 35 MHz phased array was prototyped and characterized, showing broad bandwidth (> 80%) and high sensitivity. This has significant impact on advancing the start-of-the-art phased arrays (< 20 MHz) for sophisticated ultrasound applications.

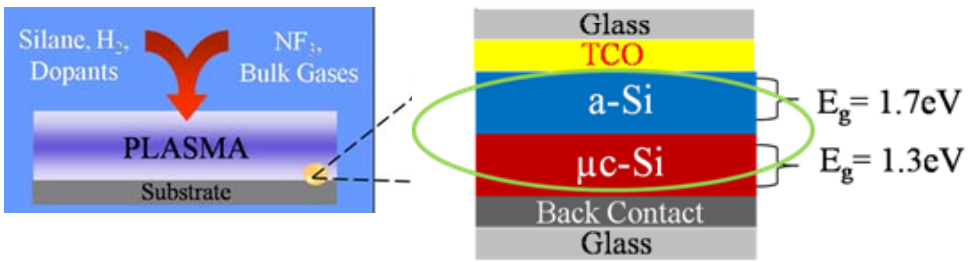
Work performed at Penn State Nanofabrication Laboratory

Patterning and reactive ion etching of micron-scale high-aspect ratio complex oxide materials enables higher resolution ultrasound.

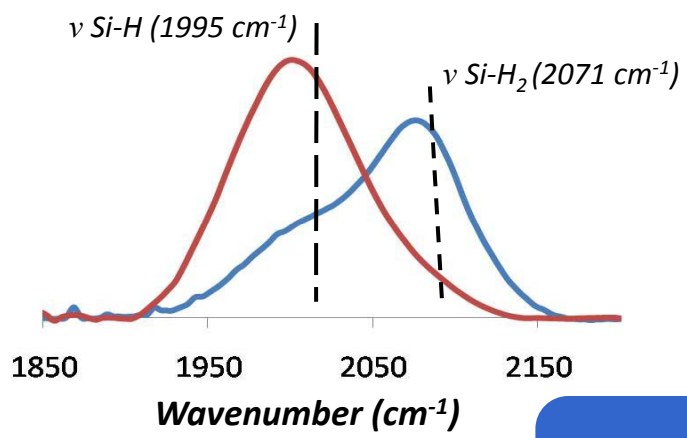
Enhancing a-Si and nc-Si Deposition Rates for Low-Cost Thin Film Solar Cells

P. T. Hurley and R. G. Ridgeway, Air Products and Chemicals, Inc. Allentown, PA.

TF-Si Solar Cell Manufacturing Process



New additives provide controlled bonding environment and superior a-Si:H material for solar industry



The Penn State NNIN Site is being used to develop and validate an advanced plasma chemical vapor deposition process to increase the growth rates and reactant utilization for a-Si:H and nc-Si thin films for solar cells. These new processes are directly compatible with manufacturing facilities for early and rapid deployment.

Once developed and commercialized, these additives could be used by all thin-film Si (TF-Si) manufacturers, whose production is expected to be ~5.2 GW by 2012. If all 5.2 GW of TF-Si manufacturing were to adopt these additives and save ~$0.115 per watt, this would result in annual savings of ~$600 million per year to the photovoltaic industry.

Work performed at Penn State Nanofabrication Laboratory

Penn State maintains strong partnerships to support corporate research program that would result in annual savings of ~$600 million to photovoltaic industry

Low-Cost Pyroelectric Detector Arrays

Chien-Hung Wu, Bridge Semiconductor, Pittsburg, PA.

The Penn State NNIN site is being used to deposit, pattern, and etch doped $Pb(Zr_{0.30}Ti_{0.70})O_3$ (PZT) pyroelectric films for uncooled thermal imaging systems.

Video frame-rate imaging has been demonstrated upon integration with CMOS read-out integrated circuit (ROIC) electronics.

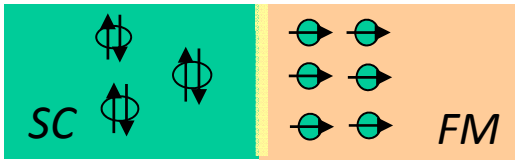
Ultimately, image quality is expected to be superior to other uncooled thermal imagers, including resistive bolometers.

Work performed at Penn State Nanofabrication Laboratory

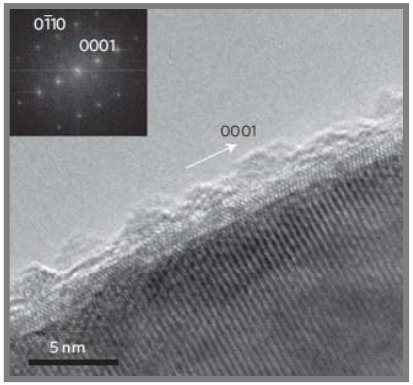
Integrating pyroelectric films to a CMOS ROIC with associated system electronics enables high-performance, low-cost infrared cameras.

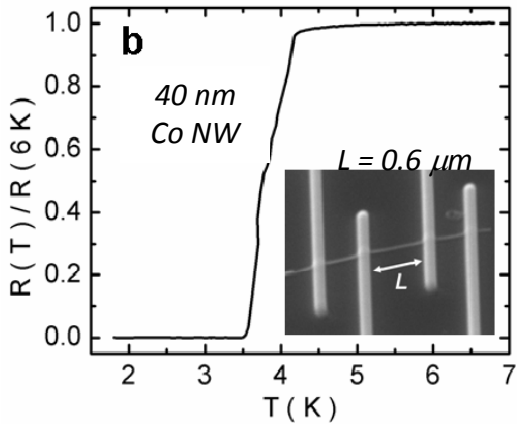
Interplay Between Superconductivity and Ferromagnetism in Cobalt Nanowires

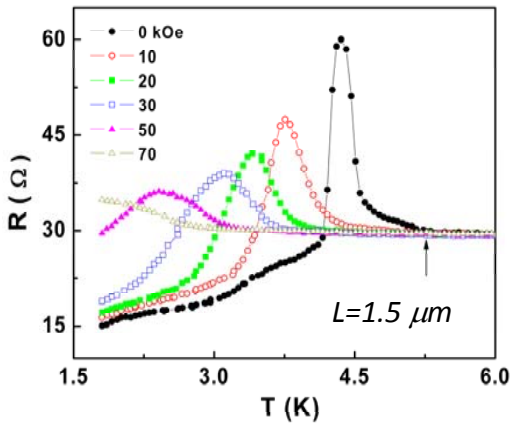
J. Wang, M. Singh, M. Tian, N. Kumar, B. Liu, C. Shi, J. Jain, N. Samarth, T. E. Mallouk & M .H. W. Chan, Center for Nanoscale Science, Penn State University, University Park, PA.



conflicting spin orders in the interfacial region







Superconducting (SC) electrodes are not expected to be effective in inducing superconductivity in ferromagnetic (FM) cobalt nanowires due to contrasting electronic spin orders. Surprisingly, we found 40 nm cobalt wires of 0.6 μm in length to be fully superconducting when contacted by superconducting W electrodes. In a longer wire exhibiting incomplete superconductivity, a large and sharp resistance peak is found preceding the onset of superconductivity.

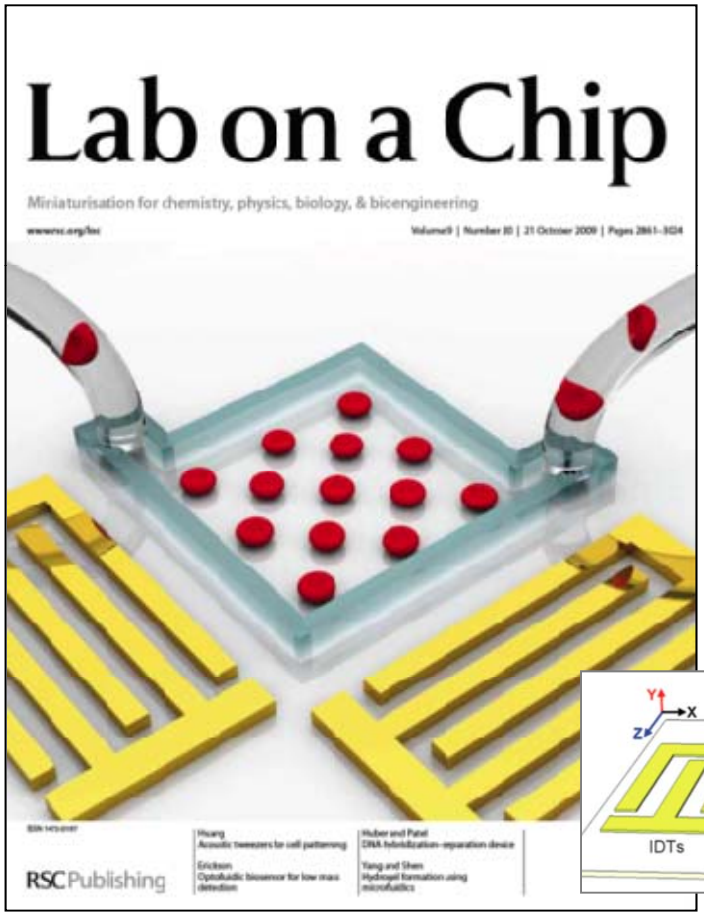
J. Wang, et al., Nature Physics, 6, 389-394 (2010).

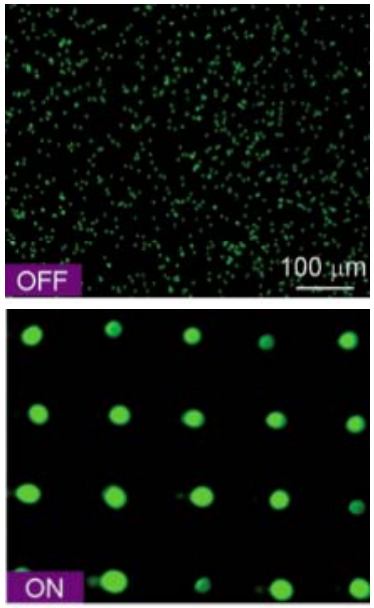
Work performed at Penn State Nanofabrication Laboratory

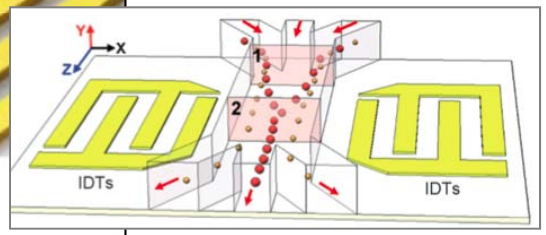
Integrating reliable electrical contacts onto individual nanowires allows new and surprising discoveries in materials and physics.

Acoustic Tweezers: A New Cell Patterning Tool

J. Shi, D. Ahmed, X. Mao, S.-C. Lin, H. Huang, Z. Stratton, & T. J. Huang,
Penn State University, University Park, PA.







This NNIN-enabled research demonstrates a new type of cell patterning tool driven by sound, named "acoustic tweezers." This new technique can pattern cells regardless of shape, size, charge or polarity.

Acoustic tweezers enable on-chip continuous particle separation through standing surface acoustic wave (SSAW)-induced acoustophoresis in a microfluidic channel.

Work performed at
Penn State Nanofabrication Laboratory

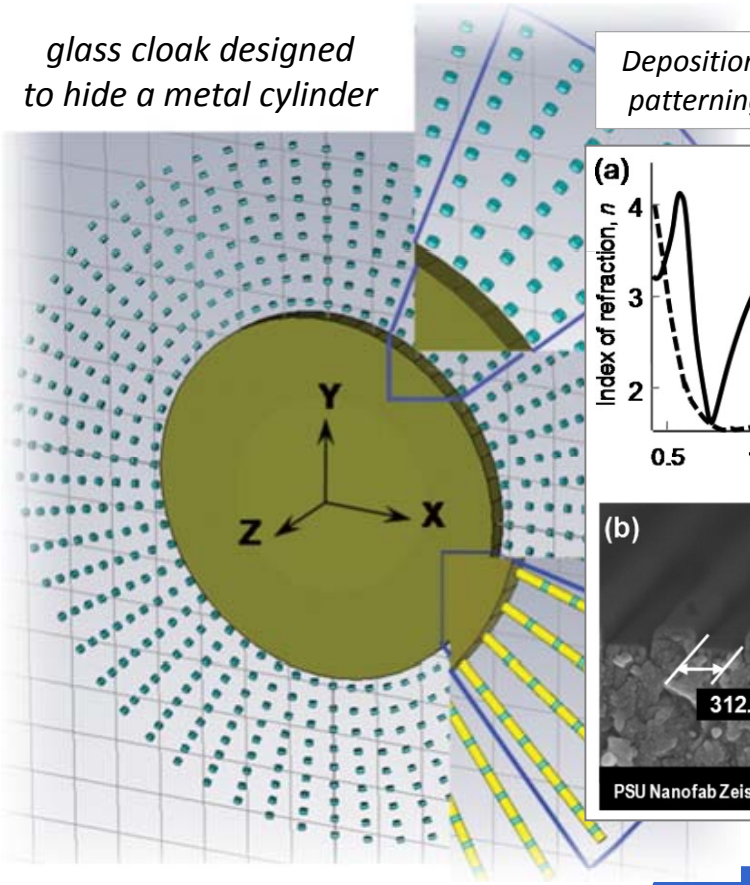
Shi et al., Lab Chip, 9, 2890 & 3354 (2009).

"A system that uses sound as a tiny tweezers can be small enough to place on a chip." -U.S. News and World Report

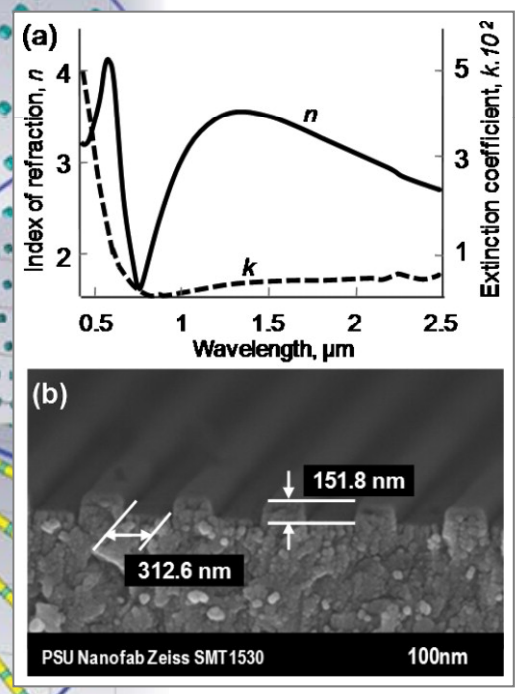
Toward an Infrared Invisibility Cloak

E. Semouchkina, C. Huang, D. H. Werner, G. B. Semouchkin, & C. Pantano,
Penn State University, University Park, PA.

glass cloak designed to hide a metal cylinder



Deposition, characterization, and patterning of GeSbSe ChG glass.



The Penn State NNIN site is developing processes to support the deposition and patterning of chalcogenide (ChG) glasses such as GeSbSe. The ChG's have unique properties for infrared optical devices, including metamaterials:

(1) tailoring the refractive index by varying the composition of the component materials (e.g., GeSbSe).
(2) low a optical loss in the infrared wavelength regime .

Work performed at Penn State Nanofabrication Laboratory

Semouchkina et al., Appl. Phys. Lett., 96, 233503 (2010).

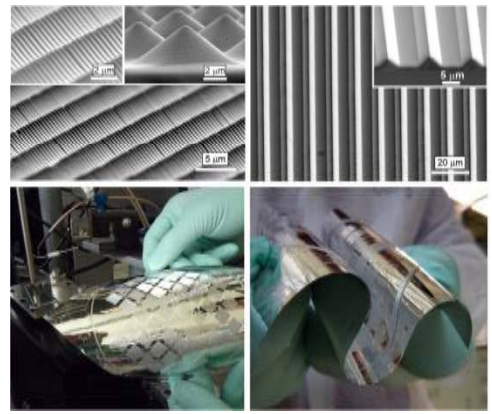
A new invisibility cloak for the infrared wavelength regime has been designed using organized arrays of nanoscale chalcogenide glass resonators.

Stanford University

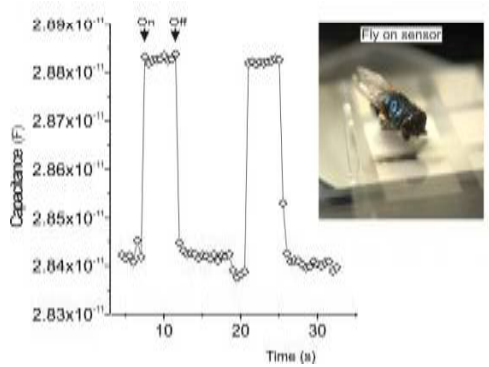
Highly Sensitive Structured Elastomers as Rubber Dielectric Layers for Organic Transistors

Flexible, capacitive pressure sensors with unprecedented sensitivity and very short response times that can be inexpensively fabricated over large areas by micro-structuring of thin films of the biocompatible elastomer polydimethylsiloxane have been demonstrated. The pressure sensitivity of the micro-structured films far surpassed that exhibited by unstructured elastomeric films of similar thickness and is tunable by using different microstructures. The micro-structured films were integrated into organic field effect transistors as the dielectric layer, forming a new type of active sensor device with similar excellent sensitivity and response times.

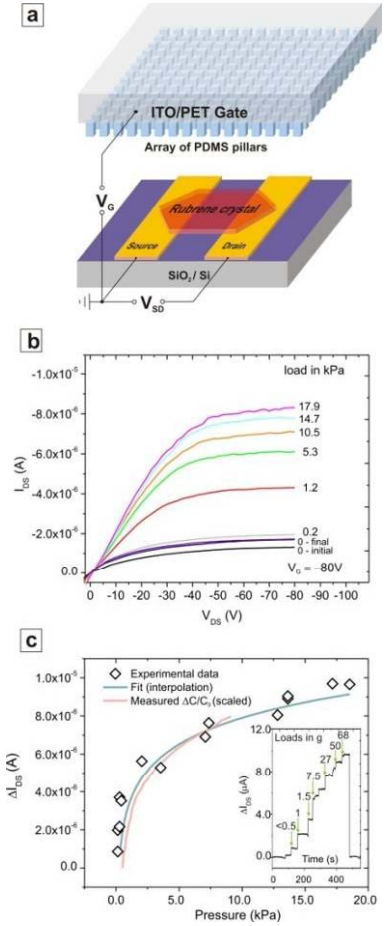
Benjamin Tee[1] and Professor Zhenan Bao[2]
Departments of Electrical Engineering[1] and Chemical Engineering[2]
Stanford University
Work performed at Stanford Nanofabrication Facility



Large area fabrication of rubber dielectric on flexible sheets



High sensitivity and rapid response time



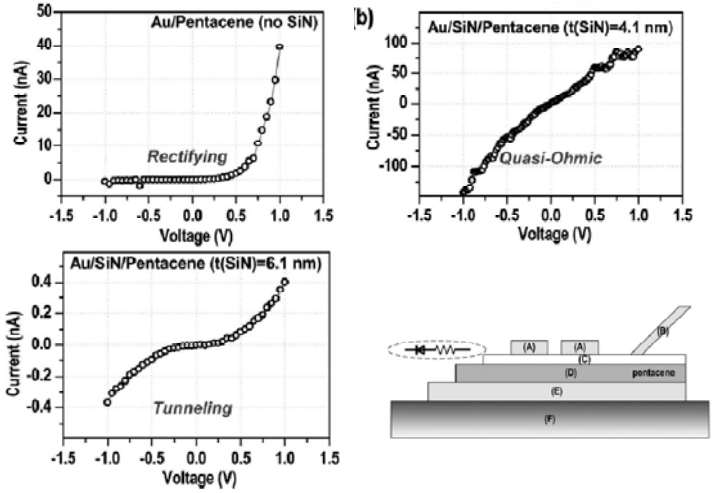
Pressure sensor response in OFET configuration

SCB Mannsfeld, Benjamin CK Tee, RM.Stoltenberg, et. al.,, "Highly sensitive flexible pressure sensors with micro-structured rubber dielectric layers", Nature Materials, accepted July 2010

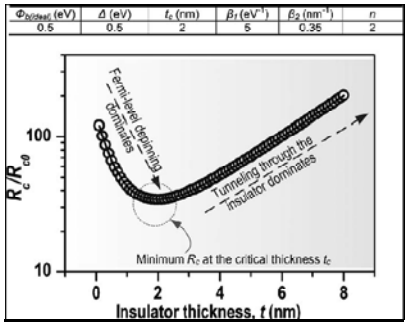
Organic Semiconductor Contact Engineering via Fermi Level Depinning

Organic or carbon semiconductor devices are promising for both nanoelectronic and macroelectronic applications. To achieve high performance of these devices understanding and improvement of the metal-organic (M/O) interface is necessary. Fermi level depinning at the M/O interface by insertion of an ultrathin interfacial Si_3N_4 insulator has been demonstrated. The M/O contact behavior is successfully tuned from rectifying to quasi-Ohmic and to tunneling by varying the Si_3N_4 thickness from 0 to 6 nm. Detailed physical mechanisms of Fermi-level pinning/depinning responsible for the M/O contact behavior are clarified based on a lumped-dipole model and a simple depinning model. This work sheds light on the fundamental understanding of the M/O interface properties and also proves a practical engineering method of achieving low-resistance quasi-Ohmic contacts for organic electronic devices.

Zihong Liu[1], Professor Zhenan Bao[2], Professor Yoshio Nishi[1]
Departments of Electrical Engineering[1] and Chemical Engineering[2]
Stanford University
Work performed at Stanford Nanofabrication Facility



I-V characteristics of the Au/ Si_3N_4 /pentacene diodes with different Si_3N_4 thicknesses. The Au/pentacene diode has been tuned to rectifying, quasi-Ohmic, and symmetric tunneling behavior.

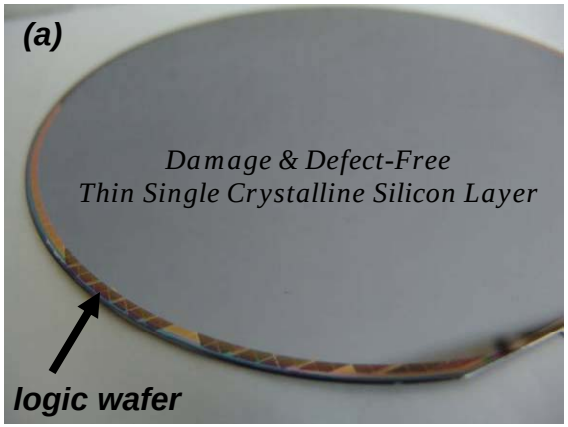


Simulation plot of the contact resistance with respect to the interfacial insulator thickness at the M/O interface based on a simple depinning model.

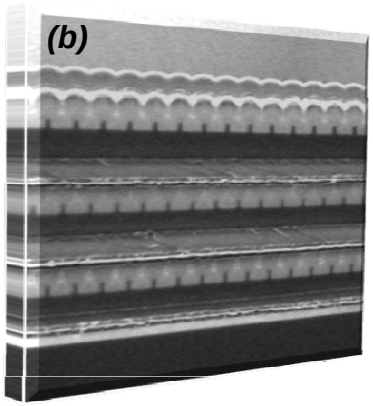
Multi-Layer Stacked 3-Dimensional Integrated Circuit Technology

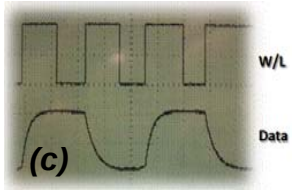
This 3D IC technology includes four single-crystalline silicon layers having 200 nm to 60 nm feature size vertical device structures which are uniquely processed at low temperatures, below 400 degree Celsius. The four single-crystalline silicon layers are formed above a silicon substrate with a metal interconnection region between them. Unlike conventional 3D packaging technologies and 3D through silicon via technologies, where memory control logic circuits are stacked in 3D along with memory arrays, this 3D IC technology combines the control logic on the bottom substrate with the 3D memory arrays. This 3D IC scheme allows heat to be dissipated much more efficiently. Ultimately, this 3D IC could be an alternative solution for device scaling of conventional CMOS in vertical dimension.

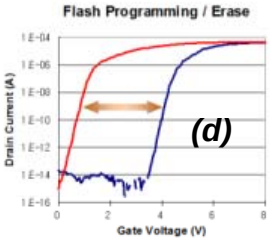
Junil Park[1], Sang-Yun Lee[1] and Prof. Yoshio Nishi[2]
[1]BeSang Inc.
[2]Dept. of Electrical Engineering at Stanford University
Work performed at Stanford Nanofabrication Facility



(a) Damage and defect-free thin single crystalline silicon layer has been formed on top of underlying logic wafer.



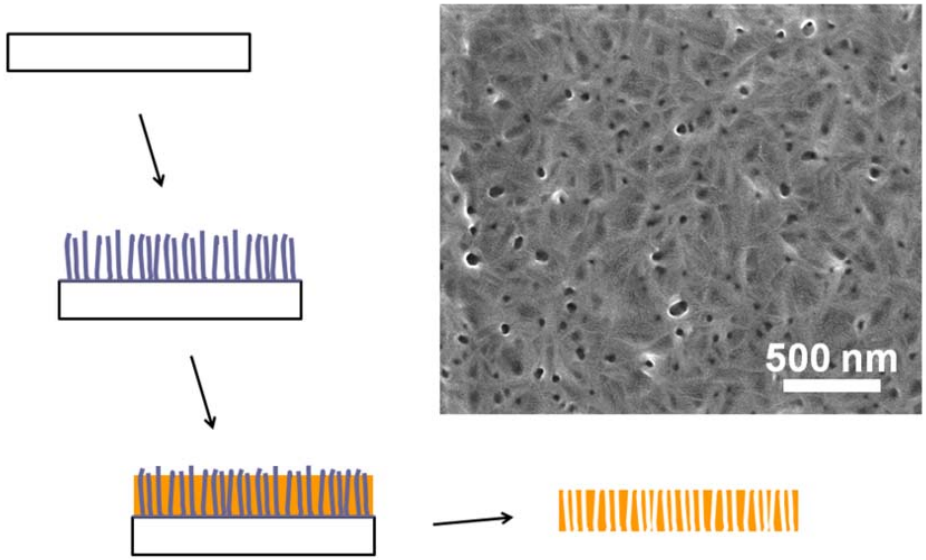




(b) Multi-layer 3D IC
(c) DRAM read/write/refresh performance
(d) Flash program/erase performance

Nanoporous Biodegradable Polymers for Delivery of Protein Therapeutics

Nanostructured biodegradable polymers have been fabricated and characterized for use in biomedical applications. Characteristic diffusion of fluorescein and albumin across nanoporous membranes were shown to be first- and zero-order, respectively, indicating structural size can be used to control transport behavior. Doing so, such materials can be useful for a variety of drug delivery or filtration applications. This technique is widely applicable and is valuable in the development of future biomedical devices.



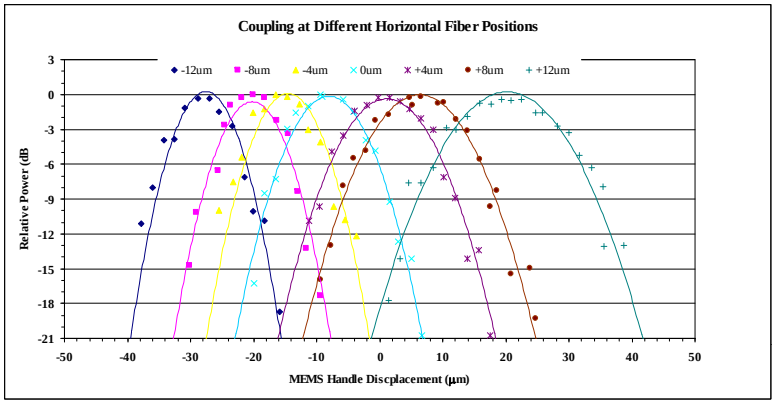
Schematic showing growth of zinc oxide nanorods, casting of the biodegradable polymer poly(caprolactone), and resulting nanostructured film upon etching, along with SEM showing typical structures.

Daniel Bernards, Professor Tejal Desai
Department of Bioengineering and Therapeutic Sciences
University of California, San Francisco
Work performed at Stanford Nanofabrication Facility

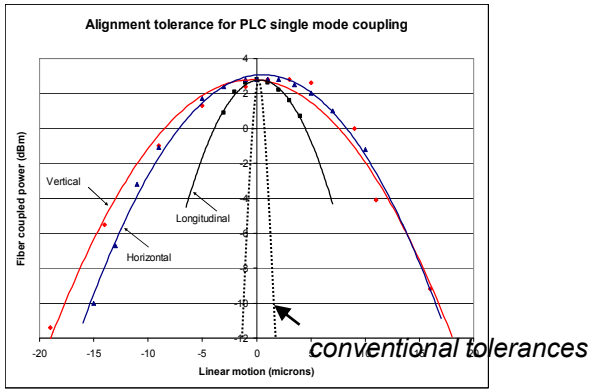
MEMS-based Alignment of Single Mode Optical Packages

Single mode fiber optics are used to carry data for distances greater than 100m and form the connections that enable the majority of the world's communications infra-structure. Unlike electronic packaging that needs relatively low precision assembly of chips and wirebonds, single mode fiber optics requires sub-micron tolerances given that the mode size is on the order of the wavelength of light in the optical fiber and other optical devices such as semiconductor lasers, modulators, and planar waveguides. Kaiam Corporation has developed a MEMS-based platform at SNF that allows for automatic adjustment and alignment of hybrid optoelectronic packages, and thereby increases the tolerances of single mode optics to that of standard electronic packaging. This allows a variety of complex hybrid integrated photonic circuits to be fabricated simply at high yield.

Dinh Ton, Gideon Yoffe, Thomas Schrans, and Bardia Pezeshki,
Kaiam Corporation, Newark, California
Work performed at Stanford Nanofabrication Facility



Placement errors of +/12 microns are compensated using MEMS and the power is recovered

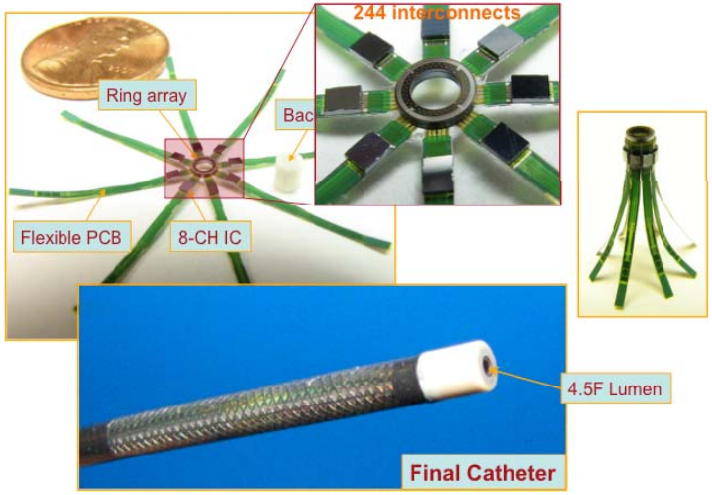


Conventional tight tolerances are expanded using silicon MEMS in the vertical and horizontal directions

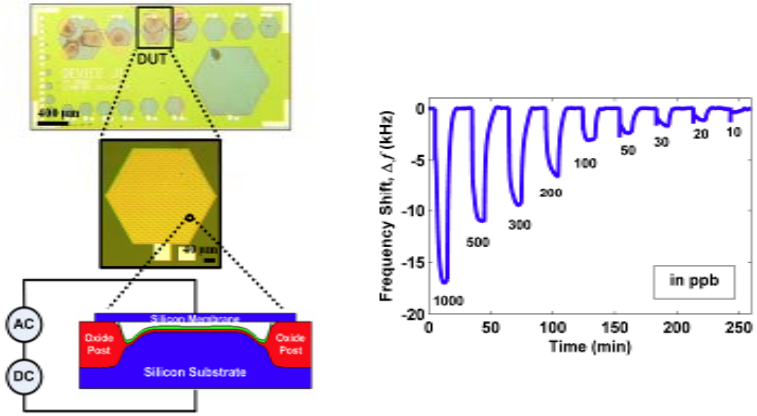
Capacitive Micromachined Ultrasonic Transducers (CMUTs)

Capacitive micromachined ultrasonic transducers in the form of single elements, 1-D, 2-D, annular and annular ring arrays using standard IC fabrication techniques have been fabricated. Applications of this platform transducer technology include medical anatomical and functional imaging, therapy, chemical and biological sensing, secure voice communications, non-destructive testing, filters, and microphones. Several generations of fabrication technologies for making CMUTs. Some of these technologies are: sacrificial etching based membrane definition, fusion wafer bonding based membrane definition, gap definition by local oxidation of silicon, doped polysilicon filled through wafer vias as electrical interconnects, trench isolated silicon pillars as electrical interconnects, polymer filled through wafer trenches for flexible ultrasound array implementation, and chip-to-chip bonding for integration with electronic circuits.

Professor Pierre Khuri-Yakub
Department of Electrical Engineering
Stanford University.
Work performed at Stanford Nanofabrication Facility.



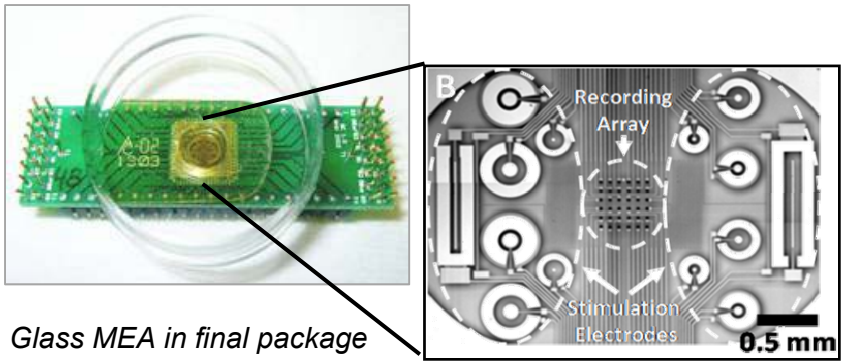
A 10-MHz 64-element CMUT ring array integrated with front-end electrical circuits on a 12-F catheter for 3-D intracardiac imaging.



A CMUT-based resonant chemical sensor and its response to an analyte.

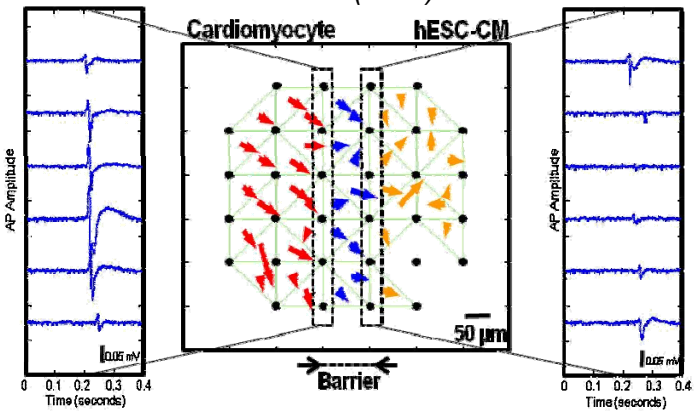
In Vitro Electrophysiologic Model For Cardiac Stem Cell Integration

Functional integration of the stem cell grafts to treat cardiac diseases is of increasing interest. The electrical properties of grafted cells are important to ensure an homogeneous conduction of the electrical signal (depolarization), and to reduce risks of arrhythmia, often seen in current *in vivo* experiments. The platform for studying *in vitro* the electrical maturation and integration of stem cell-derived cardiomyocytes was developed based on microelectrode arrays built in the SNF. Platinum recording electrodes of 20 μm diameter, as well as larger stimulation electrodes, were patterned on glass substrates. The platform was successfully used to highlight and quantify mismatches in the conduction of the electrical depolarization between host cells and graft cells of various types and maturities. Electrical stimulation experiments also revealed the small, yet significant impact of such stimulation on differentiation and integration of embryonic stem cells.



Glass MEA in final package

Close-up of microelectrode array (MEA)



Characterization (vector field) of the propagation of electrical depolarization between host cardiomyocytes (left side, red arrows) and human embryonic stem cell-derived cardiomyocytes (right side, yellow arrows). The propagation at the boundary is shown as blue arrows. Lateral panels show recorded signals.

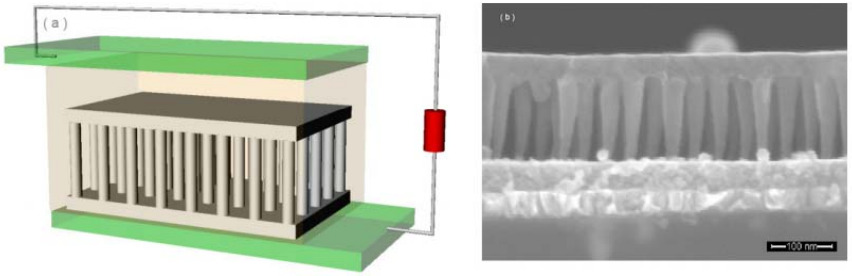
Professors Gregory Kovacs and Laurent Giovangrandi
Department of Electrical Engineering
Stanford University.

Work performed at Stanford Nanofabrication Facility.

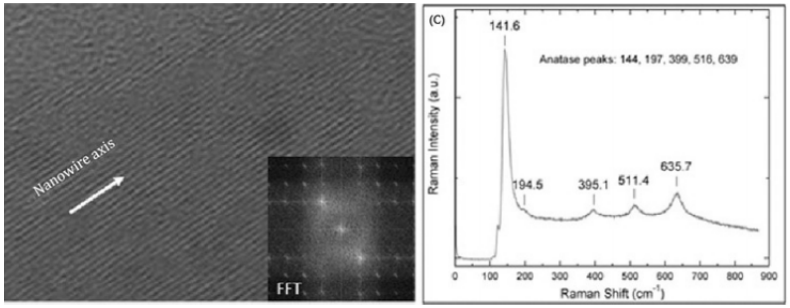
Synthesis of TiO_2 Nanoframe for a Prototype Solar Cell

Nanoframes containing 20 nm diameter TiO_2 nanowire arrays were synthesized with polymer templates via cathodic sol-gel deposition followed by 450° C sintering. Raman spectra indicated that they are composed of pure anatase TiO_2. The nanowire array inside the nanoframe was confirmed to be single crystalline by high resolution TEM. Dye sensitized solar cells based on this nanoframe were fabricated and the effect of the top cover was shown to not prevent the I^- and I_3^- ions underneath from diffusing freely in the electrolyte, causing no deterioration of the cell performance. This is a promising device since nanoframe arrays can be strengthened and the effective internal surface area can be increased without sacrificing the advantages of nanowire cells.

Ying Chen, Dr. Ho-Cheol Kim*, Dr. Jim McVittie, Dr. Chiu Ting and Professor Yoshio Nishi
Department of Electrical Engineering
Stanford University
*IBM Research, San Jose, CA
Work performed at Stanford Nanofabrication Facility



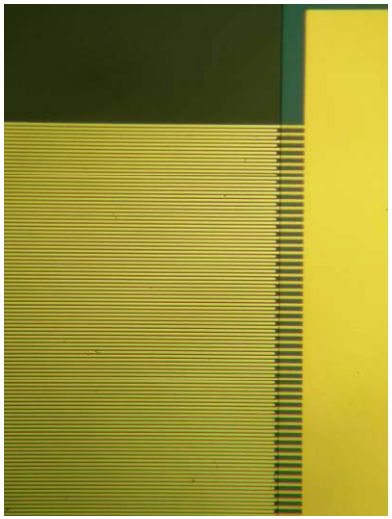
The nanoframe dye-sensitized solar cell based on a titania nanoframe. Schematic diagram of the cell (left) and SEM cross section of the actual nanoframe (right).



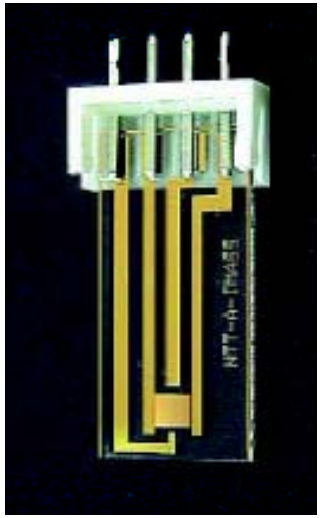
High resolution TEM (left) and Raman spectra of TiO_2 nanoframe grown in a sol-gel bath.

Interdigitated Electrode Arrays for Evaluation of Electrocatalysts

Interdigitated electrode arrays have advantages over conventional rotating electrode techniques when rate constants for fast catalytic reactions need to be measured. These electrodes arrays fabricated at SNF have been applied for catalytic hydrogen evolution with new non-precious metal catalysts synthesized at the Pacific Northwest National Laboratory.



2 μm width, 2.5 μm gap
2 μm width, 2 μm gap
2 μm width, 1.5 μm gap
2 μm width, 1 μm gap
2 μm width, 0.75 μm gap



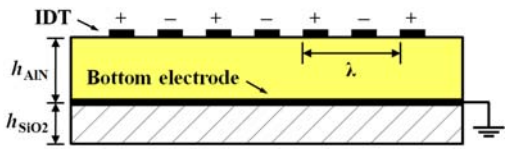
Specifications for Electrodes
thickness – 0.1-0.2 μm
length – 2-10 mm
pairs of fingers – 50-75
quartz substrate
titanium adhesion layer

Fei Liu and Professor Bruce Parkinson
Department of Chemistry
University of Wyoming
Work performed at Stanford Nanofabrication Facility

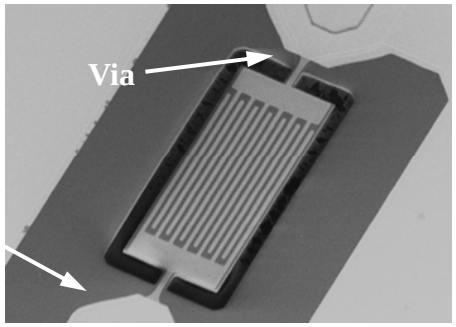
Temperature-Compensated Aluminum Nitride Lamb Wave Resonators

A Lamb wave resonator based on a stack of AlN and SiO_2 layers can achieve a zero first-order temperature coefficient of frequency with the addition of a compensating layer of silicon dioxide with an appropriate thickness. Using a composite membrane consisting of 1 μm AlN and 0.83 μm SiO_2, a Lamb wave resonator operating at 711 MHz exhibits a first-order TCF of –0.31 ppm/°C and a second-order TCF of –22.3 ppb/°C^2 at room temperature. The temperature-dependent fractional frequency variation is less than 250 parts per million (ppm) over a wide temperature range from –55°C to 125°C.

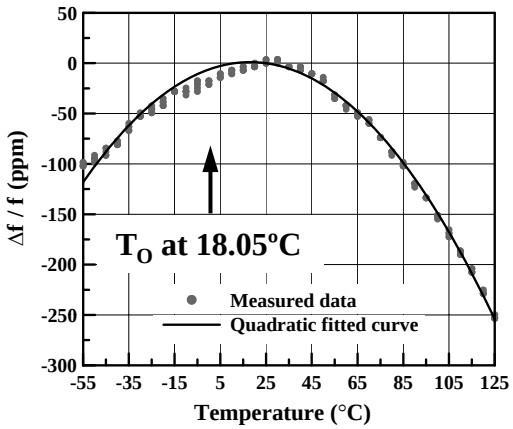
Chih-Ming Lin and Professor Albert P. Pisano
Department of Mechanical Engineering
University of California at Berkeley
Work performed at Stanford Nanofabrication Facility



(a)



(b)



(c)

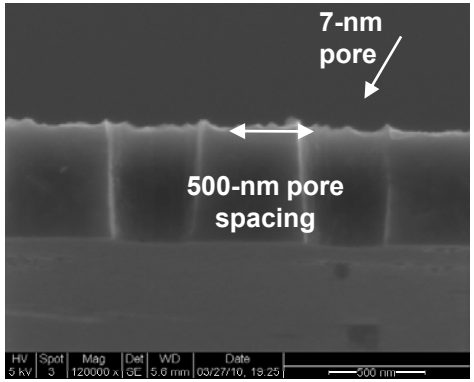
(a) Illustration of the cross-section of the thermally compensated Lamb wave resonator using IDT electrodes with a metalized (short-circuited) surface at the AlN/SiO_2 interface of the composite stack. (b) The scanning electron microscope (SEM) of the fabricated resonator using edge-type reflectors. (c) Measured fractional frequency variation versus temperature of the thermally compensated AlN/SiO_2 Lamb wave resonator at room temperature. A turnover temperature (T_O) was found at 18.05°C for a composite stack with 1 μm AlN and 0.83 μm SiO_2.

C.-M. Lin, T.-T. Yen, Y.-J. Lai, V. V. Felmetsger, M. A. Hopcroft, J. H. Kuypers, and A. P. Pisano, "Temperature-compensated aluminum nitride Lamb wave resonators", IEEE Trans. Ultrason. Ferroelectr. Freq. Control, 57, 524-532 (2010).

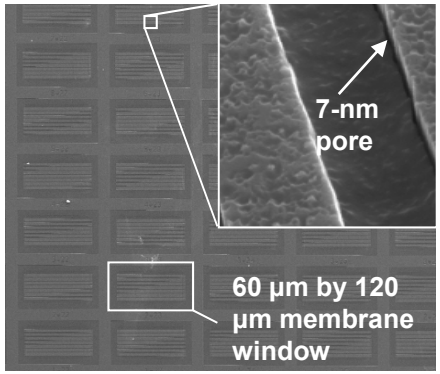
Silicon Nanoporous Membranes for Hemofiltration

A renal replacement device to selectively filter blood toxins based on molecular size we has been developed a silicon nanoporous membrane using a microfabrication process that enables high nanopore performance, density, yield, and manufacturing throughput. Nominally, nanopores are 7 nm in size but can be tuned to any size if needed, and spaced at intervals of 500 nm. Work performed at SNF has enabled a 17x increase in pore density (porosity) from first generation membranes, enabling device miniaturization necessary for human implementation. Further process enhancements have increased membrane permeability through thickness reduction and improved membrane packing efficiencies. The work performed at SNF has enabled fabrication of dense nanopore arrangements that reduce testing times from several weeks to several hours.

S. Roy, University of California, San Francisco
K. Goldman, H-Cubed, Inc.
A.J. Fleischman, Cleveland Clinic
Project Funding: *NIH/NIBIB Grant R01EB008049*
Work performed at Stanford Nanofabrication Facility



SEM micrograph of a silicon nanoporous membrane showing a 7-nm pore size and pores spaced at 500 nm.

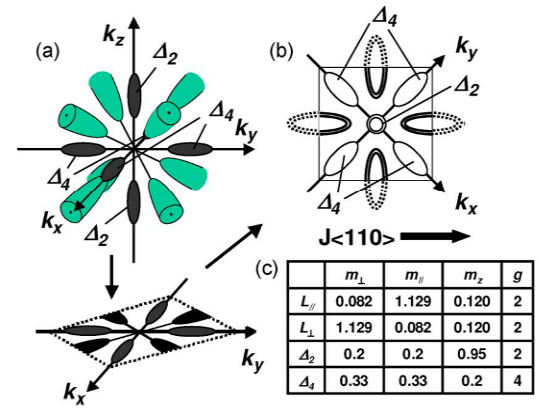


SEM micrograph showing a global view of an array of densely packed silicon nanoporous membranes. Membranes are spaced at 30 micron intervals.

Uniaxial Stress Engineering for High-Performance Ge NMOSFETs

Replacing silicon with germanium in the channels of complementary metal-oxide-semiconductor technology promises to boost device performance. Uniaxial stress technology can further enhance the performance of Ge MOSFETs. The effect of uniaxial stress was experimentally and theoretically investigated. The gate dielectric for the Ge NMOSFETs was fabricated using a novel radical oxidation technique resulting in high vertical field mobility values. The mobility enhancement was experimentally measured by applying mechanical uniaxial stress to the Ge NMOSFETs and the mobility enhancement under such strain indicates that the device performance in the ballistic transport regime can achieve as much as 48% drive current gain for the 15 nm technology node.

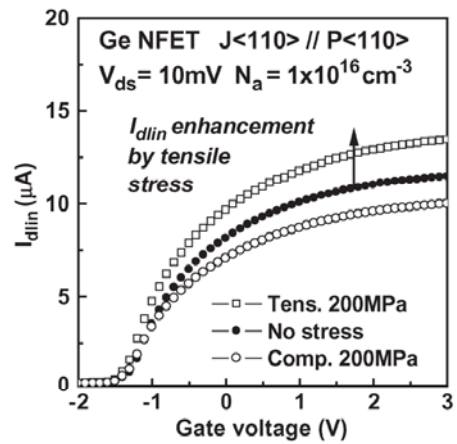
Masaharu Kobayashi, Dr. Toshifumi Irisawa*, Dr. Blanka Magyar-Kope and Professors Krishna Saraswat, Philip Wong and Yoshio Nishi
Department of Electrical Engineering
Stanford University
*Toshiba Corporation
Work performed at Stanford Nanofabrication Facility



(c)

	$m_\perp$	$m_{//}$	m_z	g
$L_{//}$	0.082	1.129	0.120	2
$L_\perp$	1.129	0.082	0.120	2
Δ_2	0.2	0.2	0.95	2
Δ_4	0.33	0.33	0.2	4

(a) Schematic of the equivalent Ge L and Δ valleys. (b) Projection of the equivalent Ge valleys on the k_x-k_y plane in the first Brilliouin zone. (c) Summary of the effective mass and number of degenerated valleys in the channel direction, channel width direction and out-of-plane direction.

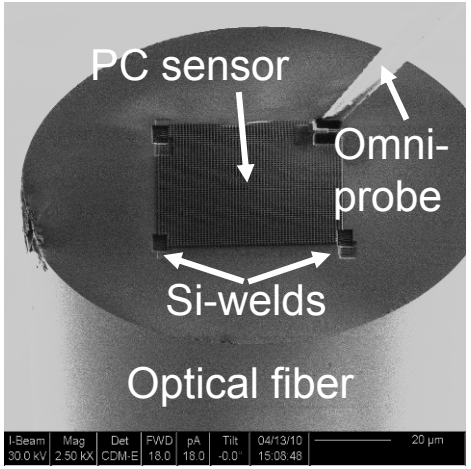


Measured Idlin-Vg characteristics for the fabricated Ge NMOSFETs under a fixed amount of longitudinal stress.

Fiber Sensors for Challenging Environments

A family of fiber sensors that use photonic-crystal interferometers to read the measurement data remotely over optical fibers has been developed. The optical interface, small size, and robust packaging of these PC sensors allow them to operate reliably in high temperature, corrosive environments, under large vibrations, and in the presence of high electromagnetic interference. The upper figure depicts a high-temperature sensor consisting of a 2-dimensional, silicon, photonic crystal attached to the facet of a standard single-mode optical fiber. The lower figure shows a miniature fiber microphone with high sensitivity and stability. It consists of a high-finesse Fabry-Perot made of a photonic-crystal mirror fabricated on a deflectable Si membrane and placed against the reflective, metalized end of a fiber. The first prototype achieved a sensitivity of ~1 μPa/Hz$^{0.5}$.

Professor Olav Solgaard
Departments of Electrical Engineering
Stanford University
Work performed at Stanford Nanofabrication Facility



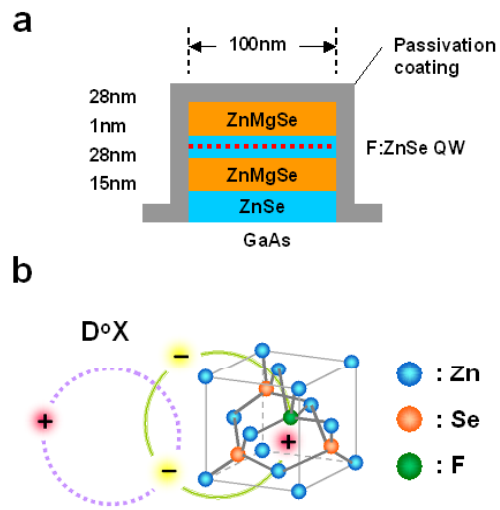
SEM of a high-temperature, Si Photonic-Crystal fiber sensor that operates reliably to 700 degrees C.

Photograph of thermally-robust acoustic fiber sensor. The dark square is a Si chip with a pressure-sensing photonic crystal diaphragm bonded to the single-mode fiber through a, all-silica structure.

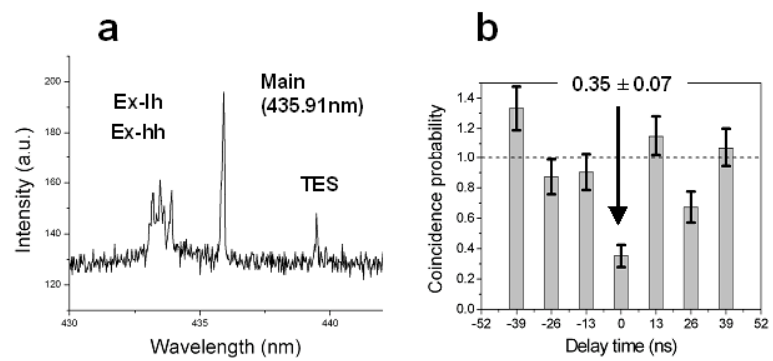
Single-Photon Sources using ZnSe:F

Many schemes for quantum computation and quantum communication depend on the quantum interference effects between indistinguishable single photons generated by large numbers of remote sources. Solid-state systems like semiconductors allow the integration of such sources on a small chip scale. Radiative decay processes of excitons bound to isolated fluorine donor impurities in ZnSe/ZnMgSe quantum well performs such indistinguishability and small inhomogeneous broadening simultaneously. An issue about these sources is the tunability of wavelengths of emitted single photons. More than 200GHz tunability by varying the input power of local-heating laser has been observed. Such tunability of single-photon sources gives more flexibility to achieve quantum interference between multiple, remote, independent emitters.

Kaoru Sanaka, Alexander Pawlis, Yoshihisa Yamamoto
Departments of Applied Physics and Electrical Engineering
Stanford University
Work performed at Stanford Ginzton laboratory



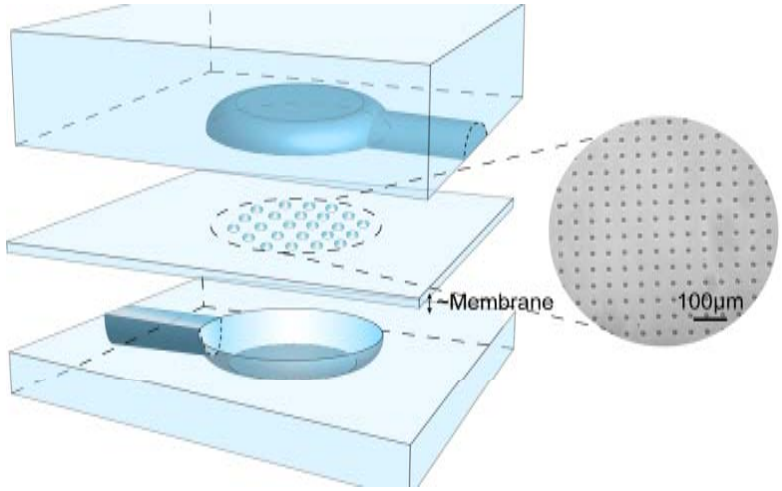
(a) Device structure of single-photon source with ZnSe:F and (b) atomic structure of ZnSe:F.



(a) Spectrum from single ZnSe:F and (b) photon correlation measurements from the main line that is tunable about 200GHz.

Cell Sorter Based on Integration of Porous Membranes into Microfluidic Devices

PDMS has been used as a porous membrane itself to fabricate monolithic microfluidic devices. In this case, the integration of a porous PDMS membrane can be completed without clogging microchannels by plasma oxidation. To prepare porous PDMS membranes, SU-8 posts with different sizes are created on a silicon wafer. A thin film of PDMS is prepared by spin coating the wafer. The resulting thin PDMS with holes is lifted cleanly off the wafer using a specially designed cured PDMS frame. This method allows varying sizes of pores on a single membrane, compared to commercially available porous membranes with a fixed pore size. This concept was successfully used to separate platelets and white and red blood cells from each other. A microfluidic chip for sorting full blood samples was generated achieving separation efficiencies of 99.7%. Even better separation was observed with polystyrene particles. Since leukaemia cells differ from other bone marrow cells in size a possible application is to sort, count and further analyze leukaemia stem cells.



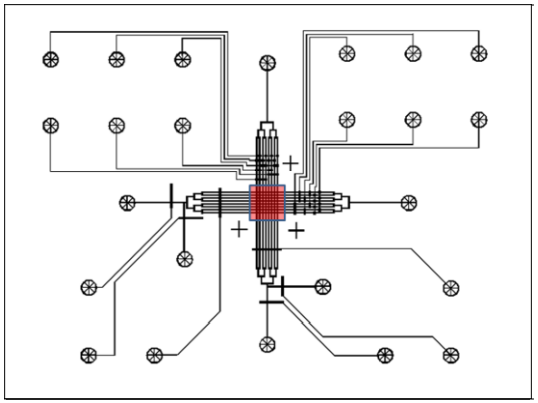
Schematic of a microfluidic device for blood cell sorting with an integrated porous membrane

Dr. Romana Schirhagl, Prof. Richard Zare
Departments of Chemistry
Stanford University
Work performed at Stanford Nanofabrication Facility

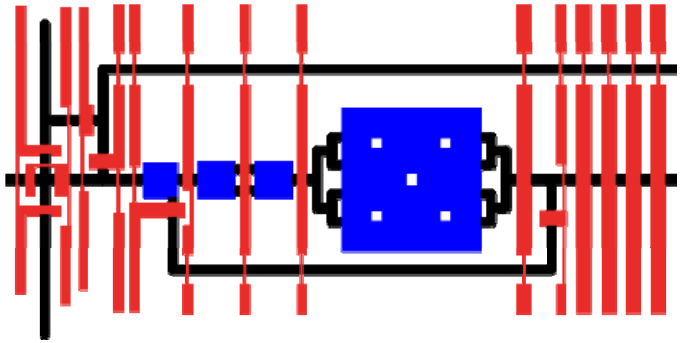
Single-Cell Analysis on a Microfluidic Platform

Recent advances in microfluidics have opened up new possibilities in single-cell biology by providing the necessary toolkits for handling and analyzing individual cells. The investigation of the individuality of cells is challenging because important information relevant to the most pressing biological questions is likely obfuscated by ensemble averaging techniques. A device capable of capturing a single cell and delivering precise amounts of reagents, and an on-chip chemical cytometer integrated with a picoliter micropipette for cell lysis and derivatization has been developed. Recently, this technology has been extended to the study of the phycobilisome degradation process in individual cyanobacteria cells.

Eric Hall, Romana Schirhagl and Prof. Richard Zare
Department of Chemistry
Stanford University
Work performed at Stanford Nanofabrication Facility



Microfluidic channels and control valves (black) facilitate the capture of single cells on a nanoporous membrane (red).

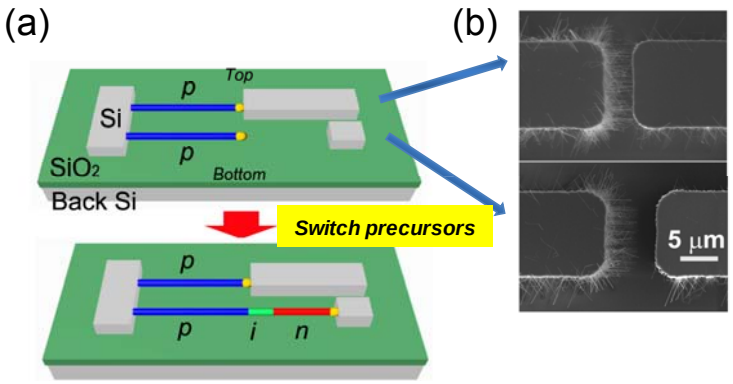


Cells are manipulated with microfluidic channels (black) and control valves (red) into chambers (blue) designed to deliver specific nanoliter volumes of reagents.

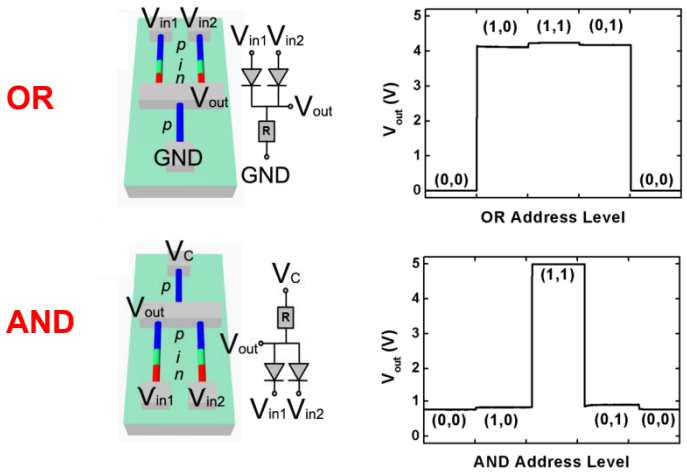
Direct Growth of Nanowire Devices

Bottom-up nanowires have the potential to control their physical and chemical properties at the nanoscale. However, assembling nanowires into large-scale integrated systems remains as a critical challenge that becomes even more daunting when different nanowires need to be simultaneously assembled in close proximity to one another. A new method to directly grow nanowire devices consisting of different nanowires has been achieved. The method is based on the epitaxial growth of nanowires from the sidewalls of electrodes and on the matching of electrode design with synthesis conditions to electrically connect different nanowires during growth. Specifically, the method was used to grow silicon nanowire-based AND and OR diode logic gates with excellent rectifying behaviors, and silicon nanowire-based photovoltaic elements in parallel and in series, with tunable power output.

Dong Rip Kim, Chihwan Lee, Professor Xiaolin Zheng
Department of Mechanical Engineering
Stanford University
Work performed at Stanford Nanofabrication Facility



(a) Schematics illustrating the direct growth of (Top) a p-type NW resistor and (Bottom) a p-i-n NW diode. (b) SEM images of SiNWs bridging two electrodes of different gaps. The bottom SiNWs can continue to grow with axial modulation.

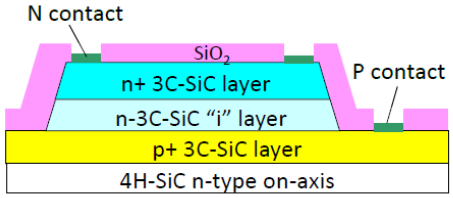


Direct growth of NW OR and AND logic gates.

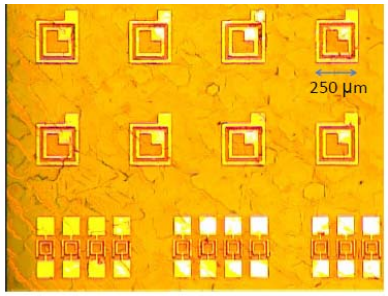
University of Colorado

Cubic Silicon Carbide Avalanche Photodiodes

- 3C-SiC avalanche photodiodes for near-ultraviolet detection (300-450 nm)
- Application:
  - Scintillation detection (gamma detection, e.g.) replacing photomultiplier tubes for medical imaging, homeland security, and oil well drilling.
- Advantages:
  - Low dark current
  - Broad UV response (indirect gap)
  - Very low noise
  - Operation at high temperatures
- Result:
  - Demonstration of the first 3C-SiC APD with good quality diodes, repeatable breakdown at 1.1MV/cm, quantum efficiency of 10% and gain >10. The devices were fabricated at the Colorado Nanofabrication Laboratory.

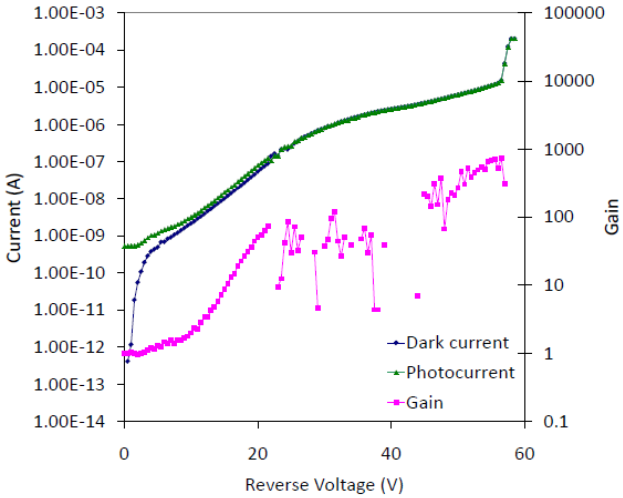


Device cross-section of 3C-SiC pin APDs:



Examples of finished devices showing rough domain structure

Dark current/photocurrent/gain



L. B. Rowland, J. L. Wyatt, and S. Bishop,
Aymont Technology, Inc
Work performed at the Colorado Nanofabrication Laboratory

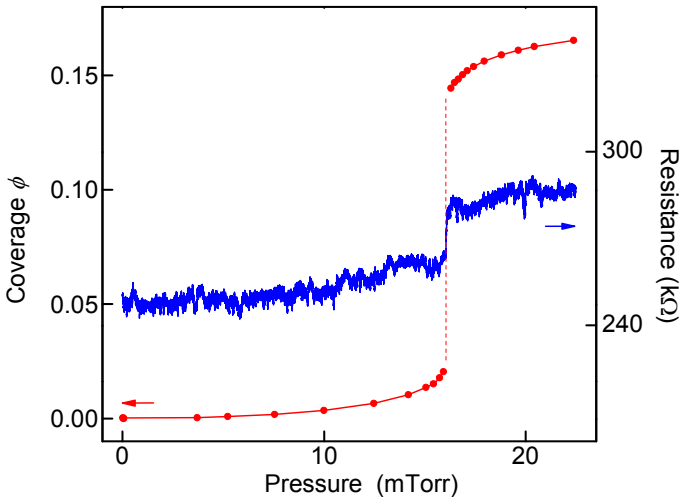
University of California at Santa Barbara

Detecting Phase Transitions on the Surface of an Individual Nanotube

Phase transitions of adsorbed atoms and molecules on two-dimensional substrates are well explored, but similar transitions in the one-dimensional limit have been more difficult to study experimentally. Suspended carbon nanotubes can act as nanoscale resonators with remarkable electromechanical properties and the ability to detect adsorption at the level of single atoms. We used single-walled carbon nanotube resonators to study the phase behavior of adsorbed argon and krypton atoms as well as their coupling to the substrate electrons. By monitoring the resonance frequency in the presence of gases, we observed the formation of monolayers on the cylindrical surface, phase transitions within them, and simultaneous modification of the electrical conductance.

Zenghui Wang, Oscar Vilches and David Cobden, University of Washington, Seattle
Work performed in part at UCSB.

Z. Wang, J. Wei, P. Morse, J.G. Dash, O.E. Vilches and D.H. Cobden, *Phase transitions on the surface of a carbon nanotube*, Science **327**, 552 (2010)



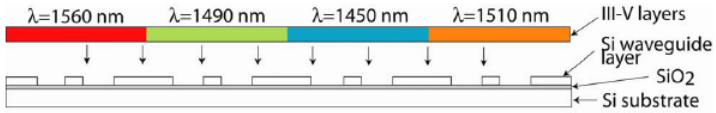
A sharp phase transition observed in both coverage (red curve) and nanotube resistance (blue curve) for Kr at 77K

Resonator consisting of a single-walled nanotube suspended across a 1 μm trench

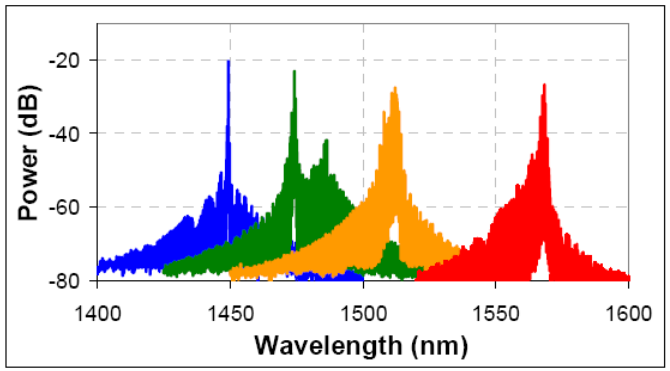
Supported by NSF DMR 0606078 and 0907690

Gain Measurements of Quantum Well Intermixed Hybrid Silicon Evanescent Lasers

We have demonstrated a four channel array of hybrid silicon Fabry-Perot lasers with an optical bandwidth >100 nm using quantum well intermixing. Fabrication of the laser requires only a single bonding step along with coarse alignment between pre-patterned III-V and SOI wafers. Device performance is similar for the four different bandgaps as determined by laser measurements and net gain measurements. In future structures, silicon based gratings can be used to fine tune the lasing wavelength within a given intermixed bandgap. This would allow for dense wavelength division multiplexing over a >100 nm range, generating hundreds of channels from a single bond. Alternatively, this could allow for tens of coarsely spaced wavelengths with more relaxed wavelength spacing for uncooled applications.

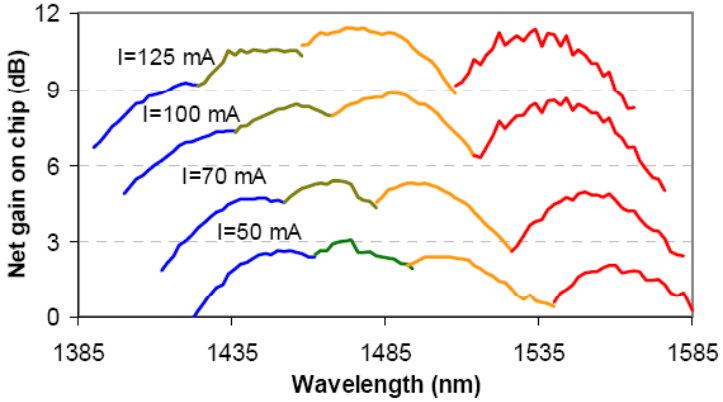


a.



b.

a. Schematic showing an alignment cross-section of the intermixed III-V active material and silicon waveguides material prior to bonding. b. Continuous wave lasing spe



Aggregate net gain of the four different bandgaps versus wavelength

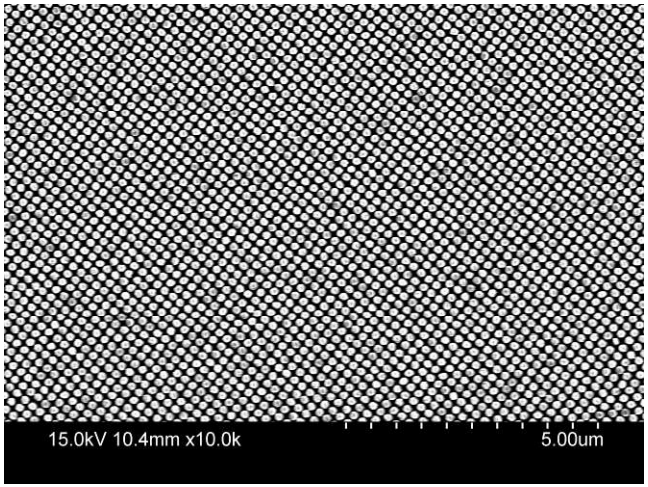
Koch, Sysak, Jones, Intel Corp.
Work performed in part at UCSB.

Proceedings of the 2009 6th IEEE International Conference on Group IV Photonics. GFP 2009

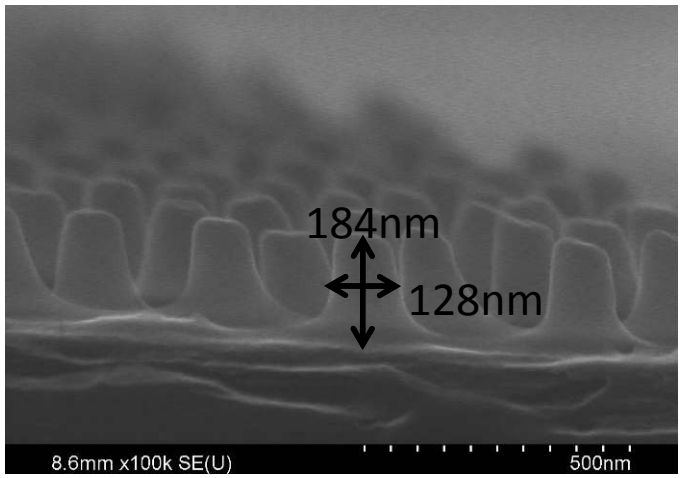
Nanoimprinted Carbon Electrodes For Li-ion Batteries

The goal of this research is to develop nano-architectured carbon electrodes. These carbon electrode structures can provide the benefit of increasing charge-discharge rates for Li-ion batteries, can be used as high capacity "supercapacitor" electrodes, and can be beneficial for high efficiency fuel cells. Nanoimprinting is being used to develop the structures from molds fabricated at the UCSB Nanofabrication Facility. Large area carbon electrode nano-architectured arrays have been fabricated with billions of pillars per square centimeter. The nanoimprinting technique is easily scalable to very large areas needed for production environments. SEM images show the density and sizes of the carbon electrode structures.

Nanostructured C-electrodes



Top View SEM



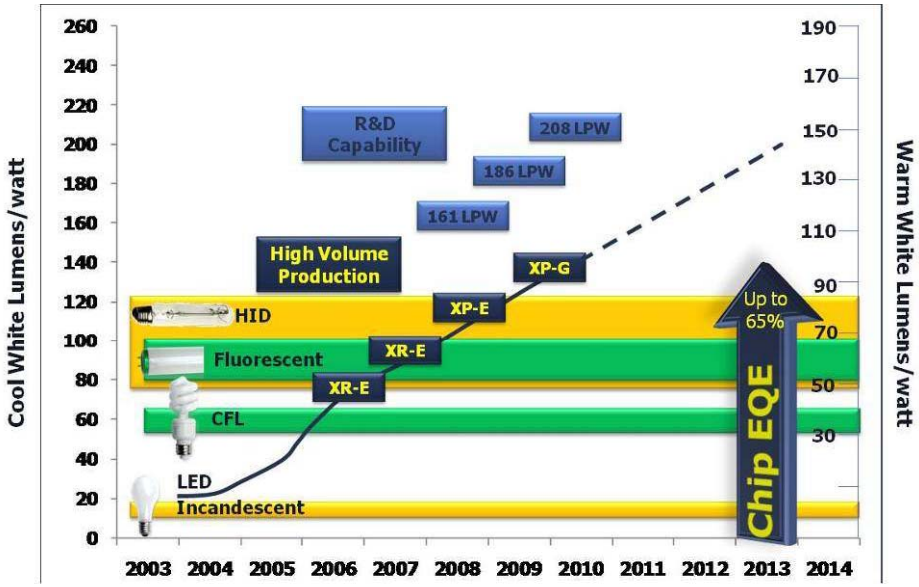
Cross-Sectional View SEM

Jayan Thomas and Palash Gangopadhyay
University of Arizona
Work partially performed at UCSB

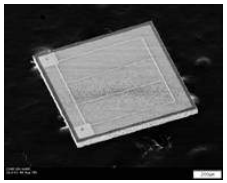
Funding source: DesTech Investment Group

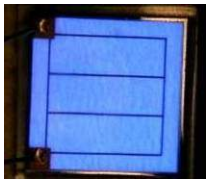
High Power LEDs for Solid State Lighting

Solid-State white lighting is poised to displace both incandescent and fluorescent lamp technology in the coming years. Cree EZBright™ surface emitter chip technology was first developed at NNIN. Continuous improvements over years of research and development have resulted in white LED efficacy >200 lumens per watt in R&D. Commercial components with efficacies up to 140 lm/W are now in volume production. This surface emitter chip technology serves as the "Filament" for high performance solid state lighting systems. The graph shows the progress in both R&D and production over the years of development.

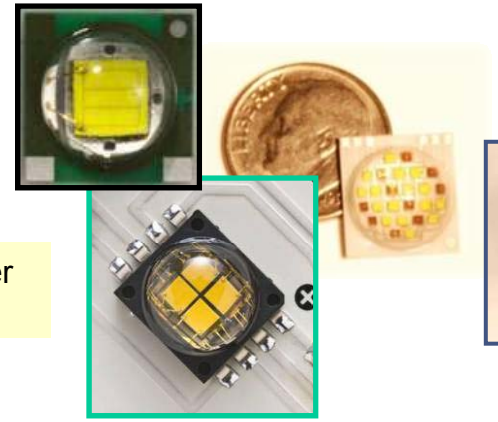


Chips





XLamp® Components



Lamps

Cree, Santa Barbara Technology Center
R&D work partially performed at UCSB

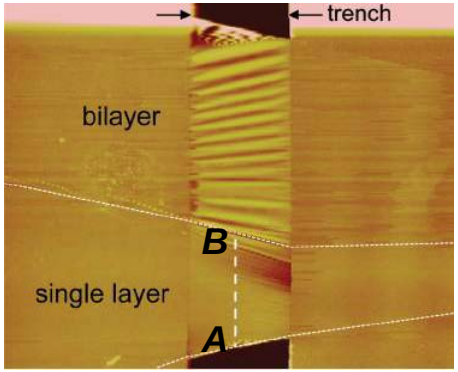
Raman Spectroscopy of Ripple Formation in Suspended Graphene

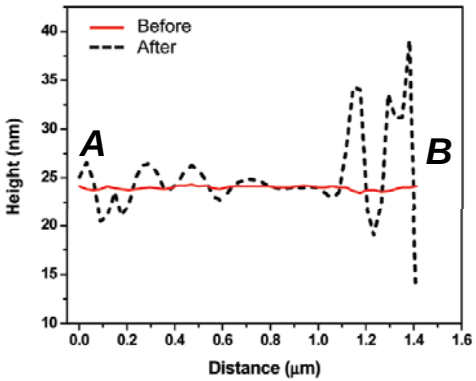
Using Raman spectroscopy, we measure the optical phonon energies of suspended graphene before, during, and after thermal cycling between 300 and 700 K. After cycling, we observe large upshifts (~25 cm-1) of the G band frequency in the graphene on the substrate region due to compression induced by the thermal contraction of the underlying substrate, while the G band in the suspended region remains unchanged. From these large upshifts, we estimate the compression in the substrate region to be ~0.4%. The large mismatch in compression between the substrate and suspended regions causes a rippling of the suspended graphene, which compensates for the change in lattice constant due to the compression. The amplitude (A) and wavelength (λ) of the ripples, as measured by atomic force microscopy, correspond to an effective change in length $\Delta l/l$ that is consistent with the compression values determined from the Raman data.

Nanoletters **9** (12), 4172 (2009)

Lau Group, UC Riverside
Cronin Group, University of Southern California
Work partially performed at UCSB

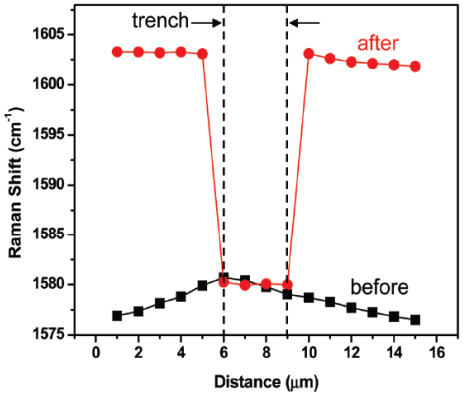
AFM Image of single and bilayer graphene across a trench after thermal cycling to 700K and back





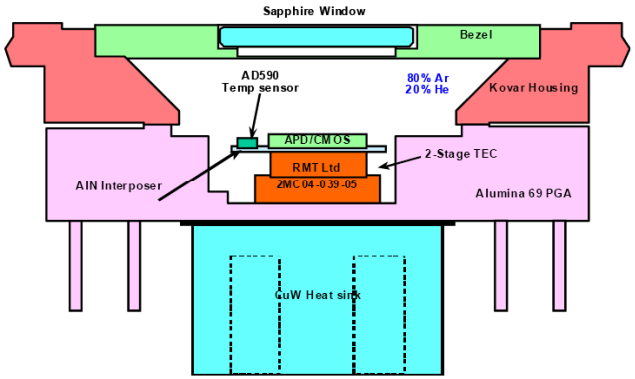
Cross section of graphene across a trench before and after thermal cycling to 700K and back

Raman Shift of graphene layer before and after thermal cycling

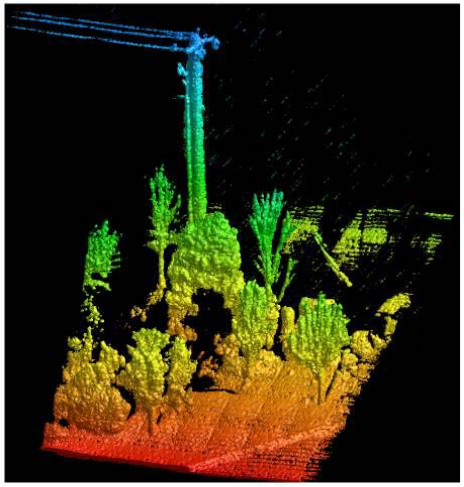


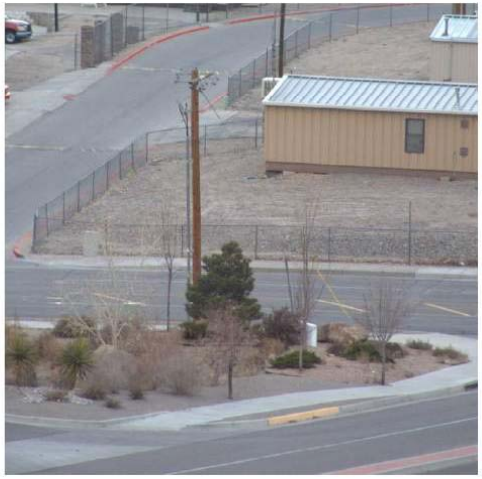
32 x 32 Geiger-mode LADAR Cameras

We have integrated our 100-µm pitch 32x32 GM-APD arrays with CMOS 2002 ROICs designed by MITLL, and assembled them into SCAs for SWIR single-photon-level imaging applications. By integrating with readout and supporting circuits, we developed Spectrolab Gen-I LADAR camera. With 12-bit temporal resolution provided by CMOS 2002 ROIC, the operation gate can cover 2 µsec, with a resolution of 0.5 ns and a frame rate up to 20 kHz. The data download and command control are realized by a CameraLink connection in the base configuration. With a signal 28-V power supply, the power consumption is less than 20 W. Without the front lens, the camera weighs less than 5 lbs, and the volume is about 4.5”x4.5”x4.5



The crosssectional view of a sensor chip assembly for Spectrolab Gen-I LADAR camera.



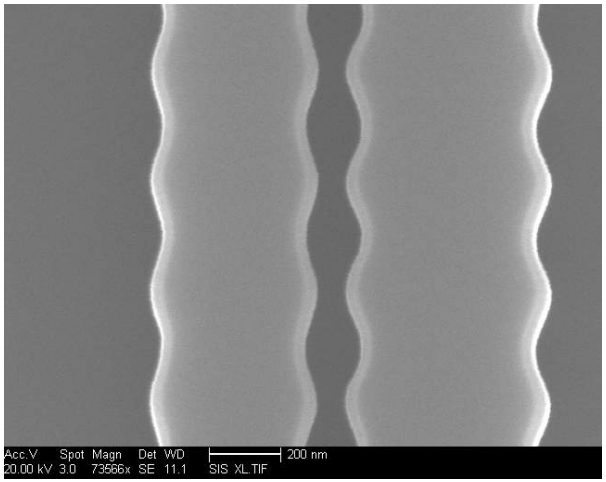


The 3D image taken with Spectrolab Gen-I LADAR camera. The picture is color coded with ranging information. The right panel shows the 2D image taken from the same angle.

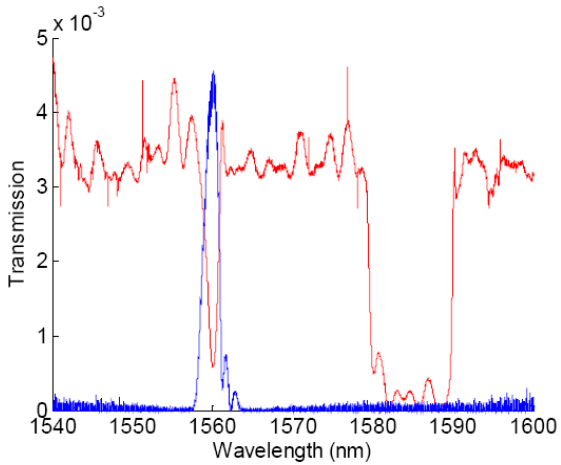
Sudharsanan et. al., Spectrolab Corp.
Hybridization performed in part at UCSB.

Coupled Vertical Gratings on Silicon for Applications in WDM

Much of today's WDM technology is fiber based. However, extensive research in recent years has gone into exploring silicon on insulator as a viable platform for realizing integrated devices and subsystems. The ability to take advantage of the mature complementary metal oxide semiconductor fabrication infrastructure ensures the cost effectiveness of fabricating on SOI. To realize sophisticated silicon integrated systems for potential applications in data networks, it is necessary to study a major building block of these systems, the wavelength division multiplexer. The add/drop filter forms the basis of a more complex multi-channel WDM system realizable on the silicon on insulator platform. Such a system is implemented by cascading several devices, each with a slightly different value of *W*2. The large free spectral range of >70nm enables a large number of WDM channels to be implemented using this technique. The measured transmission spectra of the add and drop ports of several devices with different gap widths have been presented, confirming the inverse trend between gap width between the coupled gratings and channel bandwidth. Tailoring of the channel bandwidth by adjusting the gap width has been experimentally demonstrated. A reduction of channel bandwidth from 3nm to 1.2nm is achieved by increasing the gap width from 60nm to 300nm.



Scanning electron micrograph of a fabricated coupled vertical grating add/drop filter. The gap width in this case is 60nm



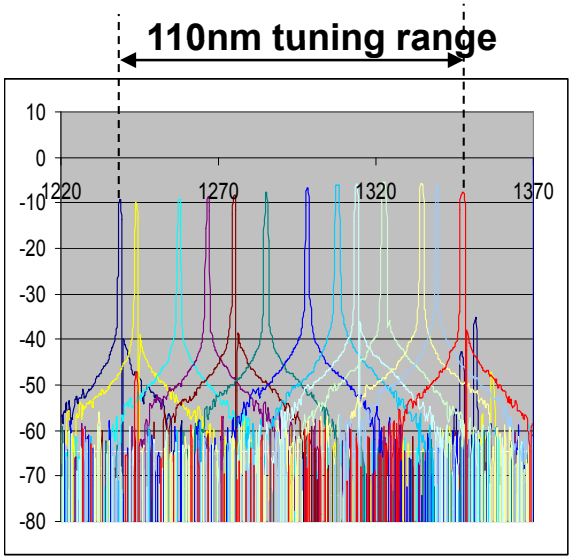
$G = 104$nm, $L = 400\mu$m, Measured $\Delta\lambda = 1.9$nm.

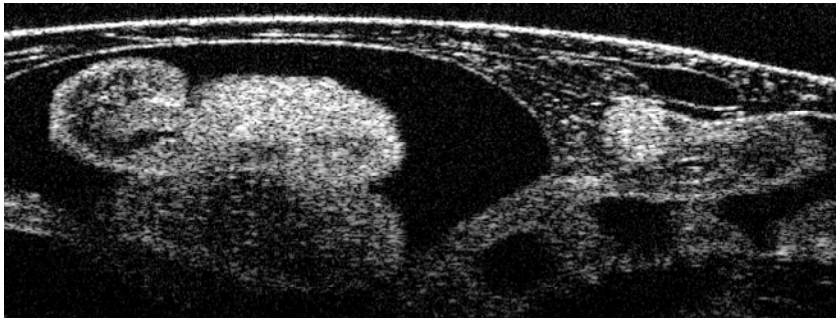
Measured transmission spectra for add (red) and drop (blue) ports

Fainman Group, ECE Dept. UC San Diego
Work partially performed at UCSB Nanofabrication Facility

Broadband Sources for Optical Coherence Tomography

Optical Coherence Tomography (OCT) constructs subsurface images of biological samples by measuring echo time-delay of backscattered and back-reflected light. OCT can be configured as spectral domain (SDOCT) or swept source (SSOCT) systems employing either broadband superluminescent diodes (SLDs) or widely tunable lasers, respectively. Praevium, under funding from the National Cancer Institute and commercial partner Thorlabs, has developed both record bandwidth SLDs and record tuning range vertical cavity surface-emitting lasers (VCSELs) which enhance imaging resolution of emerging OCT systems.





Tadpole heart: High Res Praevium 170nm SLED

Tadpole heart: Lower Res 90nm SLED

V. Jayaraman, Praevium
Work partially performed at UCSB

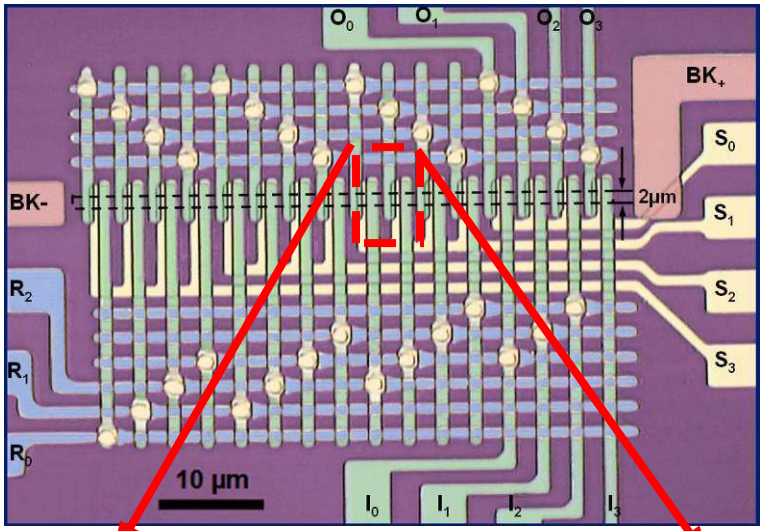
Ultra-Broadband Tunable 1310 nm VCSELs for Cancer Imaging

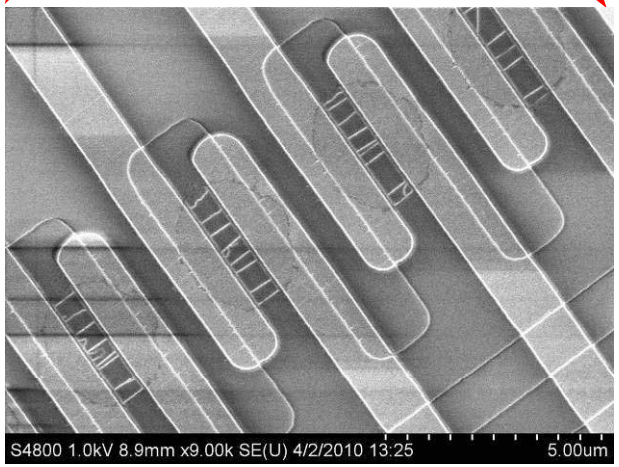
Support from NCI Grant R44CA101067and Thor Labs

Shifter Circuit Using Parallel Aligned Carbon Nanotubes

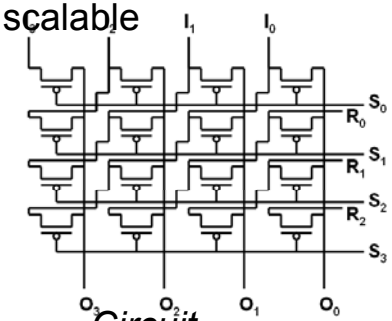
Aligned carbon naotubes are very desirable for carbon based electronic devices and integrated circuits owing to their advantages of registration-free fabrication, high device yield, and small device-to-device variation. For the aligned nanotubes, the most important technology components include increasing the nanotube density and removal of metallic nanotubes. We have achieved low-pressure chemical vapor deposition (LPCVD) ethanol synthesis of high density aligned nanotubes with density as high as 30 tubes/µm, and have addreassed the issure of co-existence of metallic and semiconducting nanotubes using an innovative scalable electrical breakdown approach. Combining these technology components, we are currently working on the demonstration of more sophisticated nanotube integrated circuits as shown in this slide. The top image is an optical microscope image showing a nanotube shifter register circuit. The circuit include 16 transistors and a pair of electrodes (BK-, BK+) that are used to remove the metallic nanotubes in all the transistors in a scalable manner.

Optical microscope image of CNT shifter circuit





SEM image of Aligned Carbon Nanotubes

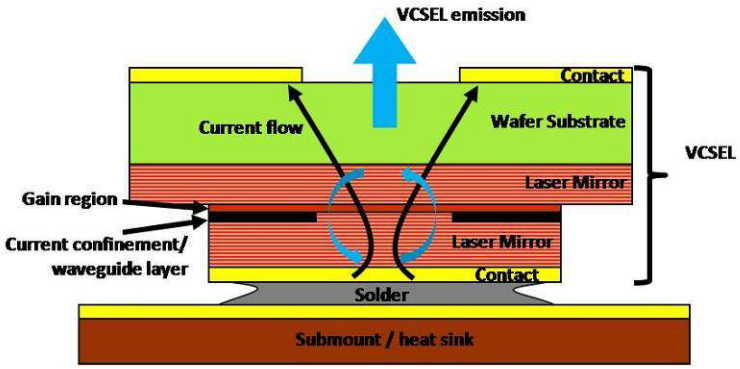


Circuit Diagram

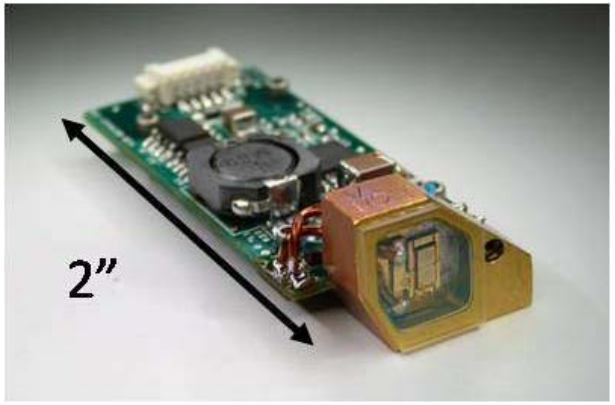
Chongwu Zhou group, University of Southern California ECE Department
Work partially performed at UCSB

High Power VCSELs for Miniature Optical Sensors

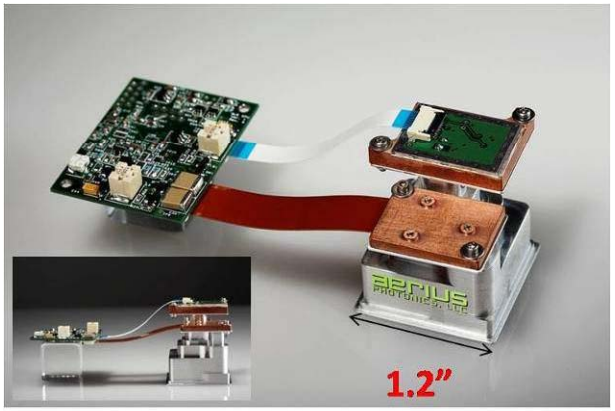
Recent advances in Vertical-cavity Surface-emitting Laser (VCSEL) efficiency and packaging have opened up alternative applications for VCSELs that leverage their inherent advantages over light emitting diodes and edge-emitting lasers (EELs), such as low-divergence symmetric emission, wavelength stability, and inherent 2-D array fabrication. Improvements in reproducible highly efficient VCSELs have allowed VCSELs to be considered for high power and high brightness applications, such as SWIR illumination and rangefinding



Packaged high power VCSEL chip used as the core building block optical sensors



SWIR Illuminator capable of producing 2-4 W of optical power from a VCSEL array.



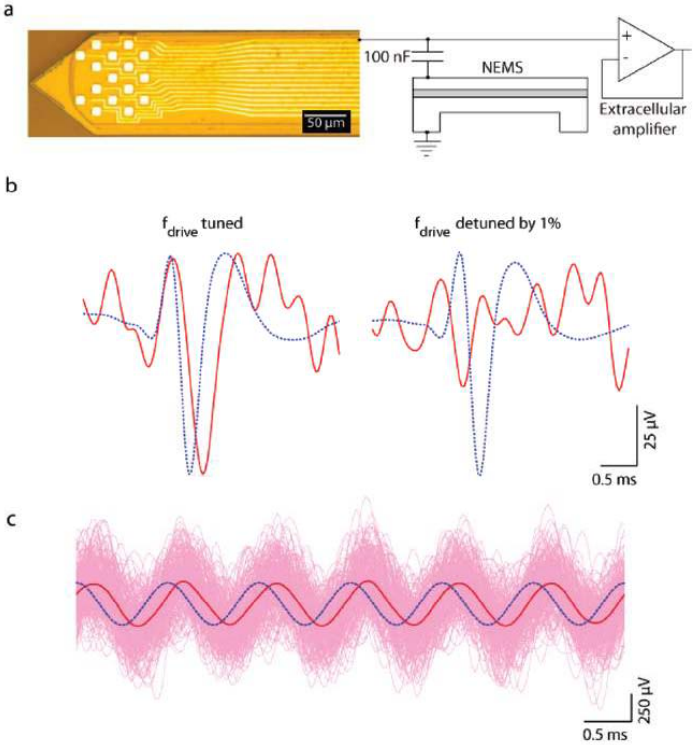
Miniature laser rangefinder using a high power VCSEL emitter capable of producing 60 W optical power

Geske, Wang, MacDougal, et. al., Aerius Photonics, LLC
Work partially performed at UCSB Nanofabrication Facility

Work supported by the Air Force Research Labs, AFRL/RWGG and AFRL/RWAV, under USAF contract number FA8651-05-C-0098

Wiring Nanoscale Biosensors with Piezoelectric Nanomechanical Resonators

Nanoscale integrated circuits and sensors will require methods for unobtrusive interconnection with the macroscopic world to fully realize their potential. We report on a nanoelectromechanical system that may present a solution to the wiring problem by enabling information from multisite sensors to be multiplexed onto a single output line. The basis for this method is a mechanical Fourier transform mediated by piezoelectrically coupled nanoscale resonators. Our technique allows sensitive, linear, and real-time measurement of electrical potentials from conceivably any voltage-sensitive device. With this method, we demonstrate the direct transduction of neuronal action potentials from an extracellular microelectrode. This approach to wiring nanoscale devices could lead to minimally invasive implantable sensors with thousands of channels for in vivo neuronal recording, medical diagnostics, and electrochemical sensing.



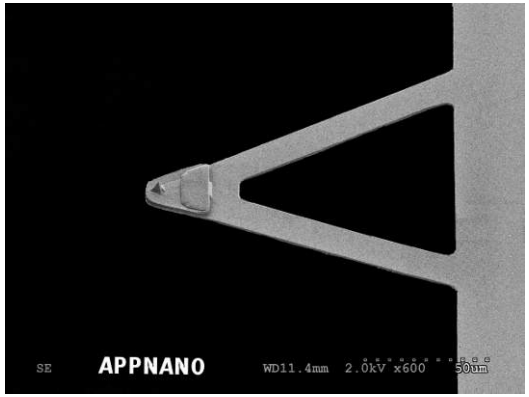
Nanomechanical transduction of extracellular action potentials. (a) Neural probe and setup (b) Detection of extracellular action potentials in a locust ganglion preparation. Demodulated signals from the NEMS device are shown in red, and the corresponding signal recorded by the amplifier is indicated by dashed blue lines. (c) The neural probe coupled to the NEMS device was used to detect an artificially generated signal in saline solution. Nanomechanical signal appears in red (250 averages). Individual, unaveraged NEMS traces are indicated in magenta. The averaged trace from the extracellular amplifier is in dashed blue. The SNR of the transduced signal is ~1:1.

Masmanidis, et. al., California Institute of Technology
Work partially performed at UCSB Nanofabrication Facility

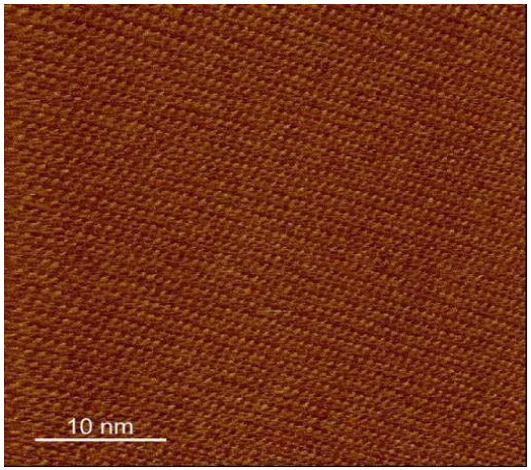
Nano Lett. **2010,** *10*, 1769-–1773

High Resolution AFM Probes for Reduced Thermal Drift

High resolution AFM imaging of samples in fluid is often required for many applications such as (i) studying proteins, lipids, sugar etc. (ii) imaging of living cells such as virus, yeast, bacteria, neurons, etc, (iii) monitoring the action of drugs on cells and tissues etc. The thermal drift caused by the mismatch of thermal expansion coefficients of metal and silicon nitride material of the AFM probe cantilever limits achieving high resolution imaging of these samples in the fluid. HYDRA Probe series from APPNANO has been designed to minimize these effects to achieve imaging resolution in sub-nanometer range. The unique design of HYDRA probe consists of a super sharp silicon tip integrated on a silicon pad attached at the free end of a soft silicon nitride cantilever. The silicon pad is used for optical detection without reflex coating to minimize the thermal drift .



Hydra probe has Silicon nitride arms and sharp silicon tip. Arms are 20um wide and the tip length is 200um



Ami Chand, Applied Nanostructures
R&D Work partially performed at UCSB Nanofabrication Facility

Image Courtesy : R. W. Friddle, M. L. Weaver, S. R. Qiu, A. Wierzbicki, W. H. Casey, and J. J. De Yoreo, PNAS published online before print December 14, 2009 , doi:10.1073/pnas.0908205107

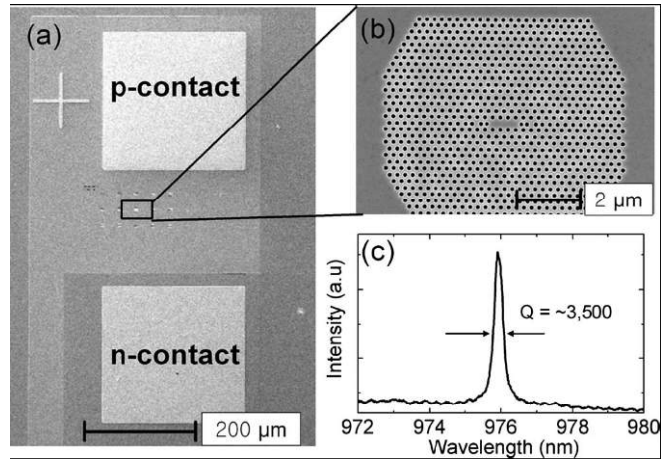
*Other Reference : APPLIED PHYSICS LETTERS **95, 233114 2009***
Gajendra S. Shekhawat, Ami Chand, Saurabh Sharma, Verawati, and Vinayak P. Dravid.

Independent Tuning of Quantum Dots in a Photonic Crystal Cavity

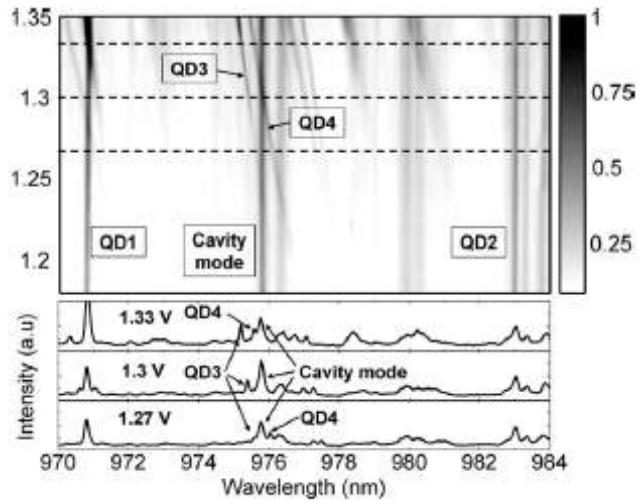
One of the main obstacles to coupling two quantum dots (QDs) to a single nanocavity mode is the ability to independently tune the QD frequencies. We developed a p-i-n diode structure with two embedded QD layers that can be integrated into a GaAs photonic crystal membrane. The frequencies of one QD layer can be tuned independently of the other by applying a voltage across only one of the layers.

Making good electric contacts to the doped layers is a challenge because of the small layer thicknesses and doping concentrations. The contact fabrication procedure involves metallization, selective etching, and annealing steps. The photonic crystal process involves the use of the JEOL JBX-6300FS Electron Beam Lithography System, as well as anisotropic and selective etching.

We demonstrated that we could independently tune QD frequencies in a high-Q photonic crystal structure. By applying deterministic QD positioning methods, this structure should allow us to strongly couple two QDs to a single cavity mode.



SEM images of (a) an isolated p-i-n diode device, and (b) a fabricated photonic crystal cavity. (c) Measured cavity mode with Q of 3500.



Stark shift tuning in a L3 cavity. QDs in the bottom layer (QD1 and QD2) show no voltage dependence. QDs in the top layer (QD3 and QD4) show Stark shift tuning with an applied voltage.

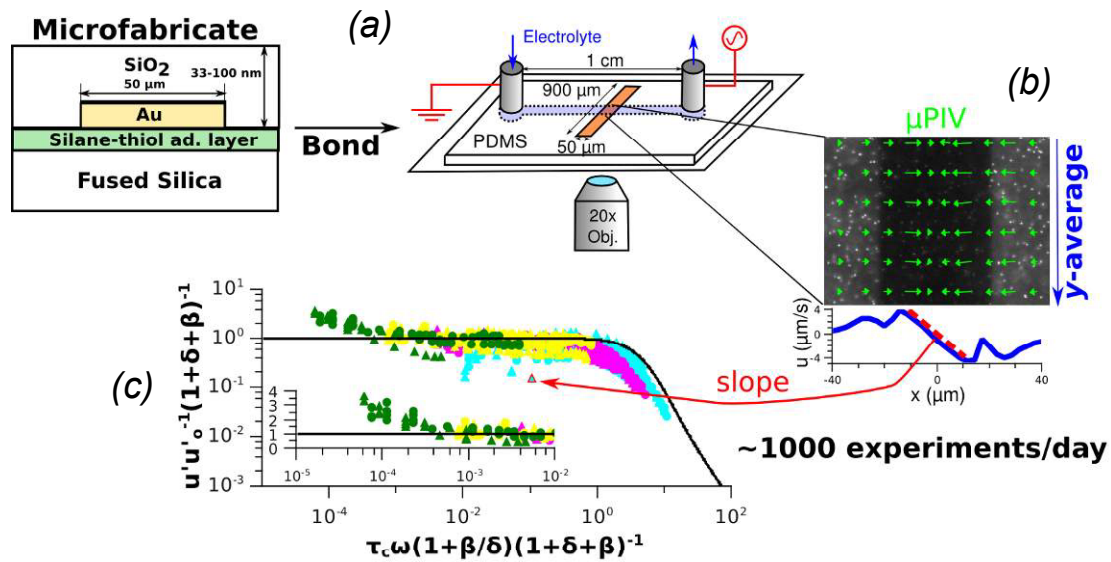
Bouwmeester Group, UCSB Physics Department
Work performed at UCSB

H. Kim, S. M. Thon, P. Petroff, and D. Bouwmeester, Appl. Phys. Lett. **95**, 243107 (2009).

NSF Grant No. 0901886 and Marie Curie Grant No. EXT-CT-2006-042580.

Induced Charge Electro-osmosis over Controllably Contaminated Electrodes

Recent studies in nonlinear electrokinetics reveal the standard theory to generally overpredict measured velocities, sometimes dramatically. Contamination of the driving surface provides a natural mechanism for electrokinetic suppression. We measure induced charge electro-osmosis over gold electrodes "contaminated" with silica layers of controlled thickness for nearly a thousand distinct conditions, in a system that enables direct comparisons between theoretical predictions and experimental measurements. Both the magnitude and frequency dependence of the measured slip velocity are captured quantitatively over the entire range of experiments by accounting for the physical capacitance and surface chemistry of the dielectric layer. More generally, the quantitative characterization enabled by our apparatus will prove invaluable for the rational design and prediction of electrokinetic systems.



(a) A micropatterned gold electrode of sits at the center of a PDMS microchannel (b) A PIV velocity field overlaid on an experimental image showing the flow-tracing microspheres along with the mean velocity profile from which the slope u0 of the red dashed line is obtained. (c) Normalized slip velocity vs dimensionless frequency confirming theory based on controlled contamination layer

Pascall and Squires, UCSB Chemical Engineering Department
Work performed at UCSB

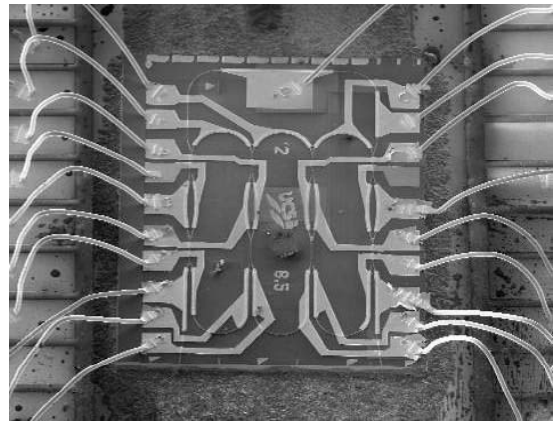
Pascall and Squires. *Phys. Rev. Lett.* **104** 088301.
Featured as an "Editors' Suggestion" and in a Viewpoint in *Physics.*

Research funded by NSF CAREER grant CBET-0645097

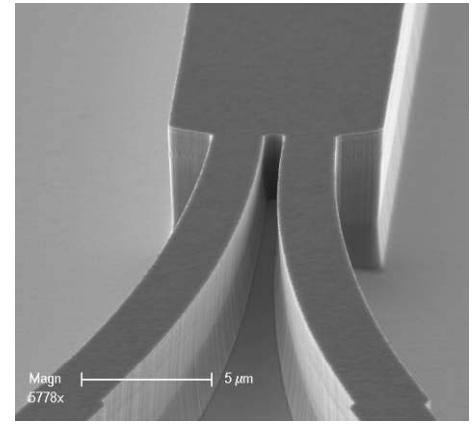
Programmable Optical Filters Integrated in InP/InGaAsP

The purpose of this research is to develop programmable optical filter photonic integrated circuits (PICs) for use in the microwave regime, integrated in the InP/InGaAsP material system. Various monolithic optical couplers are utilized in the circuits : Multi-mode interference (MMI) couplers, tunable Mach-Zehnder interference (MZI) couplers and Etched Beam Splitter (EBS) couplers. The filters are tuned in bandwidth and center frequency by current-injection phase modulators and semiconductor optical amplifiers (SOAs)

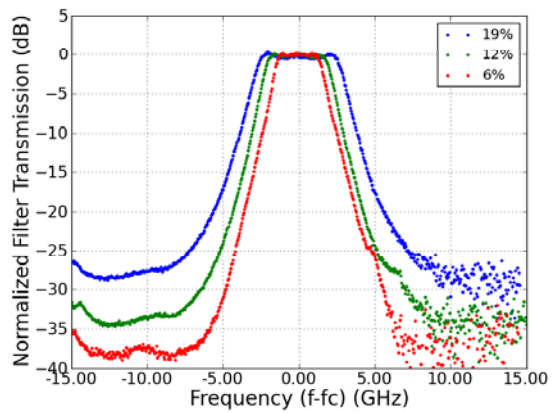
Norberg, Guzzon, and Coldren, UCSB Electrical Engineering Department
Work performed at UCSB



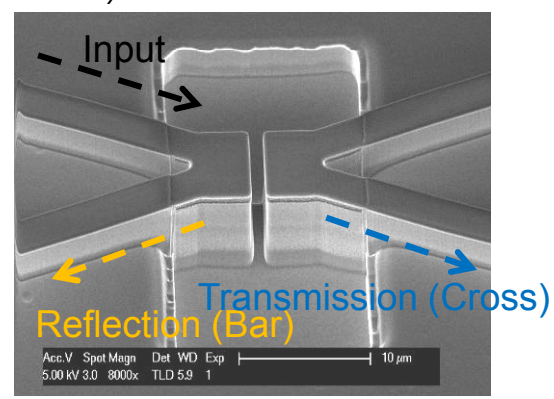
SEM of wirebonded photonic integrated circuit.



Multi-mode interference (MMI) coupler, etched 5µm deep using a Cl2:H2:Ar chemistry in the Unaxis ICP tool.



3rd order coupled-pole filter results displaying tunable bandwidth



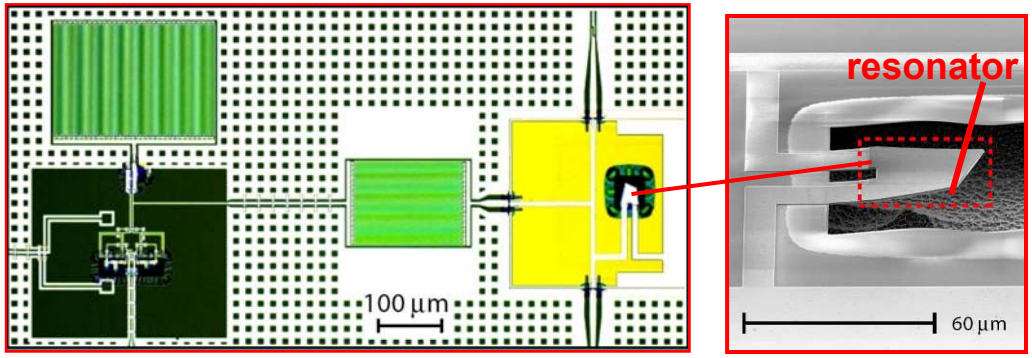
Etched beam splitter (EBS) coupler in InGaAsP/InP.

E.J. Norberg, J.S. Parker, U. Krishnamachari, R.S. Guzzon, and L.A. Coldren, IPNRA, IWA1, Honolulu, HI, July 12-17 2009.
Norberg, E. J., Guzzon, R. S., Nicholes, S. C., Parker, J. S., Coldren, L. A., Photonics Technology Letters 22, 109-111 (2010).

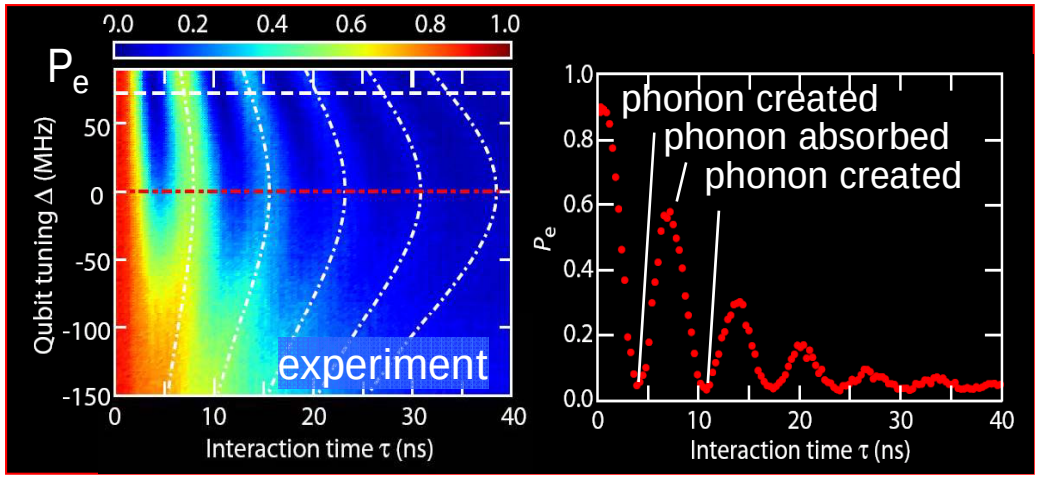
supported by DARPA through the PhASER project

Quantum Ground State and Single-phonon Control of a Mechanical Resonator

Quantum mechanics provides a highly accurate description of a wide variety of physical systems. However, a demonstration that quantum mechanics applies equally to macroscopic mechanical systems has been a long-standing challenge, hindered by the difficulty of cooling a mechanical mode to its quantum ground state. The temperatures required are typically far below those attainable with standard cryogenic methods, so significant effort has been devoted to developing alternative cooling techniques. Once in the ground state, quantum-limited measurements must then be demonstrated. Here, using conventional cryogenic refrigeration, we show that we can cool a mechanical mode to its quantum ground state by using a microwave-frequency mechanical oscillator—a 'quantum drum'—coupled to a quantum bit, which is used to measure the quantum state of the resonator. We further show that we can controllably create single quantum excitations (phonons) in the resonator, thus taking the first steps to complete quantum control of a mechanical system.



Optical micrograph of the mechanical resonator coupled to the qubit and SEM of the mechanical resonator



Experimental data of qubit excited state probability, Pe. The linear plot is taken along the white dashed line from the topographic data, corresponding to a fixed detuning (between qubit and resonator) of 72MHz. Maxima correspond to the qubit being in its excited state and minima correspond to state transfer to the resonator, creating a single phonon

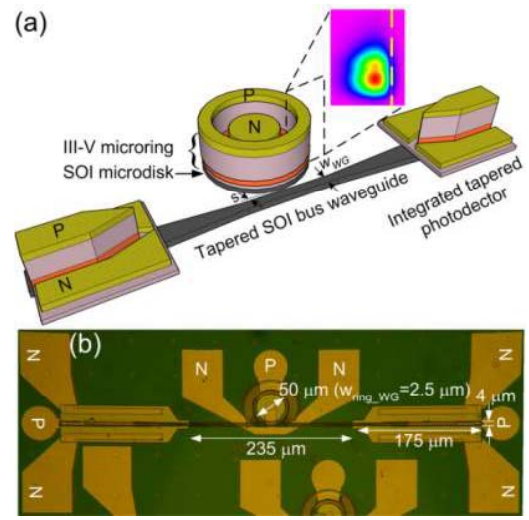
O'Connell, Cleland, Martinis, UCSB Physics
Work performed at UCSB

O'Connell, et. al., *Nature*, **464,** April 1, 2010 (08967)

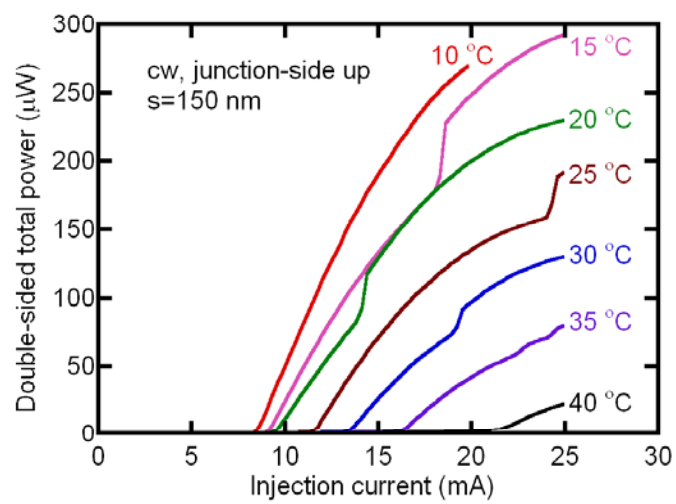
Supported by NSF, NNIN and iARPA

Electrically-pumped Compact Hybrid silicon Microring Lasers for Optical Interconnects

Diode lasers with ring or disk resonator geometries are one of the most attractive on-chip light sources for photonic integrated circuits (PICs) since their inherent traveling wave operation nature requires no gratings or Fabry-Perot (FP) facets for optical feedback. The hybrid silicon platform (HSP) [7, 8] is a promising approach to enable robust active components on a complementary metal-oxide semiconductor (CMOS)-compatible Si platform. In this research we demonstrate an electrically-pumped hybrid silicon microring laser fabricated by a self-aligned process. The compact structure (D = 50 μm) and small electrical and optical losses result in lasing threshold as low as 5.4 mA and up to 65 ° C operation temperature in continuous-wave (cw) mode. The spectrum is single mode with large extinction ratio and small linewidth observed. Application as on-chip optical interconnects is discussed from a system perspective



Schematic and optical micrograph of hybrid silicon microring laser



LI curves showing CW and elevated temperature operation

Liang, Bowers, UCSB ECE Department
Work performed at UCSB

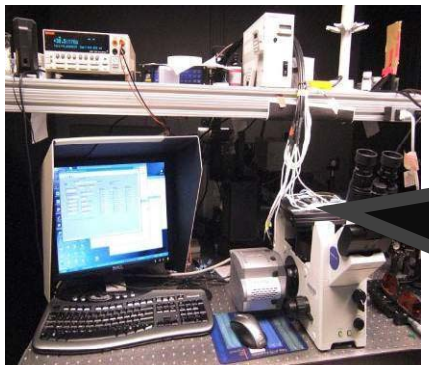
OPTICS EXPRESS, Vol. 17, No. 22, 20355

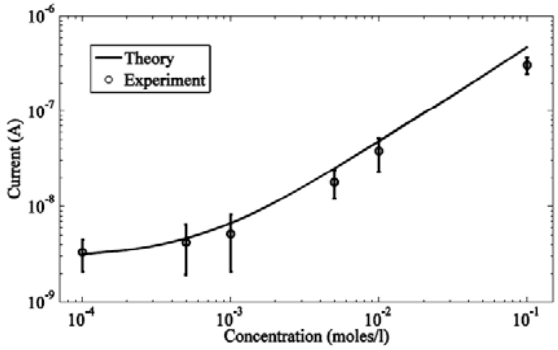
HP Labs' Innovation Research Program Award

Nanochannel Characterization and Applications Project

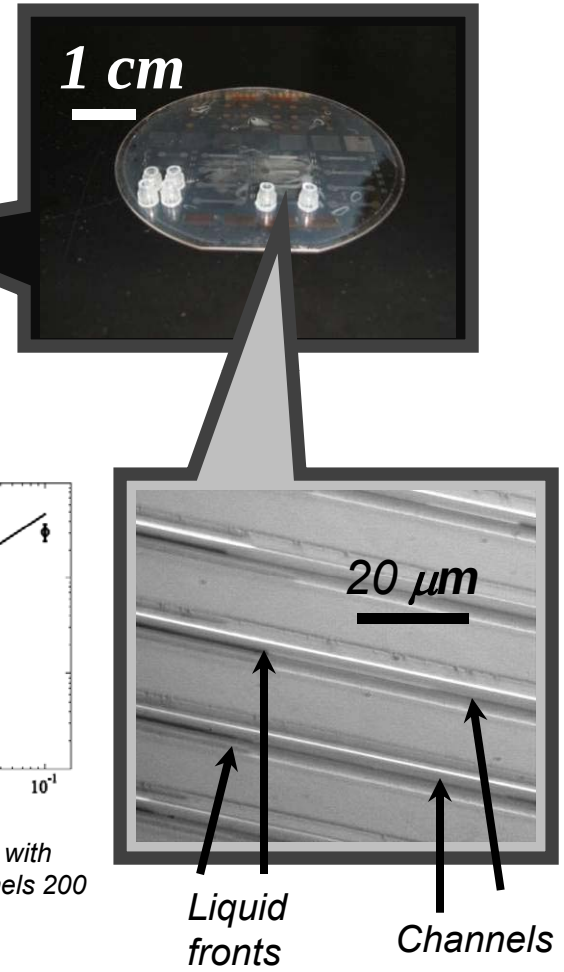
In this research we have developed a robust low temperature fabrication method for centimeter-long surface-micromachined nanofluidic channels. Unlike conventional approaches, in this method we dry etch sacrificial layers to form the cavities of the channels from the side, thereby eliminating the length restriction intrinsic to a channel etch and release process. To characterize the process, we examine the deformation of the cross section of different width nanochannels due to stress gradient of the wall material. We calculate the maximum edge deformation of a 5 μm wide channel due to stress to be ~18 nm. In addition, we modified the model describing the channel release process to account for the stress-induced deformation and compared the results with the experiment. Finally, to demonstrate the efficacy of the completed process, the nanochannels were successfully filled with ethanol and water, surface hydrophobicity was characterized by meniscus measurements of the filled fluid, and electroosmotic experiments were performed to determine the surface charge and other channel characteristics.

J. Micromech. Microeng. **20** (2010) 015040





Electroosmotic current measurement with KCl solution in 28 parallel nanochannels 200 nm high, 5 μm wide and 5 mm long



Hydrophilic nanochannels filled with KCl solutions

Pennathur group, UCSB ME Department
Work performed at UCSB

Ohmic- and Schottky Contacts to SnO_2 Thin Films

Ohmic- and Schottky contacts to semiconductors are crucial for their electrical characterization and for their application in actual devices. SnO_2 has the potential to become a new semiconductor in its own right which can improve existing applications and enables new applications as transparent electronics and optoelectronics. Using current-voltage measurements and X-ray photo electron spectroscopy we have investigated the contact properties of different metals on high-quality, semiconducting SnO_2 thin films grown in our own group:Ti and Al form good ohmic contacts (Fig. 1), in agreement with their low work function. A surface accumulation layer (Fig. 3b) was found to prevent the Schottky contact formation even when high-workfunction metals (Au, Pd, Pt) were used (see Fig. 1 and 2). An oxygen plasma treatment can remove the surface accumulation (Fig. 3c) and enable the formation of Schottky contacts (Fig. 2). The best Schottky contacts were formed by Au despite its relatively lower workfunction than Pt and Pd (Fig. 2).

Bierwagen, Nagata, Speck, UCSB
Work performed at UCSB

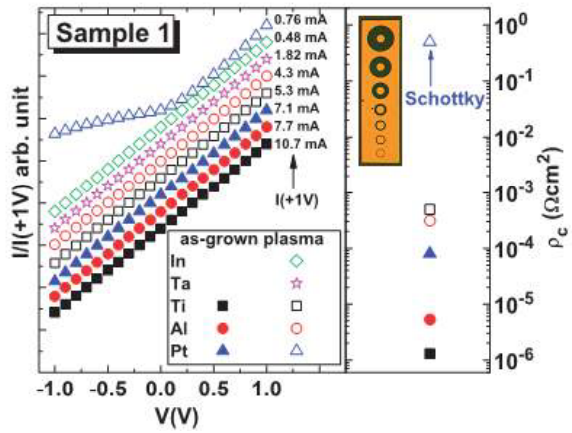


Fig.1: Measurements of the contact resistance for ohmic contacts using circular-TLM patterns (shown in the inset).

Fig.2 Measurements of the contact properties of Schottky contact metals. (Inset: planar diode structure with central square Schottky conact surrounded by ohmic contact.)

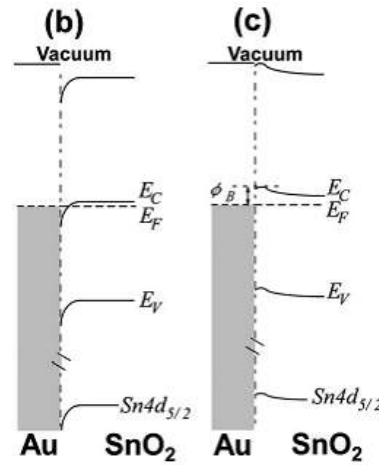
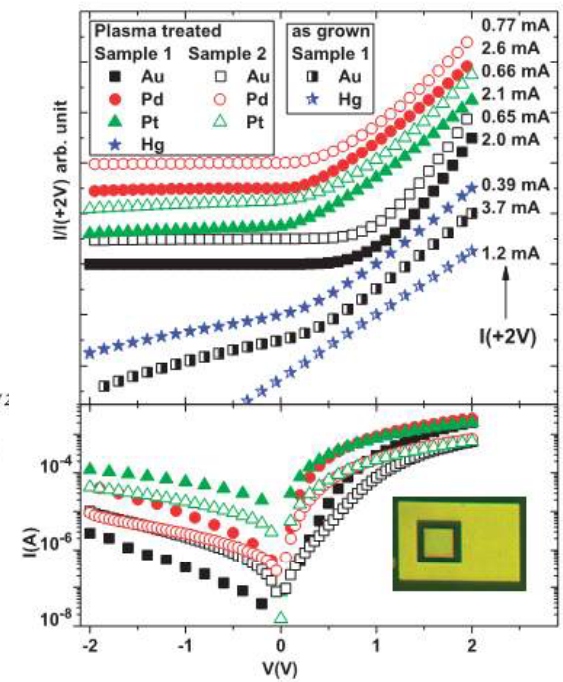


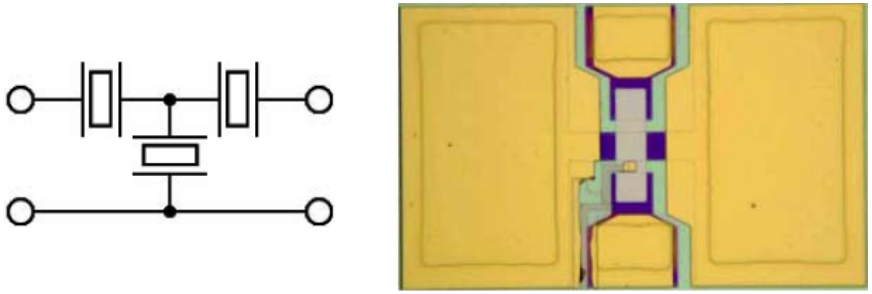
Fig.3 (b) Band bending due to surface accumulation layer preventing Schottky contact formation. (c) Oxygen-plasma treated sample without surface accumulation allows Schottky contact formation.



Appl. Phys. Express **2**, 106502 (2009)
J. Appl. Phys. **107**, 033707 (2010)

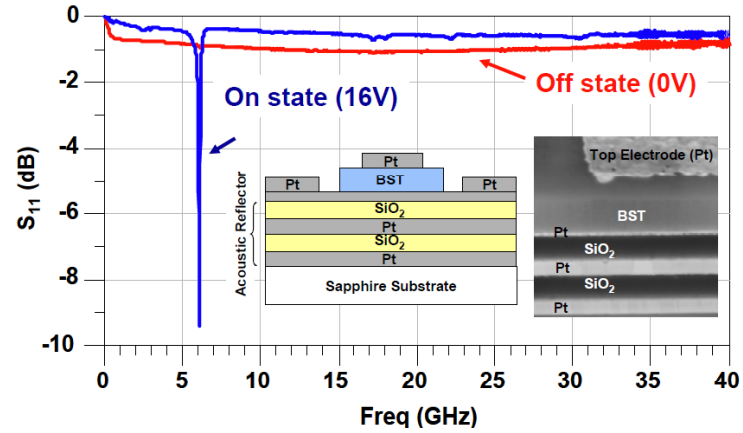
NSF MRSEC Program under award No. DMR05-20415 and by the SSLEC

Switchable and Tunable Filters for Microwave Applications

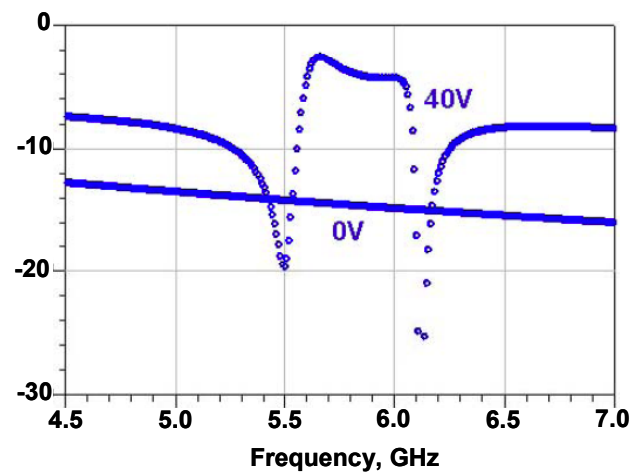


Schematic diagram and image of a simple switchable tee-filter using equal-sized series and shunt $B_{0.5}S_{0.5}TiO_3$ bulk acoustic wave solidly mounted resonators.

Bulk acoustic wave resonators are used to filter unwanted frequencies in wireless microwave applications such as cell phones. Currently used materials, such as AlN, only allow for fixed frequency and constantly on filters. At UCSB, novel thin film materials are being explored for these applications, such as $SrTiO_3$ and $(Ba,Sr)TiO_3$. These materials have the potential to allow for resonators & filters, which could be switched on/off by an applied voltage. The first ever switchable bulk acoustic wave solidly mounted filter has been demonstrated at UCSB in Prof. York's group.



BST bulk acoustic wave solidly mounted resonator fabricated at UCSB on a Pt/SiO_2 acoustic Bragg reflector, illustrating the ability to control the resonance with an applied DC bias.



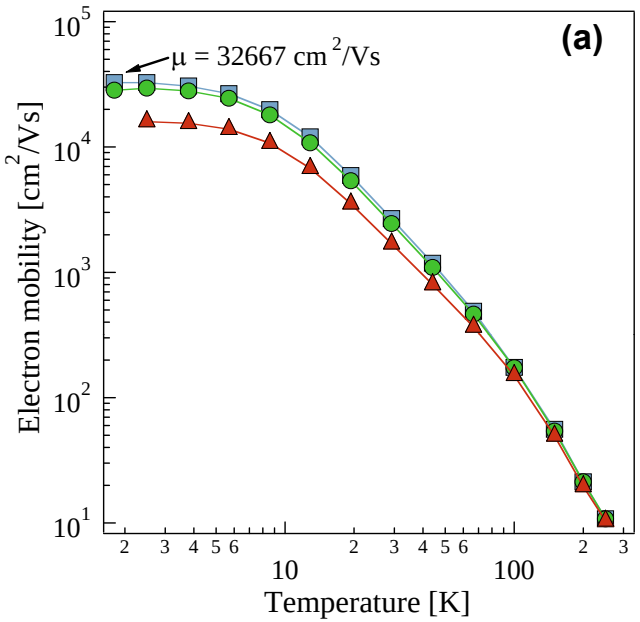
Insertion loss data at 0V and 40V of a switchable bulk acoustic wave filter (see panel B) with $Ba_{0.5}Sr_{0.5}TiO_3$ as the voltage induced piezoelectric thin film. Bandpass response is observed only with applied bias.

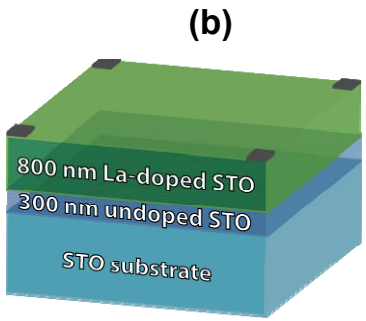
Saddik, York, UCSB ECE Department
Work performed at UCSB

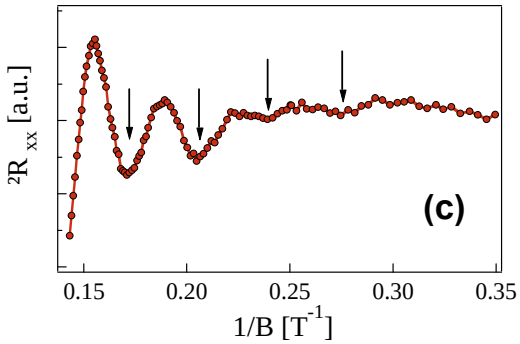
U.S. Army Research Office (Grant No. W911NF-0601-0431).

High Mobility Complex Oxide Thin Films

In this program, it was demonstrated that highly perfect $SrTiO_3$ films can be grown by a new oxide molecular beam epitaxy approach. The films show very high electron mobilities (a) and quantum phenomena, such as Shubnikov-de Haas oscillations (c). The results open the way to study novel transport phenomena in oxide heterostructures







(a) Electron mobilities as a function of temperature for 800 nm La-doped $SrTiO_3$ films grown by MBE with three different carrier concentrations, (b) device structure, and (c) Shubnikov-de Haas oscillations of the resistance in a magnetic field.

Son, Stemmer, UCSB
Materials Department
Work performed at UCSB

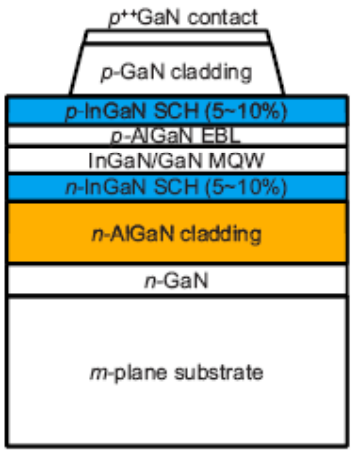
Nature Mater. (2010) doi:10.1038/nmat2750

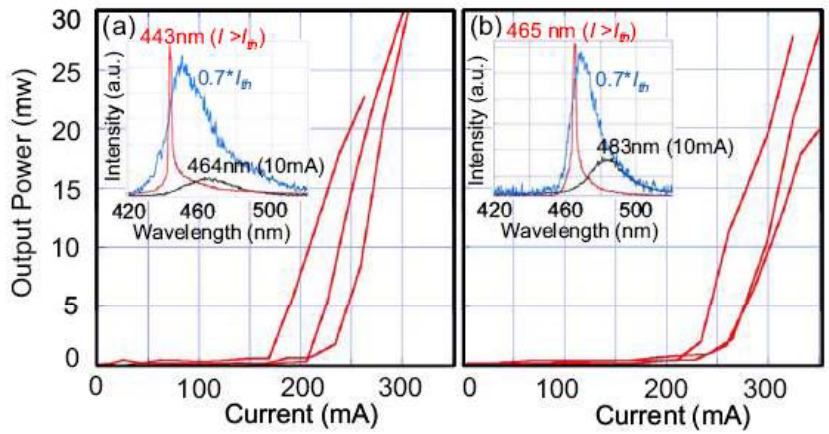
DOE-BES (grant no. DE-FG02-02ER45994) and by the UCSB MRL (National Science Foundation award No. DMR 05-20415).

M-plane Laser Diodes with p-GaN/n-AlGaN-based Asymmetric Cladding and InGaN-based Wave-guiding Layers

Asymmetric p-GaN/n-AlGaN-cladded InGaN-based pure blue 440–460 nm laser diodes were fabricated based on the nonpolar m-plane GaN technology. Simulation results showed high indium content 5%–10% InGaN wave-guiding layers mainly contributed to the optical confinement, so that n-AlGan layer can be used to control of the peak position of the optical mode to achieve high optical confinement factor and low internal loss. By using this laser structure, lasing wavelengths of 443 and 465 nm with threshold current densities 14 and 19 kA/cm2, respectively, were demonstrated without facet coating.

asymmetric *p*-GaN/*n*-AlGaN cladding laser structure





Light output power vs injected current curves of asymmetric p-GaN/n-AlGaN cladding LDs for lasing wavelength (a) 443 nm and (b) 465 nm. The insets in (a) and (b) are the lasing spectra and the spontaneous emission spectra at the current of 10 mA and 0.7I_{th}.

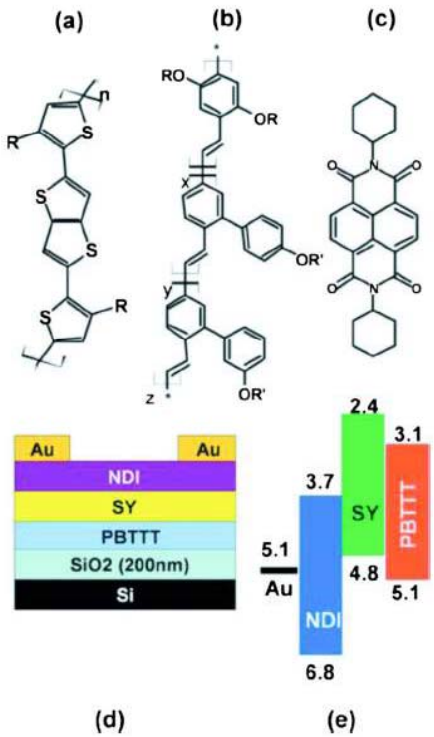
Nakamura, DenBaars, Speck groups, UCSB ECE and Materials Departments
Work performed at UCSB

APPLIED PHYSICS LETTERS 95, 081110 2009

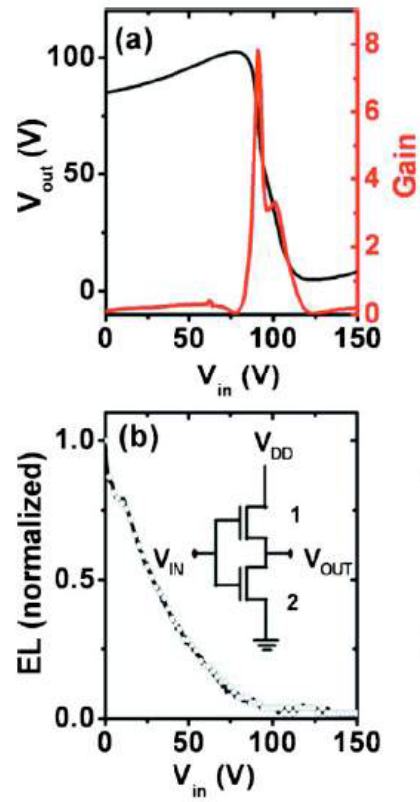
DARPA Visible InGaN Injection Lasers (VIGIL) program and UCSB's Solid State Light and Energy Center (SSLEC)

High-Efficiency Phosphorescence Organic LEFETs

In this work, we show that p- and n-type light emitting field-effect transistors LEFETs can be made using “superyellow” as a light-emitting polymer, poly2,5-bis3-tetradecylthiophen-2 -ylthieno3,2-b thiophene as a p-type material and a naphthalene di-imide as an n-type material. By connecting two of these LEFETs, we have demonstrated a light emitting complementary inverter LECI. The LECI exhibited electrical and optical characteristics in the first and third quadrant of the transfer characteristics with voltage gain of 6 and 8, respectively.



Molecular structure of (a) PBTTT; (b) SY; and (c) NDI layer; (d) Schematic diagram of the device architecture, and (e) energy level diagram showing HOMO and LUMO of NDI, SY, and PBTTT. The work function of Au is also shown



Electrical (a) and optical (b) characteristics of LECI operating in the first quadrant of transfer characteristics at VDD=+150 V. Inset show schematic representation of the LECI

Ben Hsu, Ebinazar Namdas, and Alan J. Heeger, CPOS, UCSB
Work performed at UCSB

App. Phys. Lett. 2010, 96, 043304

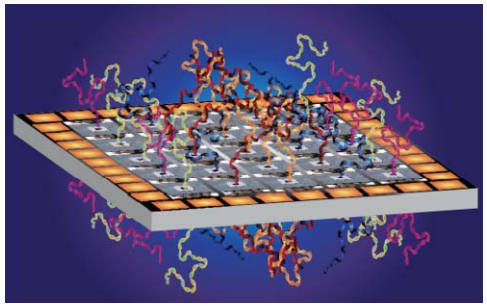
AFOSR and NSF

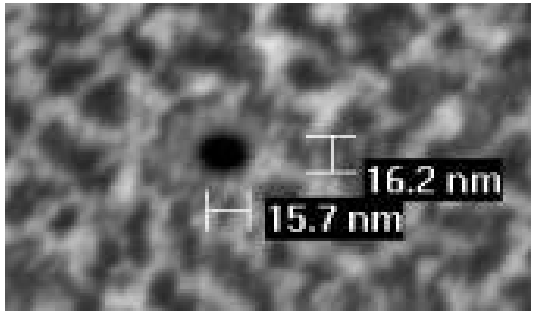
CMOS Integration of Solid State Nanopores for Sequencing DNA

Genes, proteins and other biomolecules provide a wealth of information that is essential for the diagnosis and treatment of diseases. One of the key bottlenecks to the widespread use of personalized medicine is the lack of a low-cost, high-throughput, accurate and easy-to-use biomolecule detection platform. The realization of such a detection platform will also aid in the early detection of disease, which in cases such as cancer greatly enhance the survival rate. Recently, inspired by biology, nanopores have emerged as a possible single-molecule electronic detection platform. A nanopore is an extremely tiny hole, few nanometers in diameter, in an insulating membrane that separates two ionic reservoirs. An applied voltage across the nanopore results in an ionic current that flows through the nanopore. The principle of single-molecule detection using the nanopore is based on detecting the blockage of this ionic current by the target. Nanopores show great promise of realizing fast, cheap, reliable and label-free sensors, especially for DNA sequencing. Compared to existing methods of DNA sequencing which requires several thousands of dollars and many weeks to complete a sequence, nanopores have the potential to reduce the time to a few days at a significantly lower cost. The project seeks to implement a nanopore sensor within a CMOS chip containing the necessary electronics for closed-loop control and sensing.

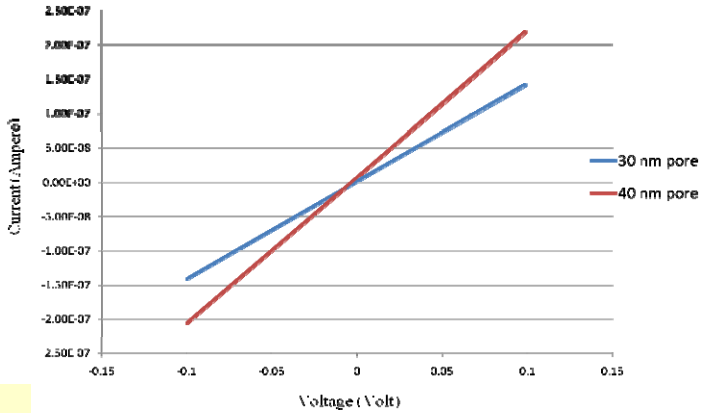
American Physical Society March Meeting, Volume 55, Number 2, Portland, Oregon, 2010

Nanopore Chip Concept





SEM image of 16 nm nanopore formed by ebeam lithography



Ionic current measured through nanopores

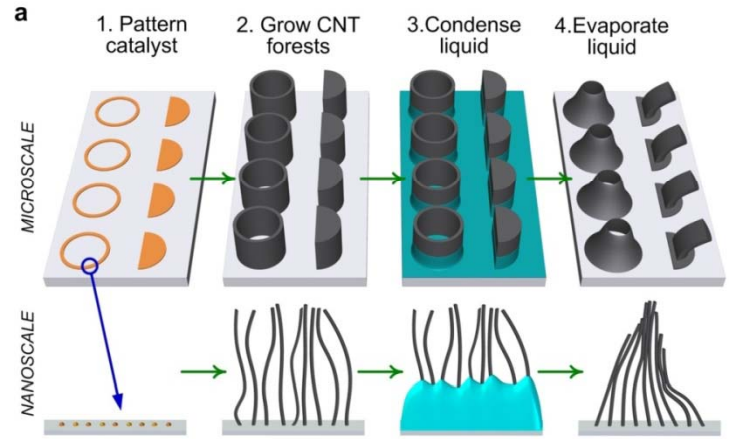
Uddin, Milaninia, and Theogarajan, ECE, UCSB
Work performed at UCSB

Sponsor: Intel Corporation

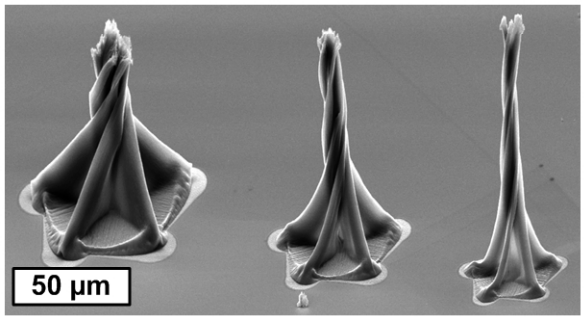
University of Michigan

3D Carbon Nanotube Microstructures

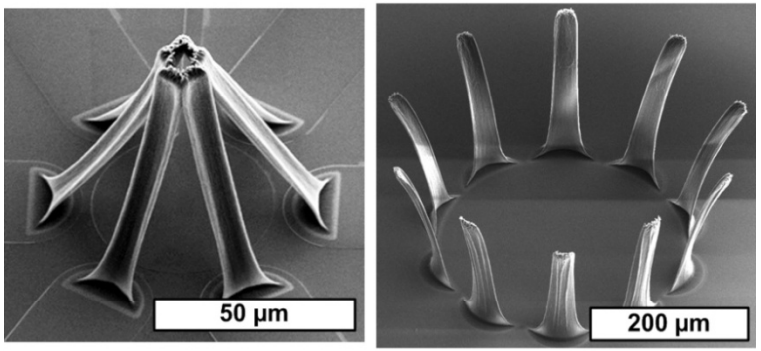
Lithographically defined patterns of vertically aligned carbon nanotubes (CNTs) are transformed into three-dimensional (3D) geometries by self-directed capillary action initiated by liquid condensation. Because this process, which we call capillary forming, is governed by the local capillary force distribution inside each assembly of CNTs, heterogeneous structures can be created simultaneously, and individual structures can be deterministically designed based on the process conditions. We demonstrate that capillary formed CNT structures are over 100 times stiffer than as-grown CNTs, and enable self-directed formation of 3D CNT/polymer nanocomposites with stiffness exceeding conventional microfabrication polymers. This work may find future applications in cost-effective fabrication of biomimetic surfaces, metamaterials, multi-scale circuits, and novel sensors and actuators.



Fabrication of 3D CNT microstructures by capillary forming



CNT micro-twists

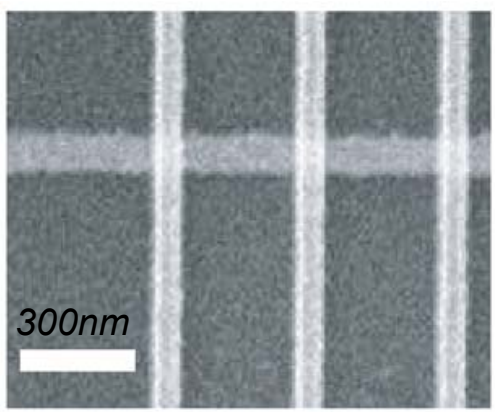


CNT micro-trusses and micro-flowers

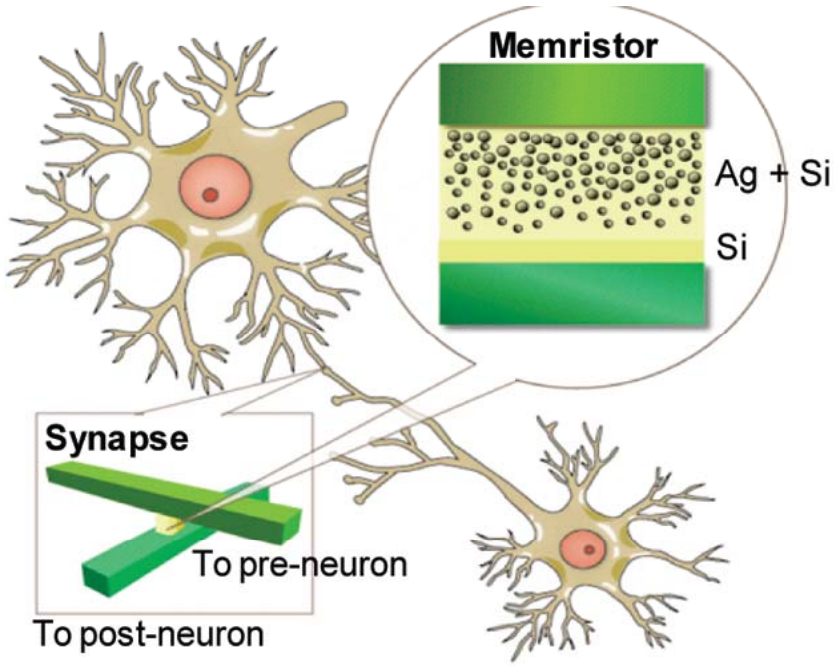
Sameh Tawfick, Michael De Volder, Sei Jin Park, Davor Copic, and A. John Hart – University of Michigan
Work performed at University of Michigan LNF

The SyNAPSE Project

The goal for the SyNAPSE project is to develop solid state devices which mimic neurons/synapses in biological systems for neuromorphic applications. The devices fabricated at LNF are the co-sputtered Si/Ag crossbar memristive devices (see figures) which intrinsically show synaptic behaviors. All lithographic steps are done by e-beam lithography. A thin PECVD a-Si layer and a co-sputter layer act as the active switching layer. Metal electrodes are e-beam evaporated.



SEM image of crossbar devices



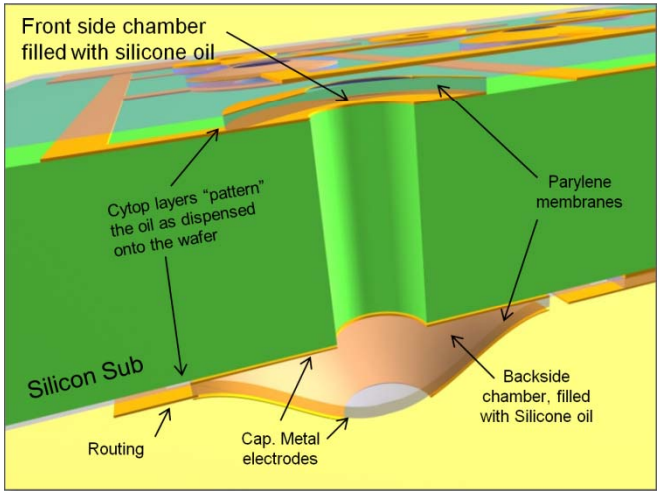
crossbar structure and cross-sectional view of a memristor device

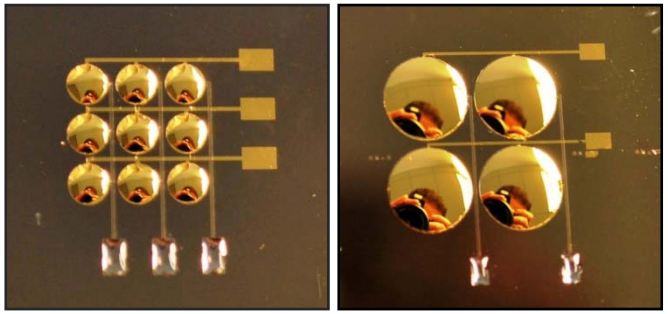
Ting Chang, Wei Lu --University of Michigan
Work performed at University of Michigan's Lurie Nanofabrication Facility

Electrostatically-driven Micro-hydraulic Actuator Arrays

High-force, large-deflection actuators are critical for devices such as micro-fluidic system valves and pumps. However existing transduction methods such as piezoelectric, electro-magnetic or electrostatic are limited in their ability to provide such actuation in low-power integrated micro-systems. We have demonstrated an all-electric individually-addressable micro-hydraulic actuator array which uses hydraulic amplification and electrostatic control. A novel high-yield, wafer-level fabrication technique involving Parylene deposition over silicon oil patterned by a hydrophobic Cytop layer, allows bubble-free encapsulation of the liquid which acts both as a hydraulic fluid and as a capacitor dielectric. The fabricated micro system consists of arrays of actuator cells. A curved electrode capacitive actuator with a diameter of 2.2 mm driven at 200 V produces 30 µm deflection on the front side at 14 kPa of pressure which corresponds to a 11 mN force generated by the capacitive actuator on the back side. Actuation occurs from DC to 15 Hz.

Schematic cross-section of the hydraulic actuator





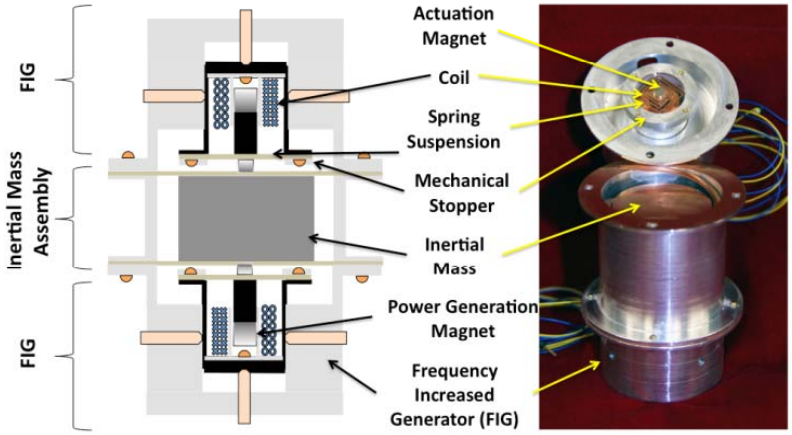
Fabricated arrays of liquid-encapsulated actuators

Mahdi Sadeghi and Prof. Khalil Najafi, EECS Department, University of Michigan
Work performed at University of Michigan's Lurie Nanofabrication Facility

A Vibration Harvesting System for Health Monitoring of Bridges

Wireless sensor nodes can be used to monitor the structural health of critical infrastructure such as bridges, but alternate power sources are needed to avoid costly battery replacement during long-term field deployment. To this end, an energy harvester capable of scavenging low-amplitude, low-frequency, and non-periodic bridge vibrations was designed, fabricated, and tested. The harvester uses a Parametric Frequency Increased Generator (PFIG) non-resonant architecture, where a bi-stable low-frequency mechanical structure is used to induce high-frequency mechanical oscillations in an electromechanical transducer. An inertial mass, responding to bridge vibrations, snaps back and forth between two Frequency Increased Generators (FIGs). The mass and FIGs latch and de-latch magnetically; when de-latched the FIG resonates to convert stored mechanical energy into electrical. Two sets of cascaded 6-stage Cockcroft multipliers rectify and boost the FIG voltage, to be stored and supplied to the sensor node. Energy harvesting has been successfully demonstrated with low-frequency (<10Hz) vibrations to power LEDs or ring oscillators.

The PFIG schematic shown alongside a photograph of the partially opened device



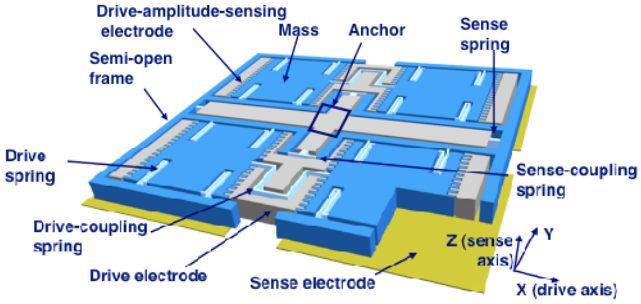
The fabricated device generated a peak power of 57μW and an average power of 2.3μW from an input acceleration of 0.55m/s^2 (55mg) at only 1Hz. The device bandwidth at 55mg is 10Hz, its internal volume is 43cm^3 (68 including casing), and it operates over an unprecedentedly large acceleration (0.55-9.8m/s^2) and frequency range (up to 30Hz) without modifications or tuning.

Tzeno Galchev, James McCullagh and Prof. Khalil Najafi, EECS Department, University of Michigan
Work performed at University of Michigan's Lurie Nanofabrication Facility

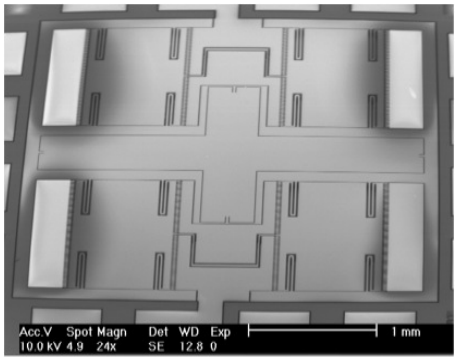
Sub-1°/hour High Performance Micro Gyroscope

Micro gyroscopes are currently used in a variety of fields including military, automotive, guidance, and consumer products. However, few micro-gyroscopes have demonstrated resolution and bias stability less than 1°/hr.

This project aims to overcome these limits through the development of a new tuning fork micro gyroscope, called the Balanced Oscillating Gyroscope (BOG). The BOG is designed to have drive and sense modes that leave zero net momentum so that the modes cannot be triggered by environmental vibration. The prototype sensor has mass of 750µg and nominal sense capacitance of 20pF. The sensor's Q is measured to be 7400 when the drive and sense modes are matched within 4Hz. It is interfaced with hybrid readout-and-control circuitry and demonstrates an angle random walk of 19.8deg/hr/√Hz and a sensitivity of 5.65mV/deg/sec. The BOG is wafer-level vacuum packaged, and the packaged gyro has demonstrated a Q of several tens of thousands over more than four months.



Structure of the prototype Balanced Oscillating Gyroscope (BOG)

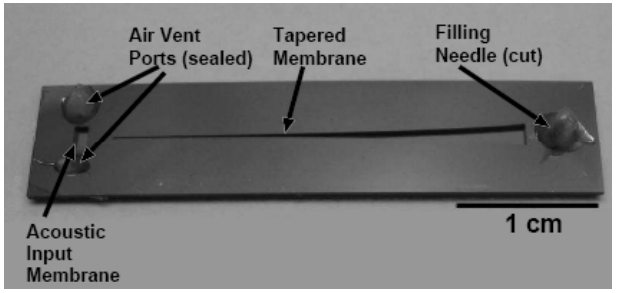


SEM photograph of a fabricated BOG.

Jae Yoong Cho, Jeffrey Gregory, Dr. Sangwoo Lee, and Prof. Khalil Najafi, EECS Department, University of Michigan
Work performed at University of Michigan's Lurie Nanofabrication Facility

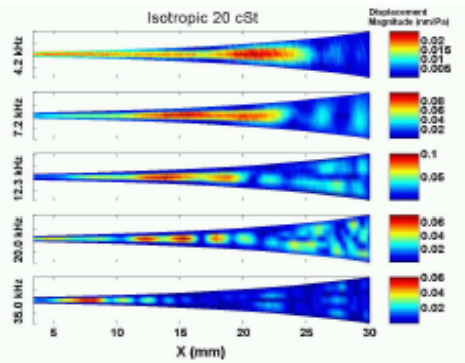
MEMS Cochlea Project

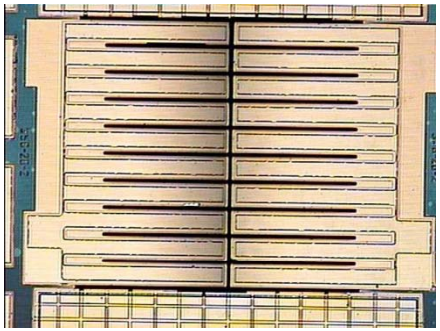
The goal of the MEMS Cochlea Project is to create a life-size physical model of cochlea, including a multi-channel nonlinear feedback control system. An artificial basilar membrane has been fabricated from polyimide and silicon nitride, on a Si wafer. The tapering along the length of the membrane allows for a tonotopic frequency response along the membrane length, as in the human cochlea. Anodically bonded to this structure is a fluid-filled chamber wet etched out of a glass wafer, which represents the scala tympani. AlN piezoelectric bimorph beams, with Molybdenum electrodes, are to be added along the length of the membrane to characterize the nonlinear driving mechanism in the outer hair cells which lie along the basilar membrane in the cochlea.



MEMS artificial basilar membrane, with input membrane and fluid-filled duct underneath.

Representative membrane frequency response, measured by laser vibrometer.



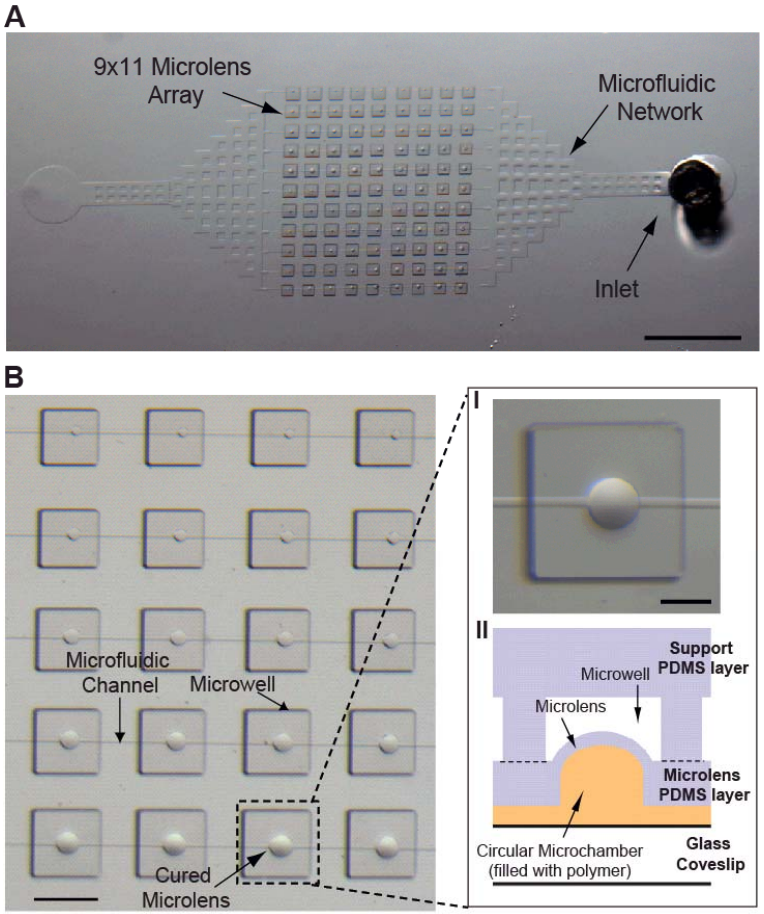


AlN bimorph beams with Mo electrodes, to be placed along the length of the membrane.

K Knisely, R Littrell, Prof K Grosh, University of Michigan - Mechanical Engineering
R White, Tufts University - Mechanical Engineering
Work performed at Lurie Nanofabrication Facility

A High Numerical Aperture, Planar Microlens Array

We have developed a novel microfabrication approach for obtaining arrays of planar, polymer-based microlenses of high numerical aperture. The microlenses arrays consist of deformable, elastomeric membranes that are supported by polymer-filled microchambers. Each membrane/microchamber assembly is converted into a solid microlens when the supporting UV–curable polymer is pressurized and cured. By modifying the microlens diameter (40-60 mm) and curing pressure (7.5-30 psi), it is possible to fabricate microlenses with a wide range of effective focal lengths (100–400 mm) and numerical apertures (0.05-0.3). btained a maximum numerical aperture of 0.3 and transverse resolution of 2.8 mm for 60 mm diameter microlenses cured at 30 psi. We envision the use of these high numerical microlenses arrays in optical applications where light collection efficiency is important.



(A) 9x11 array of PDMS-based, planar microlens array. Scale bar, 1.5 mm. (B) A close-up view of 16 cured microlenses of different diameters. Scale bar, 200 µm.

Anurag Tripathi and Prof. Nikos Chronis, University of Michigan
Work performed at Lurie Nanofabrication Facility

Clonal Culture and Chemodrug Assay Using Microfluidic Single Cell Array Chips

This project is pursuing a microfluidic platform aiming at high-throughput clonal culture and chemodrug assay of heterogeneous cells. Microfluidic arrays with hydrodynamic cell capturing scheme are deployed for highly-efficient single cell capture. Single cells are cultured separately side by side into homogeneous clonal colonies within each micro chambers. Then individual cell substypes are identified and tested with chemodrug simultaneously. Figure 1 illustrates a unit microwell structure. Using migration blocking structure, single cell is cultured into colony within each chamber. Figure 2 shows the photograph of the three subtype PC3 cells, their colonies after 5 days' culture and their viability response after drug exposure.

Jaehoon Chung, Tom Bersano-Begey, Ken Pienta, prof Euisik Yoon,
University of Michigan, Ann Arbor
Work performed at Lurie Nanofabrication Facility

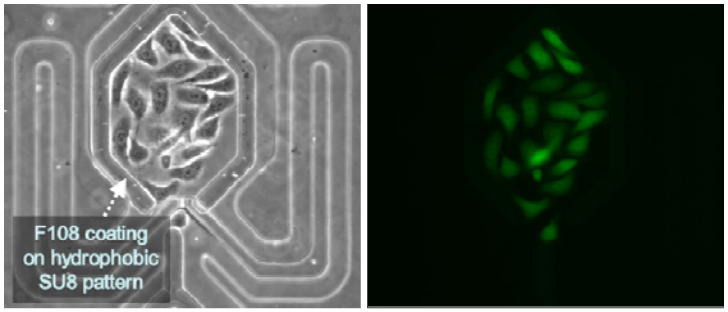


Figure 1. Photograph of migration blocking structure using selective coating on SU8 patterns.

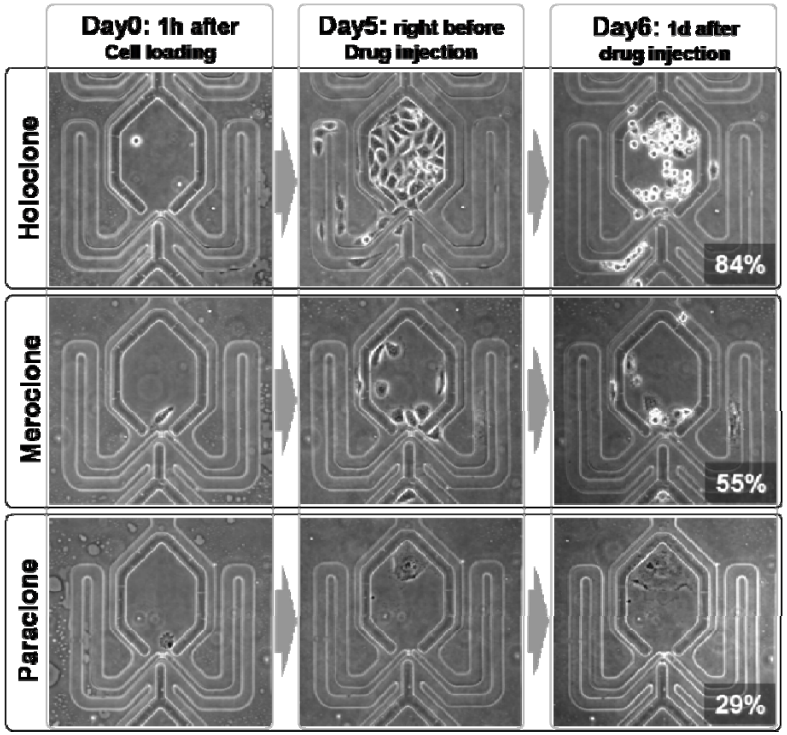
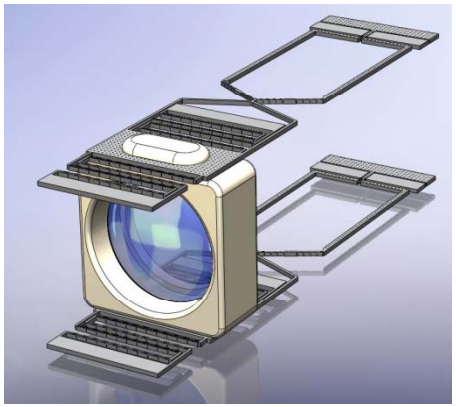


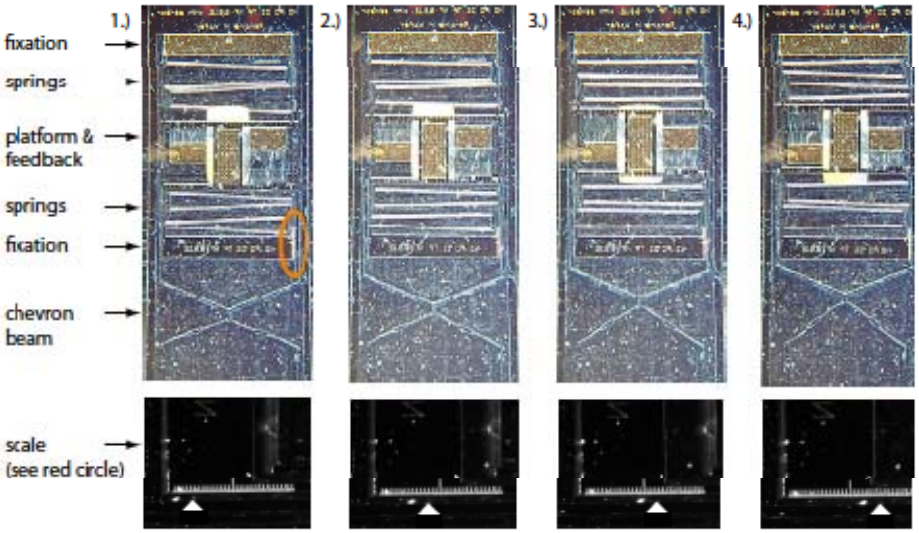
Figure 2. Photograph of single cell loading, clonal culture and chemodrug assay for PC3 heterogeneous cells.

Scanning Actuator for Miniature Two-Photon Microscopy

The purpose of this project is to produce large displacement (>450 µm), high-speed (>10 Hz) translational motion of a 4 mm diameter focusing lens in a two-photon microscope with an actuator less than 3 mm by 0.5 mm in cross-section. This is accomplished through use of a high-amplification silicon transmission, converting high-force, low-displacement motion of a piezoelectric ceramic into large displacement motion of a lens platform. Creation of a actuator providing such displacement in a small cross-sectional area will allow two-photon microscopy to be performed using an instrument compatible with hand-held and/or endoscopic use.



Conceptual view of silicon transmission driving focusing lens.

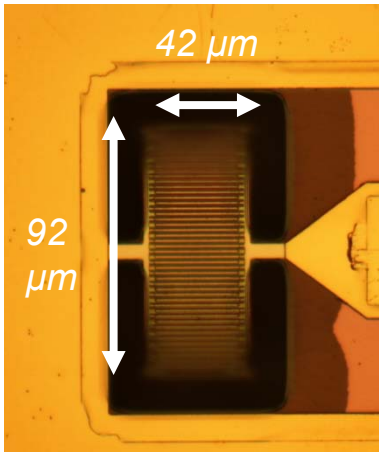


Prototype actuator demonstrating >±250 µm displacement at ±120 V

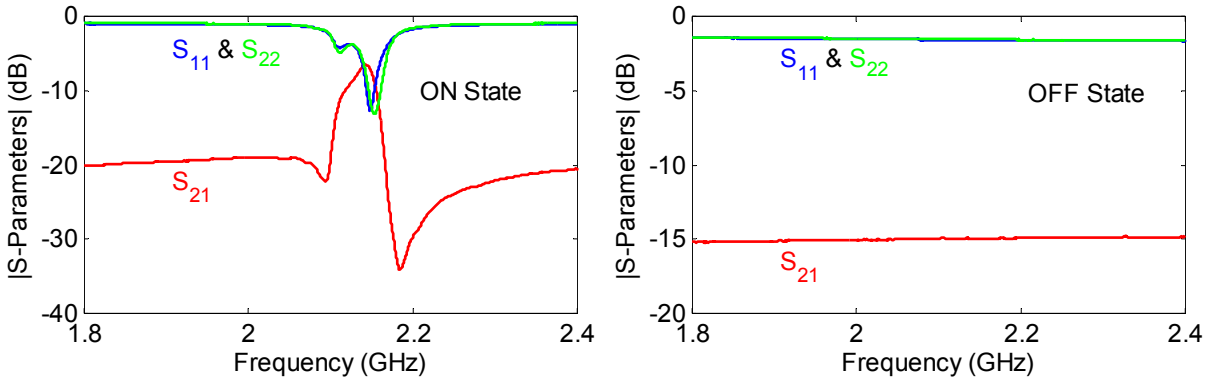
Johannes Domke, Choong-Ho Rhee and Prof Kenn Oldham
Work performed at Lurie Nanofabrication Laboratory, University of Michigan

Intrinsically Switchable Ferroelectric Resonators and Filters Project

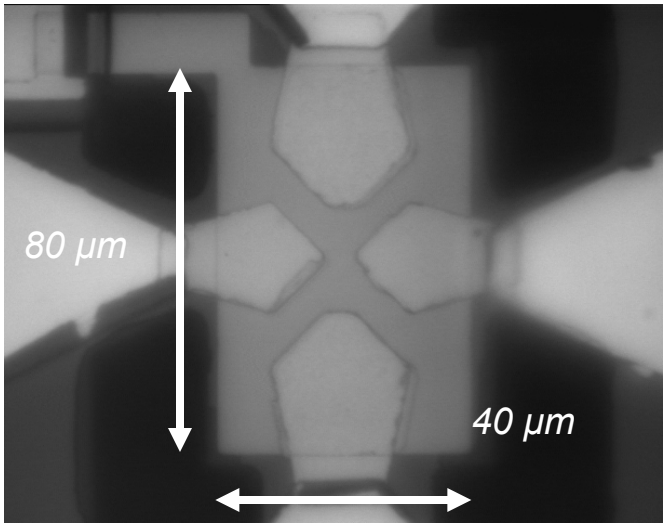
The goal is to develop reconfigurable radios such as software-defined radios and cognitive radios using ferroelectric thin film technology. Some unique properties of ferroelectrics are utilized to develop microwave resonators and filters which can be switched on and off by applying and removing a dc bias voltage. Many of these devices can be placed in parallel to form resonator and filter banks which can select the operating band of a frequency agile radio. These devices are fabricated on high resistivity Si wafers with the ferroelectric thin film sandwiched between two layer of platinum forming a membrane where XeF_2 is used to etch the Si underneath the device.



An intrinsically switchable 1.67 GHz resonator which can be turned on and off by controlling the applied dc bias voltage.



The on and off response of a ferroelectric RF bandpass filter with the application of 15 V and 0 V dc bias, respectively.



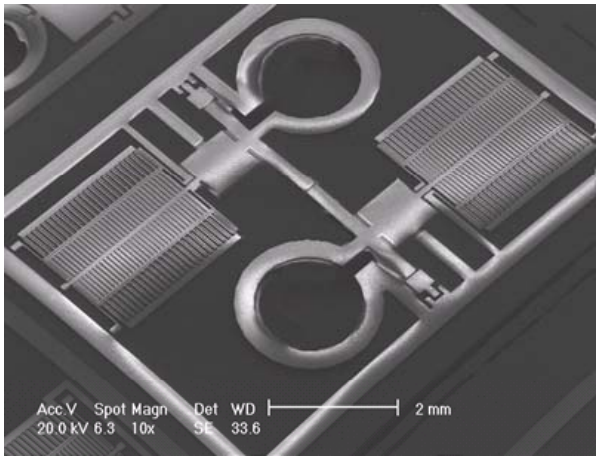
An intrinsically switchable RF bandpass filter that operates at 2.14 GHz.

Victor Lee, Seyit Ahmet Sis and Prof. Amir Mortazawi
Department of Electrical Engineering and Computer Science
Work performed at the University of Michigan Lurie Nanofabrication Facility

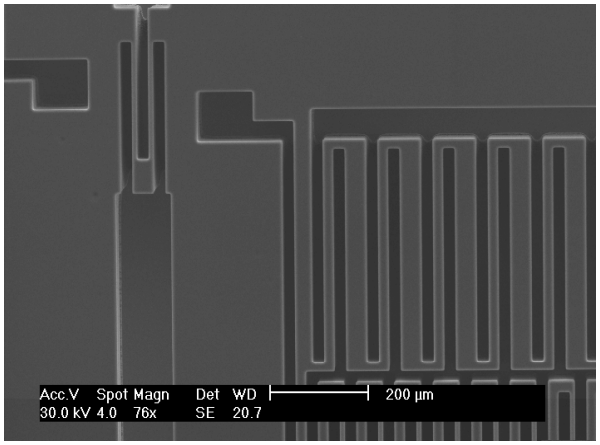
High-Aspect-Ratio Silver Micro-Machined Microwave Filters

The goal of this project is to implement tunable lumped filters with a performance beyond the limits of offered by the CMOS technology (i.e., lower insertion loss, narrower bandwidth, and wider tuning range). These tunable filters can find application in reconfigurable communication systems such as cognitive radios. To achieve high capacitance density and low resistive loss, thick silver is electroplated into a high aspect ratio silicon mold.

Thick silver structures are bonded to a glass substrate using a low temperature parylene bonding process. Initial simulations and analytical calculations show quality factors exceeding 150 for inductors and tunable capacitors using this technique.



A RF tunable filter fabricated using a silver micromachining process. The filter is centered at 640MHz and exhibits an insertion loss of 3.06dB with a bandwidth of 43MHz.

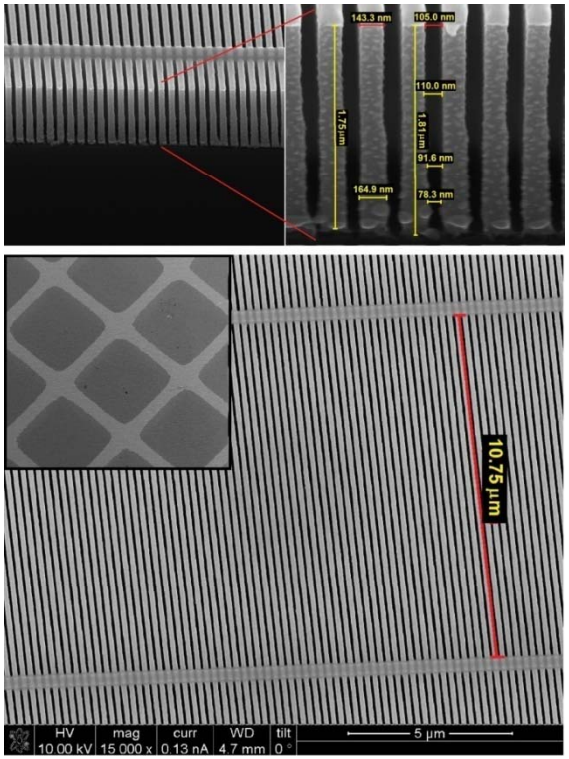


Silicon mold processed with STS Pegasus DRIE; trench aspect ratio is more than 30 : 1.

Yonghyun Shim and Prof. Mina Rais-Zadeh, University of Michigan EECS
Work performed at University of Michigan Lurie Nanofabrication Facility

Ultraviolet Filter Project

Instruments that measure solar plasma and neutral particle populations require sensitivity to individual particle impacts. Unfortunately, that sensitivity also leaves them vulnerable to ubiquitous energetic photons, which look similar to particle impacts and have a count rate approximately 10^5 that of particles. These freestanding silicon nanogratings can be used to filter out the ultraviolet photons while allowing particles through for detection. They are self-supported by a an 11 µm period grating at 90 degrees to the fine grating, and also a 1 mm period bulk silicon support pattern the full thickness of the wafer. The patterns were created by nanoimprint lithography, both for the fine grating and the crossed support grating. A liftoff process left 70 nm thick aluminum lines as the etch-mask, and deep-reactive ion etching was used to etch both sides of the silicon-on-insulator wafer, with the bulk silicon support structure on the back side and the 2 um deep fine-pitch gratings on the front.

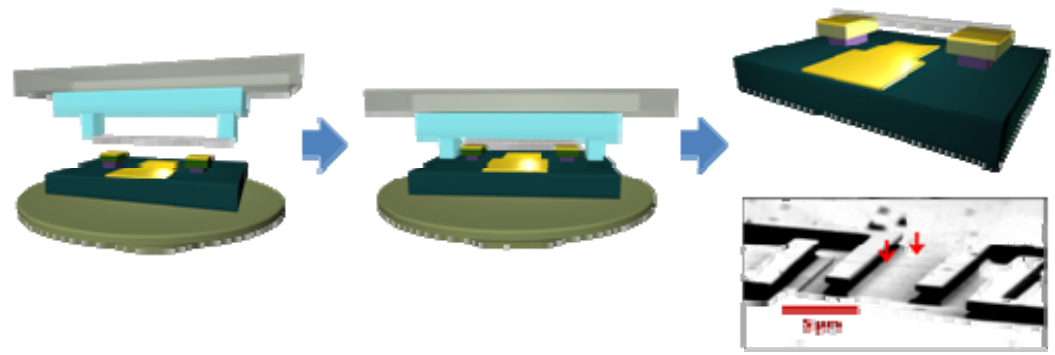


Electron micrographs of freestanding silicon grating structure. The 240 nm pitch grating has a depth of 1.8 µm (top cross-section), and narrows as it goes downward due to multiple etch steps. It is stabilized by an 11 µm pitch grating at 90◦ (Bottom, top-down image). The whole structure is supported by a 500 µm deep bulk silicon mesh of 150 µm wide lines on a 1 mm pitch, seen in the inset at 65x magnification through the top grating.

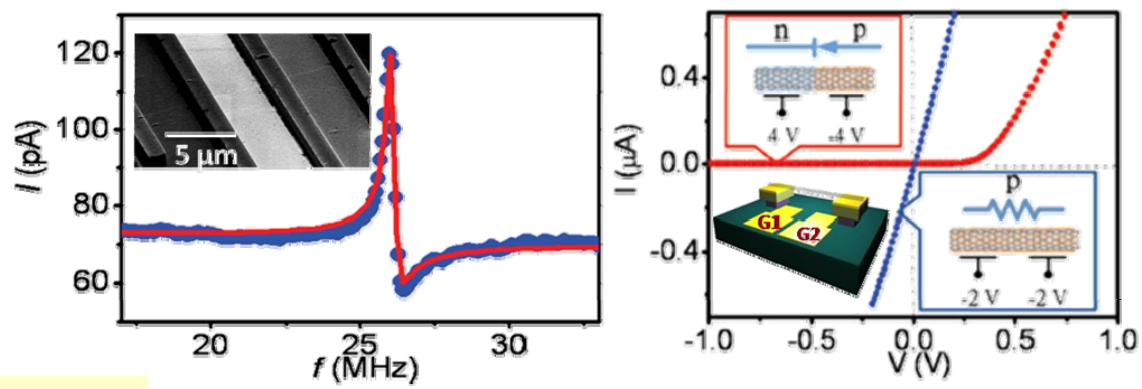
Pran Mukherjee, Prof Thomas H. Zurbuchen, and Prof L. Jay Guo,
University of Michigan (AOSS and EECS departments)
Work performed at Michigan's Lurie Nanofabrication Facility

One-Step Direct Transfer of Pristine Single-Walled Carbon Nanotubes for Functional Nanoelectronics

One-step direct transfer technique for the fabrication of functional nanoelectronics using pristine SWNTS. Suspended SWNTs grown by the chemical vapor deposition (CVD) method are aligned and directly transferred onto prepatterned device electrodes at ambient temperature. Using this technique, we successfully fabricated SWNT nanoelectromechanical (NEM) resonators with gate-tunable resonance frequencies. A fully suspended SWNT p-n diode has also been demonstrated with the diode ideality factor equal to 1.



Schematics of one-step direct transfer procedure

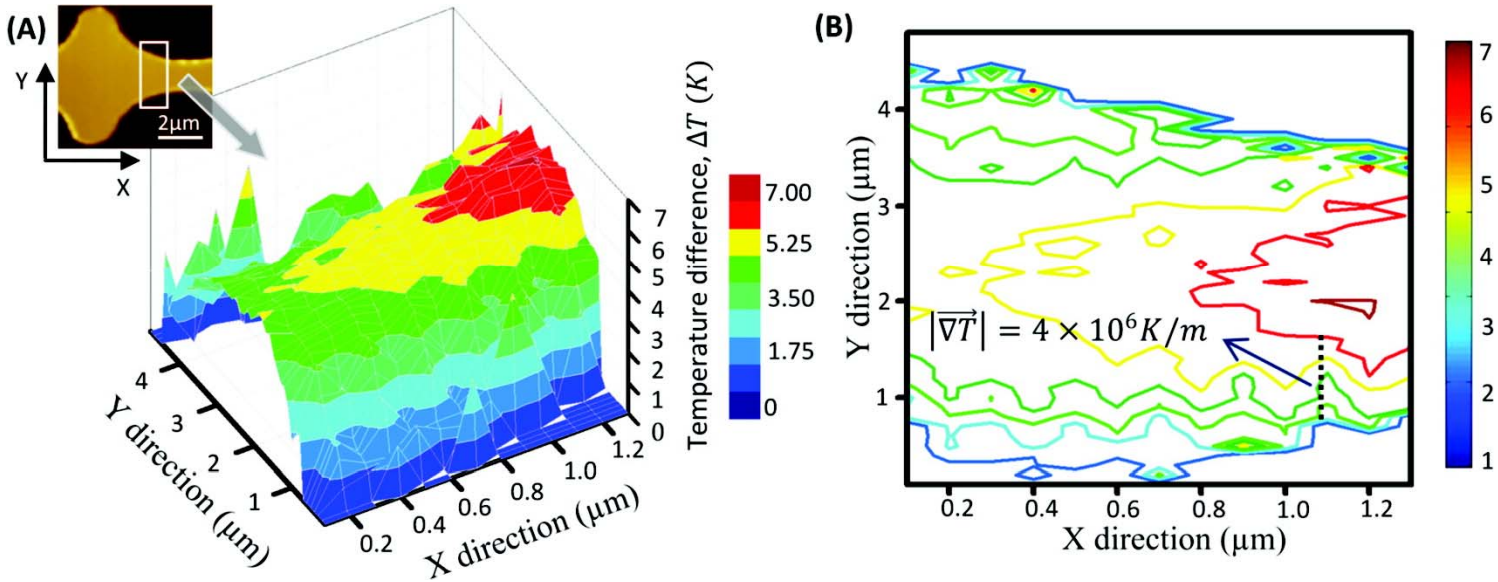


SWNT NEM resonators & fully suspended SWNT p-n diode

Chung Chiang Wu, Chang Hua Liu, and Prof Zhaohui Zhong, EECS, University of Michigan
Work performed at Lurie Nanofabrication Facility (LNF)

Nanoscale Thermometry Using Point Contact Thermocouples

Understanding energy dissipation at the nanoscale is essential to develop novel “nano-engineered” energy conversion devices that are efficient and inexpensive. Almost all energy dissipation processes have an associated thermal signature, therefore, the ability to probe temperature fields of nanometer-sized devices is critical to understand energy dissipation at the nanoscale. In this work, we present a novel atomic force microscope based approach to map the thermal fields of nanoscale devices with a spatial resolution <100 nm and a temperature resolution < 10 mK. It is expected that this approach will enable us to obtain important insights into energy dissipation at the nanoscale.



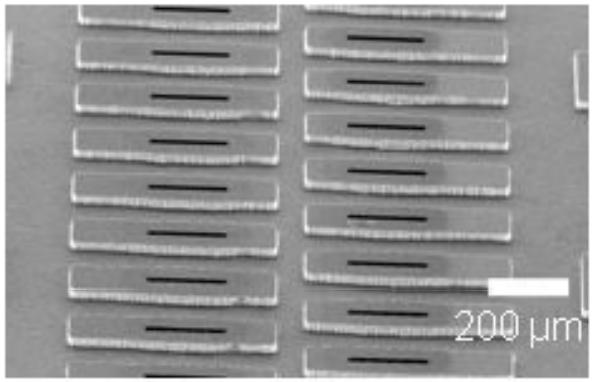
(A) Three-dimensional representation of the temperature field in a section of the test device (inset). Temperature is measured on a square grid of points separated by 100 nm without disengaging the tip−substrate contact between consecutive measurements. (B) Isotherm contour plot of the same section of the device. Temperature gradients as large as 4X10^6 K/m are detected in certain regions (shown by a dotted line).

S. Sadat, A. Tan, Y-J Chua, Prof. P. Reddy, University of Michigan Mechanical Engineering
Work performed at Lurie Nanofabrication Facility (LNF)

Organic Vapor Jet Printing (OVJP)

Organic Vapor Jet Printing (OVJP) is being developed as a cost effective method to grow patterned organic films on large area substrates. OVJP combines the patter generation capability of inkjet printing with the ability of vacuum thermal evaporation to make complex, multilayer OLED architectures. Co-deposition capability allows OLEDS to be grown using high efficiency phosphorescent materials and will facilitate scaleup.

An array of nozzles micromachined from silicon is being developed to increase print resolution and speed. This novel combination of scalability and device efficiency make OVJP a promising process for the fabrication of large area OLED displays and lighting.



(top) a mulitcolor array of OLEDs grown using OVJP.
(bottom) micrograph of high resolution OVJP nozzle array currently under development.

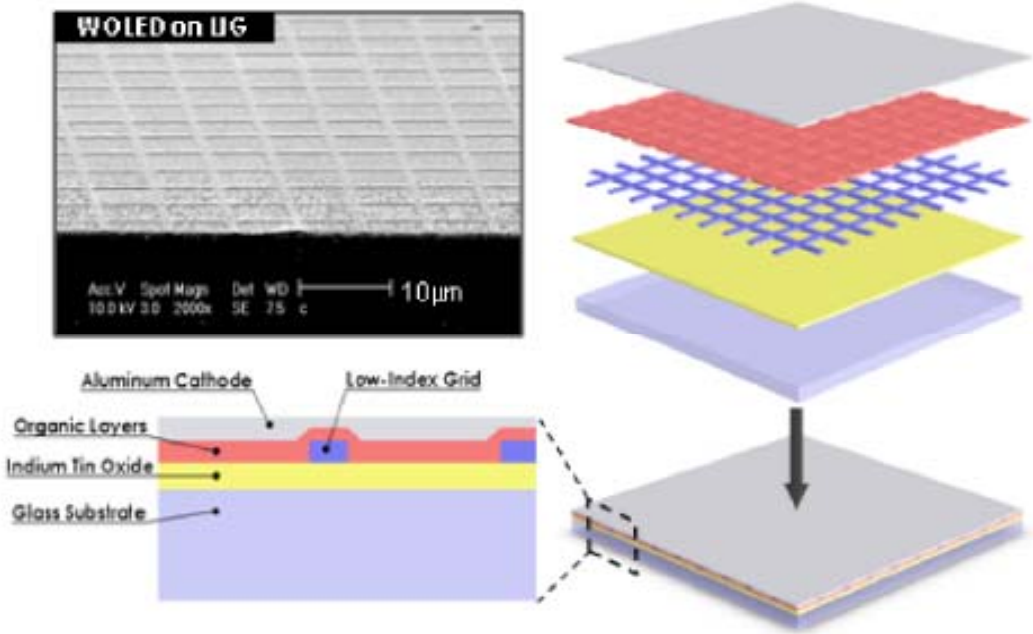
G. McGraw and S. R. Forrest, University of Michigan
Work performed at Lurie Nanofabrication Facility

Enhanced OLED Outcoupling using a Low-index Grid (LIG)

Phosphorescent OLEDs can produce light with near 100% internal quantum efficiency. Conventional OLED architectures only allow ~20% of light produced to be extracted due to internal reflection at the ITO/substrate and substrate/air interfaces.

Substantial gains in efficiency are possible by improving the outcoupling of light through the use of Full-wave electromagnetic simulations and optimization of OLED structure with Low Index Grid (LIG)-embedded organic layers through advanced depositions techniques.

Additional outcoupling is provided by micron-scale lens array on substrate surface.



M. Slootsky and S. R. Forrest, University of Michigan
Work performed at Lurie Nanofabrication Facility

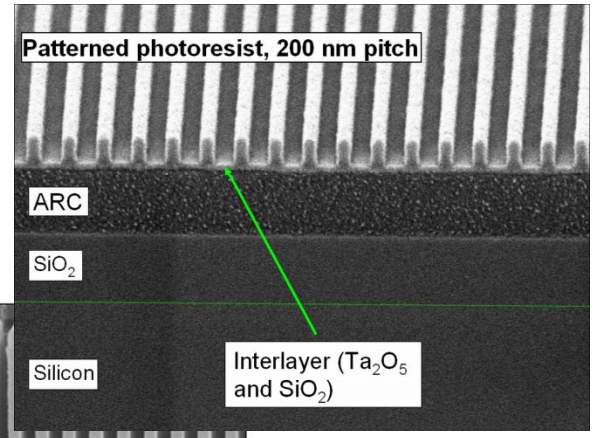
Critical-angle Transmission Grating Project

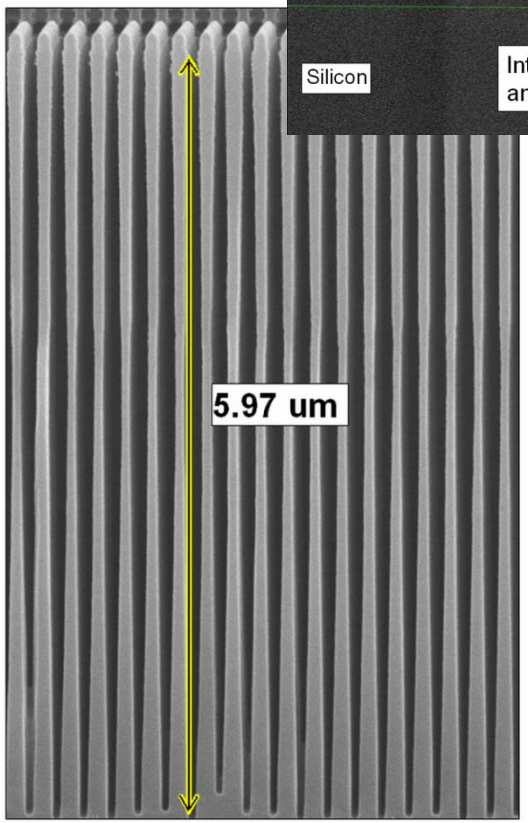
Next-generation space x-ray telescopes require advances in diffraction grating technology. Critical-angle Transmission (CAT) gratings designed by MIT's Space Nanotechnology Laboratory are one such advance, combining the advantages of transmission and reflection gratings.

Silicon-on-insulator wafers enable double-sided processing of thin films supported by a bulk silicon support structure. This all-silicon design removes any thermal expansion coefficient mismatches between the grating and its supports. The silicon oxide mask is patterned using interference lithography on an optically matched material stack, and deep-reactive ion etching is used to form both the grating and its support structure.

Pran Mukherjee, Alexander Bruccoleri, Ralf K. Heilmann, Mark L. Schattenburg, MIT
Alex F. Kaplan, and L. Jay Guo, University of Michigan
Work partially performed at U of Michigan Lurie Nanofabrication Facility

Electron micrograph of the patterned mask stack prior to any etch steps



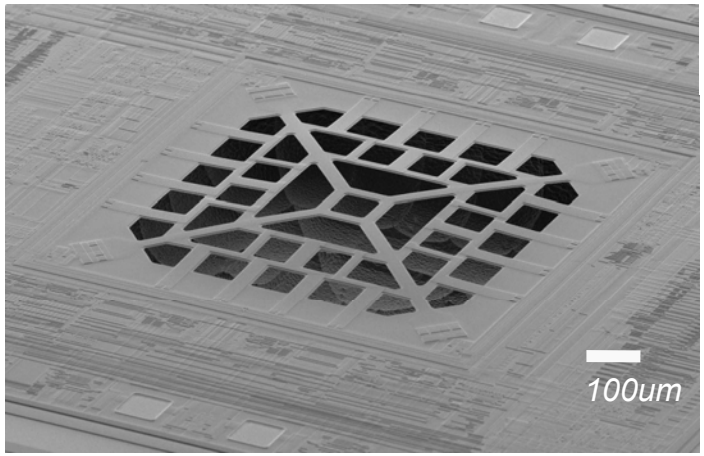


Cross-sectional electron micrograph of silicon grating etched by deep-reactive ion etching

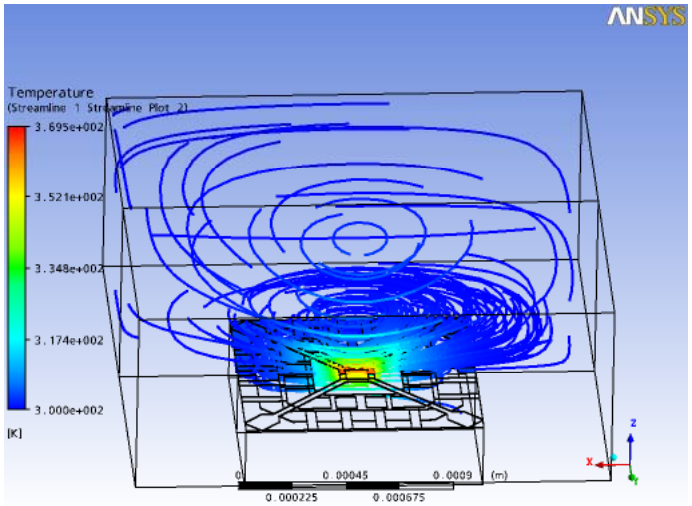
MEMSIC 2-Axis Thermal Accelerometer

MEMSIC fabricates accelerometers that rely on changes in thermal convection due to movement rather than displacement of a proof mass. Use of the LNF allows the latitude to explore many different processes and develop them for use in a manufacturing environment. MEMSIC is currently using the LNF for the optimization of a TMAH etch following release of the sensor.This etch will ultimately be implemented into MEMSIC's own production line.

A 2-axis Thermal Accelerometer (MEMSIC MX7250)



Gas convection inside sensor due to a 1g lateral acceleration.

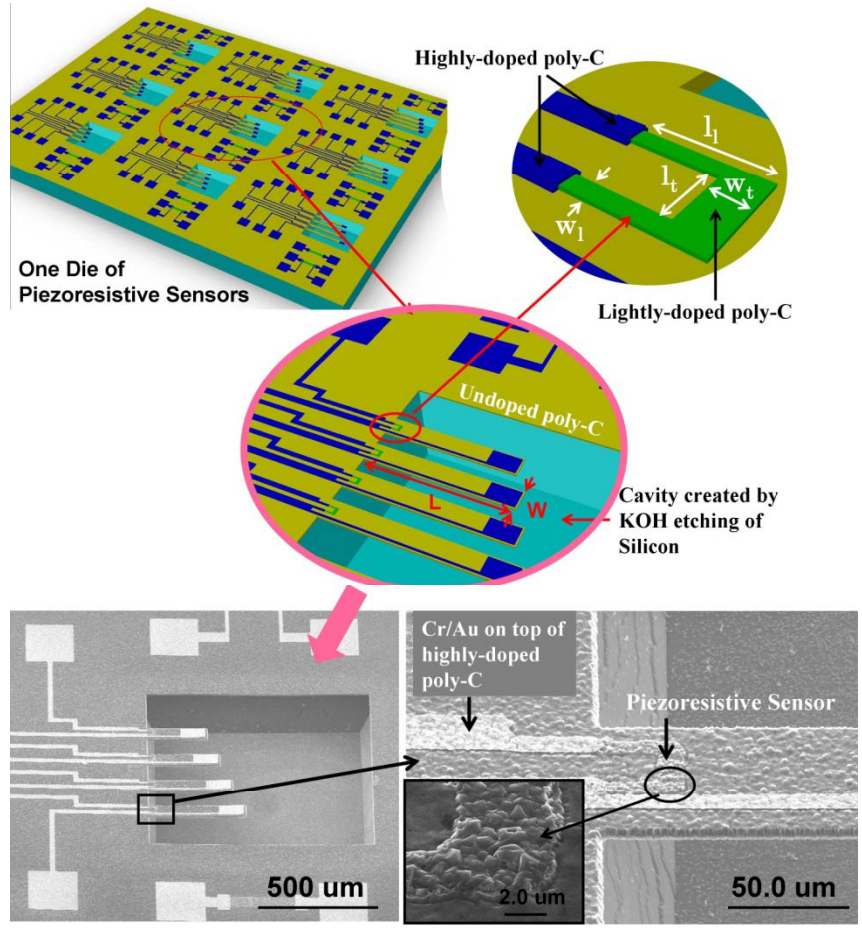


Stefan Nikles, MEMSIC
Work performed at Lurie Nanofabrication Facility

Piezoresistive RFMEMS Resonators using p-type Polycrystalline Diamond

Design, simulation, fabrication and testing of p-type polycrystalline diamond (poly-C) piezoresistive RFMEMS is reported for the first time. The use of piezoresistive detection in RFMEMS can lead to an output impedance in the range of 20 - 500 Ω and several MΩ for intra- and inter-grain piezoresistors, respectively. The inter-grain gauge factor of the poly-C film with a resistivity of 22 was estimated to be over 20. An Ohmic contact with a contact resistance of 5.21 MΩ was achieved by using a highly-doped poly-C interlayer between metal and lightly-doped piezoresistor.

Zongliang Cao and Dean Aslam, Michigan State University
Work performed at Lurie Nanofabrication Facility



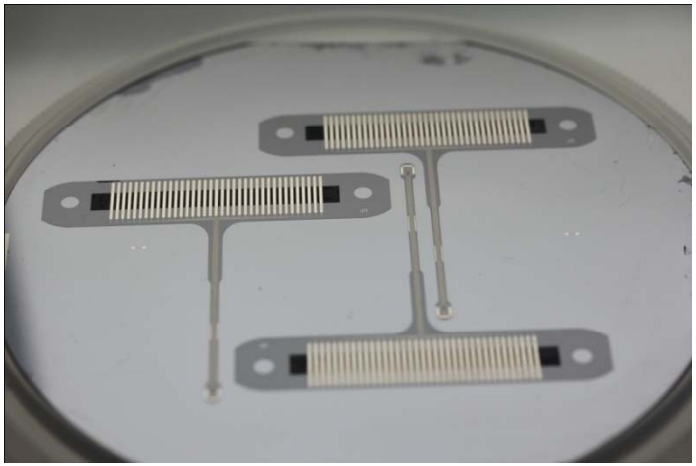
SEM pictures of Piezoresistive Sensors

Computational Platform for Characterization and Optimization of Retinal Prosthetic Stimulation

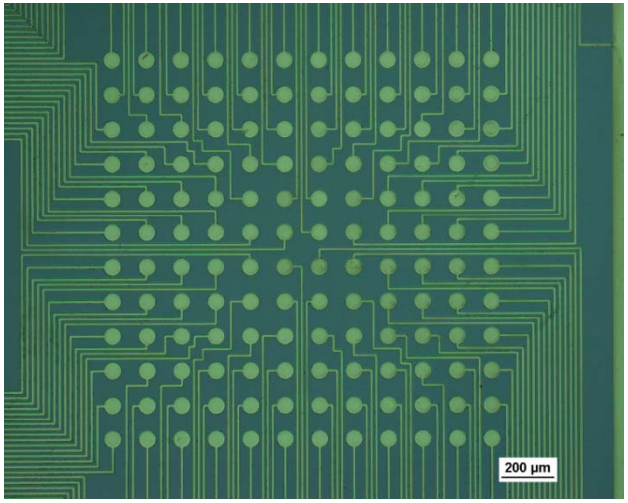
The goal of this project is to discover multi-site retinal stimulation paradigms that are capable of maximizing the amount of spatial information transmitted to the brain, and thus would have the greatest potential for generating spatially-structured visual percepts in blind humans.

Parylene stimulating electrodes for this study were partially fabricated at LNF. A 10 µm thick parylene C layer is first deposited. Then platinum traces and electrodes are evaporated and patterned using lift-off method. Finally another 10 µm thick parylene C layer is deposited and patterned to expose the electrodes and contact pads.

Yuefa Li, prof Yong Xu and Nicolas Cottaris , Wayne State University
Work partially performed at University of Michigan Lurie Nanofabrication Facility



Three electrode devices fabricated on a 5" wafer



Micrograph of a 12x12 electrode array

Time Resolved Cryo-EM of Ribosomal Subunit Reassociation using a Microfluidic Device

We developed a monolithic microfluidic device to integrate micromixer, micro reaction channel and microsprayer on one single chip. This monolithic chip is incorporated into a computer-controlled plunging apparatus. The device was used to capture macromolecular complex intermediates, along with cryo-EM technology.

We studied the reassociation of the E. coli 50S and 30S ribosomal subunits at milliseconds level. Analysis of the resulting micrographs show about 26% association of the 30S and 50S into the 70S form, consistent with the reaction kinetics of association determined biochemically. Initial analysis of the cryo-EM data collected from these association experiments shows either weaker or absent densities for some the inter-subunit bridges, suggesting that we are able to capture possible intermediates of association.

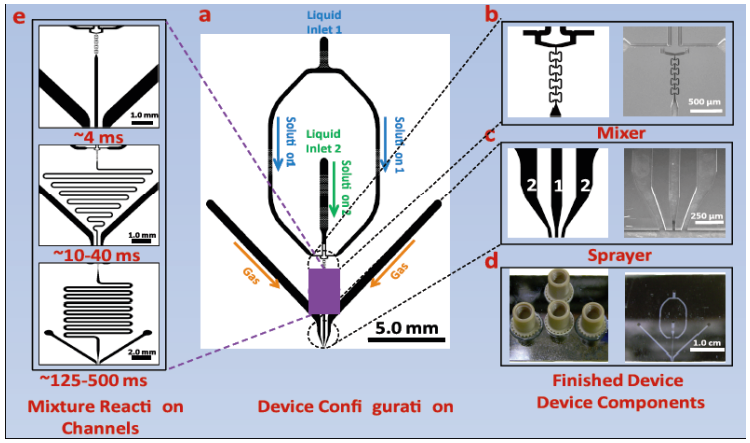


FIGURE 1. Construction of Microfluidic Devices that Combines Mixer, Reaction Channel (milliseconds), and

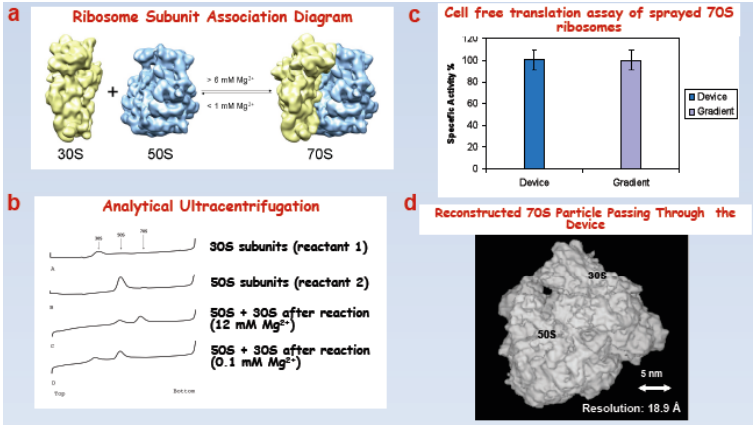


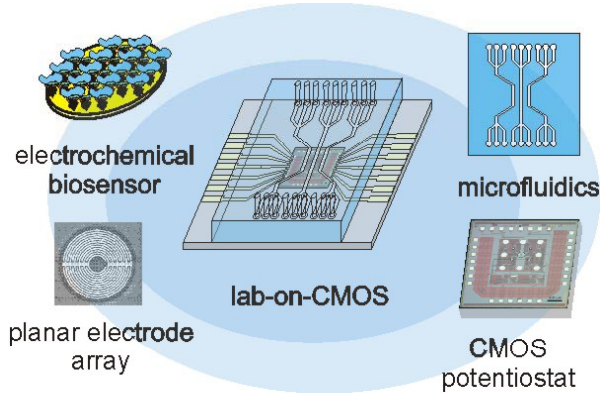
FIGURE 2. (a) Ribosomal subunit reassociation; (b) Ultracentrifugal analysis showing that nearly complete assembly of subunits can be achieved; (c) Activity of the ribosomes at different concentrations was determined; (d) Three-dimensional reconstruction of the ribosomes (70S) passed through the device

Center for Integrated Electronics, Rensselaer Polytechnic Institute
Work partially performed at University of Michigan Lurie Nanofabrication Facility

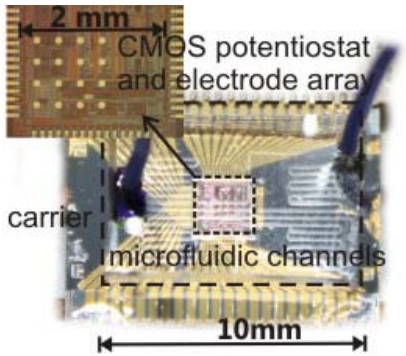
Lab-on-CMOS Project

The project goal is to package a CMOS chip for an integrated chemical sensor and fluidic delivery system. For housing the CMOS chip, a cavity in a silicon substrate is prepared by DRIE. Passivation, planarization and metalization are performed afterwards. The structure will allow fluidic to flow across a CMOS chip surface electrode through a channel.

A CMOS potentiostat was packed using above scheme. A PDMS mixer was attached on top of the structure, with the detection channels across CMOS electrodes.



Key components of a Lab-on-CMOS device.

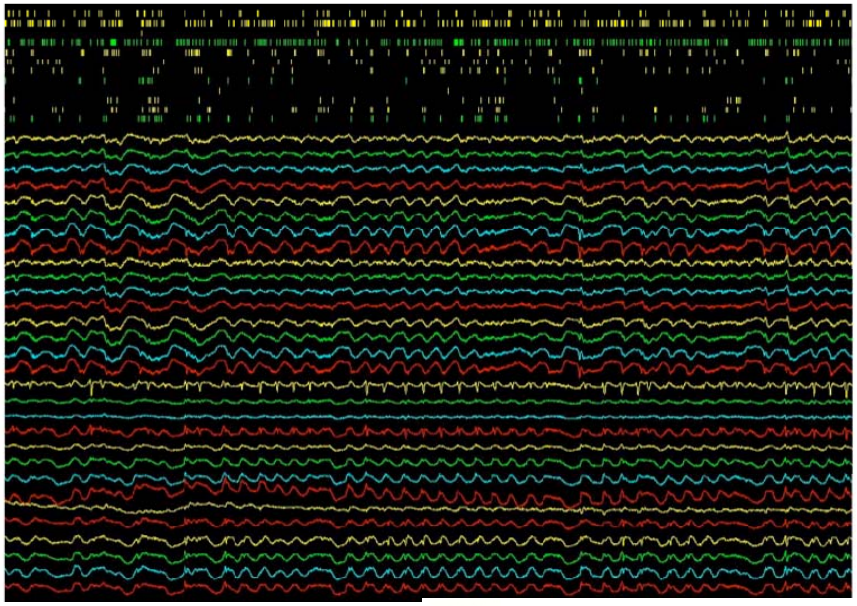


An electrochemical Lab-on-CMOS microsystem

Yue Huang, Electrical and Computer Engineering, Michigan State University
Work performed at U-Michigan Lurie Nanofabrication Facility

Polymer Electrode Arrays for ElectroCorticoGrams

NeuroNexus Technologies, Inc. *(Ann Arbor, MI), is a global leader for innovative neural interface products and technologies to meet both current and upcoming needs in neuroscience research, neurosurgery, and neurostimulation. The devices at left are 16- and 32-channel polymer electrode arrays designed to record ElectroCorticoGrams (ECoGs) from the brain's surface in lab animals. NeuroNexus ECoG arrays include holes through the substrate to allow insertion of depth arrays, also available from NeuroNexus. Plot below shows simultaneous recordings from a depth array and ECoG array implanted in rat cortex.*



Spike rasters from depth array

Field potentials from depth array

ECoG recordings

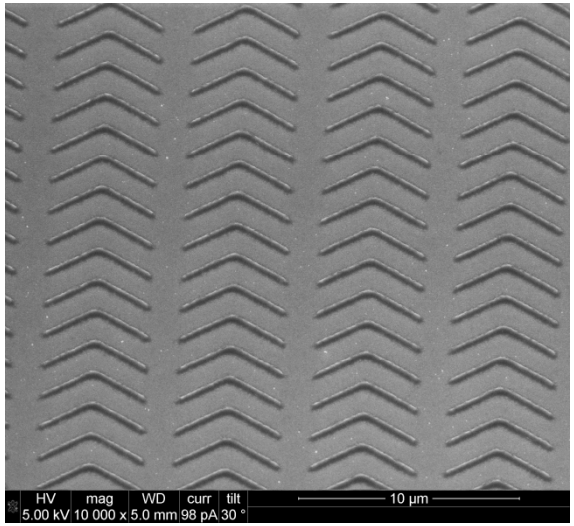
Neuronexus Technologies, Inc
Work performed at U-Michigan
Lurie Nanofabrication Facility

Fabrication of Bent-Core Colloidal Particles

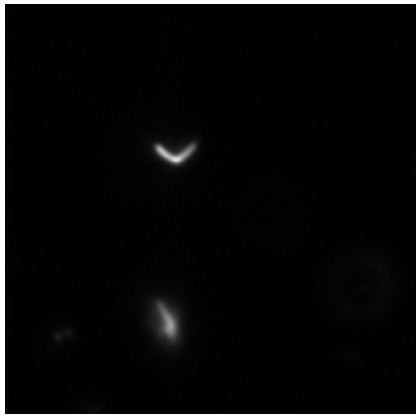
Bent-core (also called boomerang- or banana-shaped) molecules exhibit very interesting mesophases with primarily long rang orientational ordering. One illusive while very interesting topic is related to the so called biaxial nematic phase. While biaxial nematic liquid crystal phase has been predicted in theory 35 years ago, experimental evidences of its existence was only obtained recently in bent-core molecule systems, that brings in various questions of fundamental interest.

This project plans to look at the ordering and dynamics of micron-sized bent-core colloidal particles, hoping that more “molecular level” information obtained through optical microscopy be helpful in resolving several fundamental issues related to biaxial nematic liquid crystals.

An SEM picture of such particles on a Si wafer is shown in the right.



Bent-core Microparticles on a Si Wafer

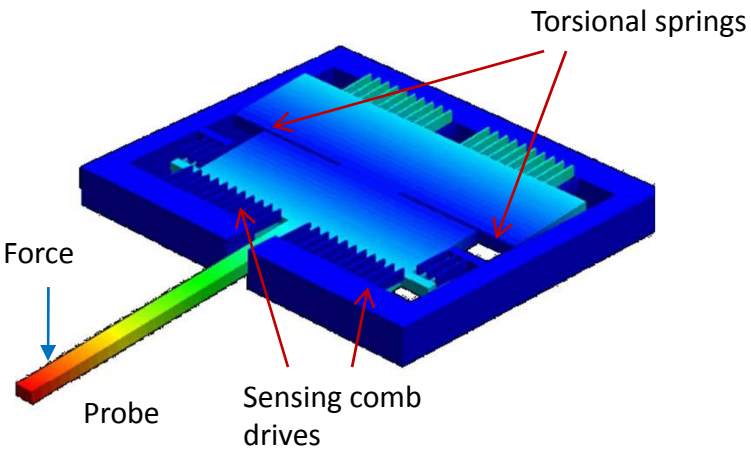


Bent-core Particles under an Optical Microscope

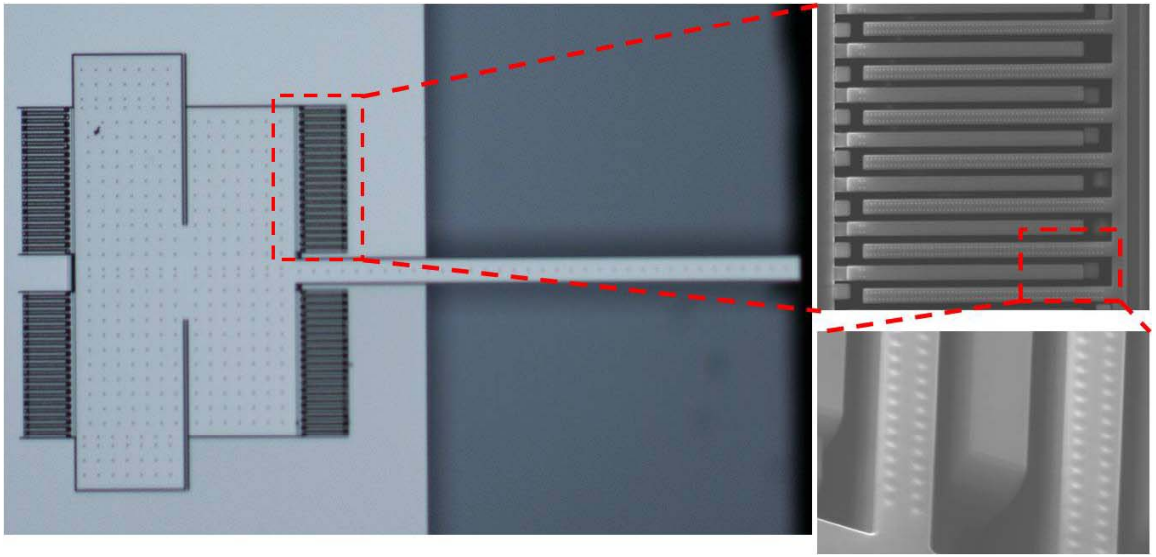
Prof Qihuo Wei, Kent State University
Work performed at U-Michigan
Lurie Nanofabrication Facility

A CMOS-MEMS Nano-Newton Force Probe

A capacitive CMOS-MEMS force sensor capable of nano-Newton measurement has been designed, fabricated, and characterized. The sensor has a sensitivity of 0.02 fF/nN with a nano-Newton detection capability. The unique out-of-plane sensing mechanism allows sensing of forces applied perpendicular to the sensor plane, which is different from most of other capacitive MEMS force sensors.



3D model of the device capable of out-of-plane force sensing.



Optical and SEM images of the fabricated device and micro structures.

Mohd Haris and Prof Hongwei Qu, Oakland University.
Work performed at the University of Michigan Lurie Nanofabrication Facility

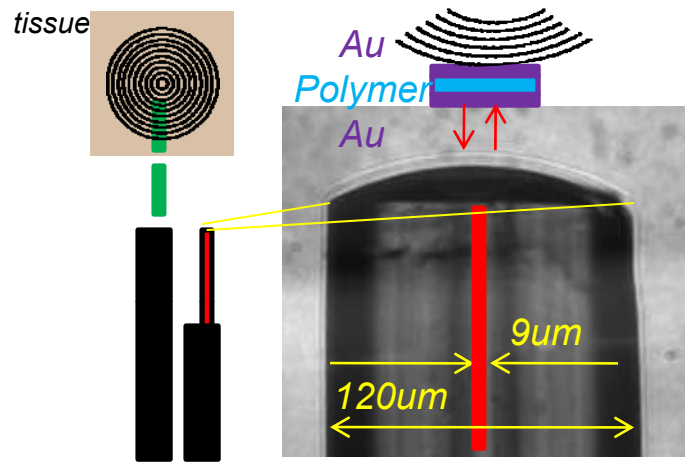
University of Minnesota

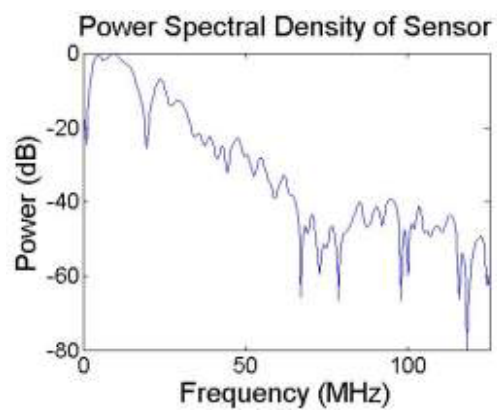
Photo-acoustic NeedleScope

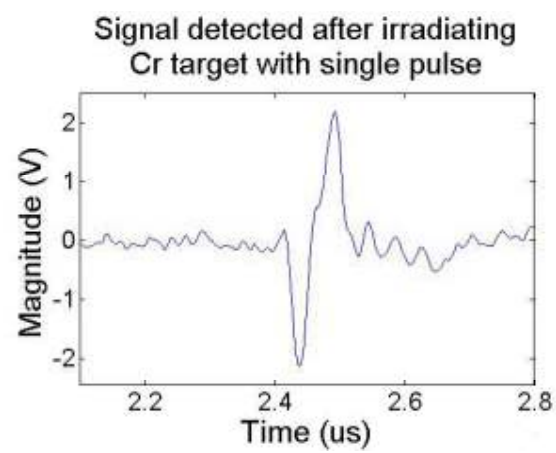
Our work aims to create a miniature ultrasound device to mount on the tip of a biopsy needle for image-guidance. We deposit materials for an opto-acoustic sensor on the tip of an optical fiber using e-beam evaporation. We pair the sensor with fiber transmitting at 532nm.

The sensor exhibits optical and mechanical resonance suitable for opto-acoustic ultrasound detection. The transmitting fiber emits intensities at a wavelength required for photo-acoustic generation in blood. These fibers have been successfully paired to create a complete transmit/receive ultrasound transducer.

Shai Ashkenazi, Clay Sheaff and Nathan Lau, University of Minnesota.
Work performed at the Nanofabrication Center, University of Minnesota.



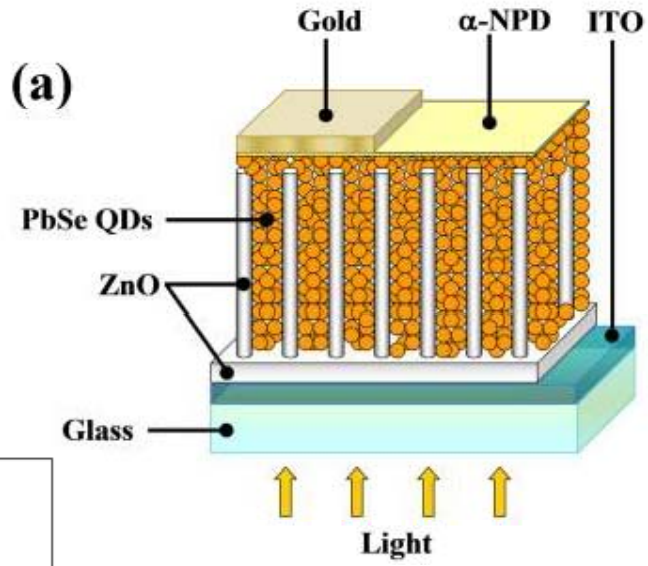


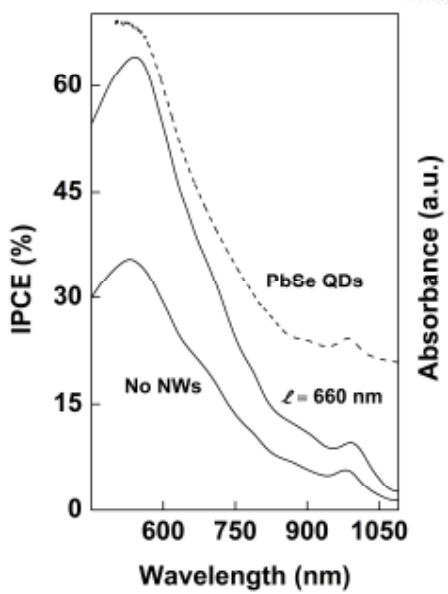


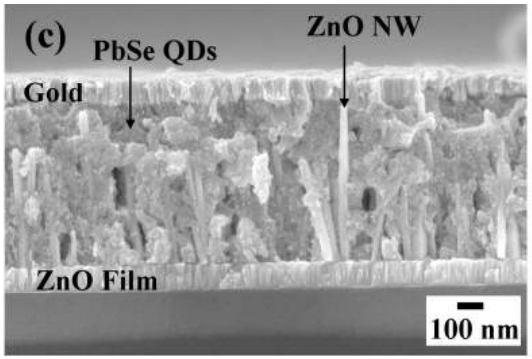
Nanowire Quantum-Dot Solar Cells

The efficiency of solar cells based on PbSe quantum dots (QDs) and ZnO films is increased by replacing the ZnO films with a vertically oriented array of single-crystalline ZnO nanowires, and infiltrating this array with QDs.

This work has demonstrated a new type of solar cell based on PbSe QDs and ZnO nanowires. With 100 mW/cm^2 illumination these solar cells exhibit efficiencies of up to 2%. It has also been shown that nanowires improve exciton collection efficiency in QD solar cells.





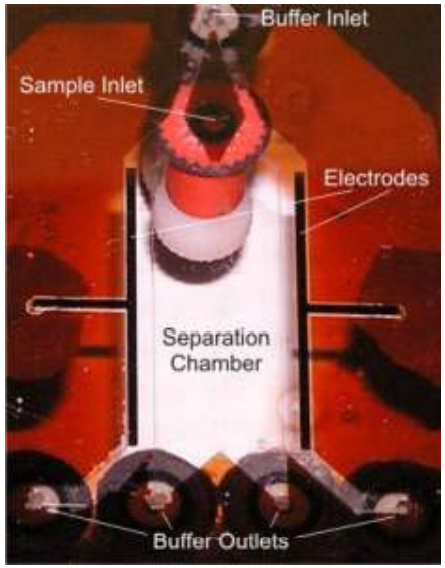


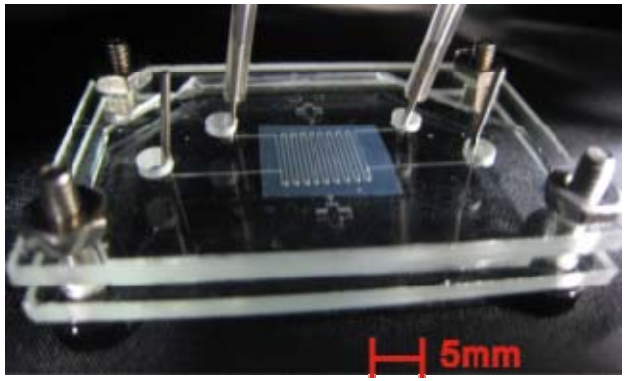
Eray Aydil, David Norris, Kurtis Leschkies and Alan Jacobs, University of Minnesota.
Work performed at the Nanofabrication Center, University of Minnesota.

Microfluidic Devices for Bioanalysis

We are developing online Micro Free Flow Electrophoresis separations. We do this by measuring single enzyme kinetics using microwell arrays, designing new microscale pumping methods, and studying counter flow extraction devices for DNA purification.

It has been observed that mFFE separations are useful for continuous monitoring or microscale preparative separations. We have also developed a piezoelectrically actuated micropump capable of flow rates as low as 30-200 nL/min. and detected individual enzyme molecules in microwell arrays.



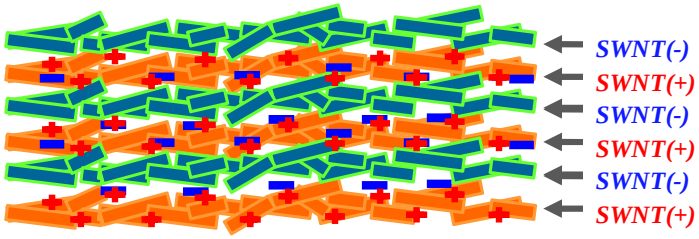


Michael Bowser, Ryan Turgeon, Nic Frost, Yixiao Shen, Jing Yang and Zhouhan Zhang, University of Minnesota.
Work performed at the Nanofabrication Center, University of Minnesota.

Low Mass Density RF Actuators

The aim of this work is the development of an all single walled carbon nanotube (SWNT) film using a layer-by-layer deposition process. We hope to demonstrate reliable and fast 3-terminal actuators and to implement high speed MEMS digital logic circuits.

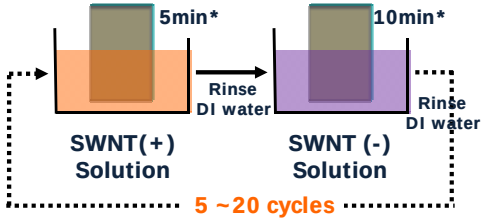
We measured the film resistivity for each annealing condition. The lowest resistivity = 8.9×10^{-4} Ω·cm@300˚C annealed. We measured film young's modulus(E) and yield strength(Y) by triboindentation from free-standing CNT beams. The highest E = 913GPa@300˚C annealed.

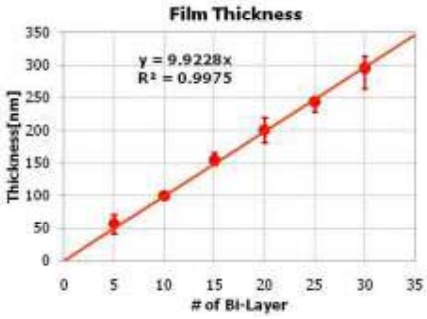


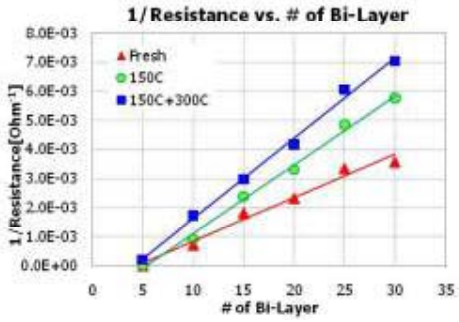
Sample pre-treatment

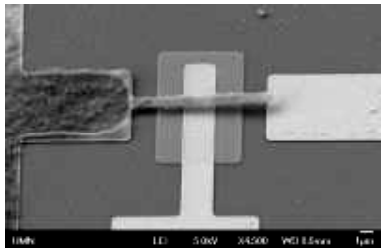
To make it be **negatively charged** (**O_2 plasma** or **Piranha** cleaning)

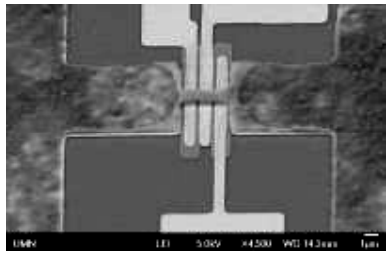
L-b-L Self Assembly











T. Andrew Taton, Tianhong Cui, David Lilja, and Stephen Campbell, University of Minnesota.
Work performed at the Nanofabrication Center, University of Minnesota.

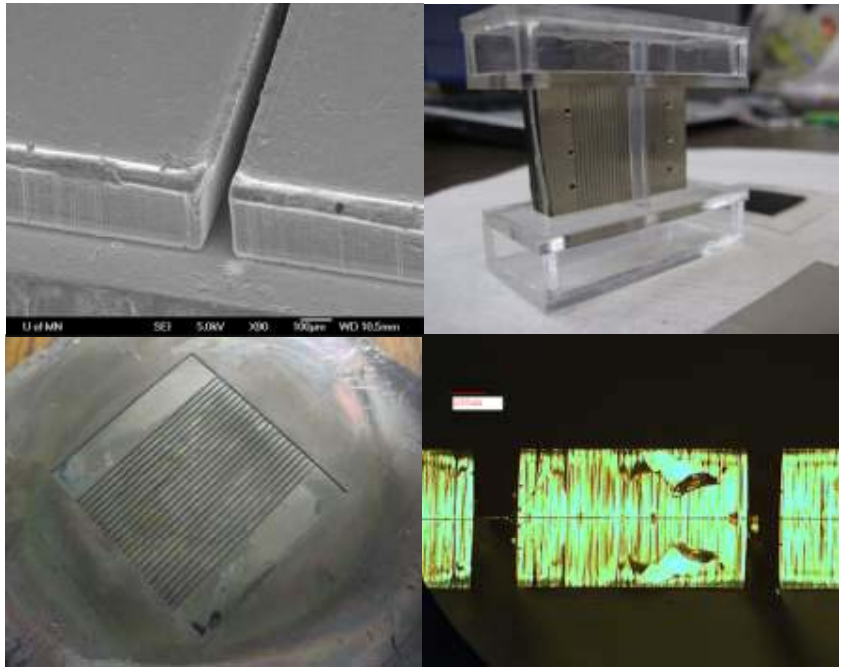
Self-pumping and Self-breathing Polymer Micro Methanol Fuel Cell (µDMFC)

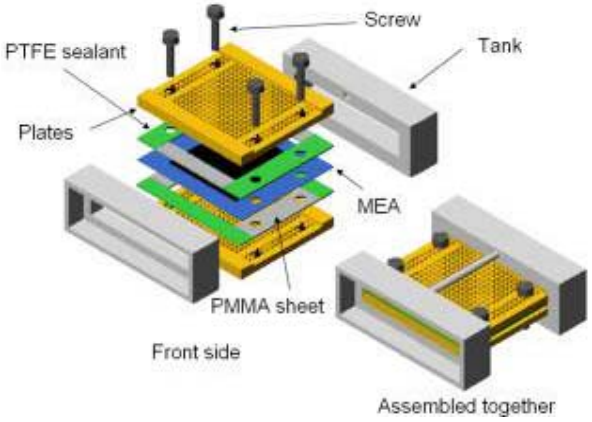
This work involves the fabrication of polymer polar plates for µDMFC by hot embossing. We use a reserved exposure of SU8, the mold is Ni electroplating on glass, hot embossing of ABS polar plates, and an ultra thick Ni layer deposit on ABS polar plates.

The fuel cell is self-pumping and self-breathing.

Anode: capillary force and two phase flow to make the methanol solution convective.

Cathode: air is transferred through the hydrophilic porous carbon electrode.



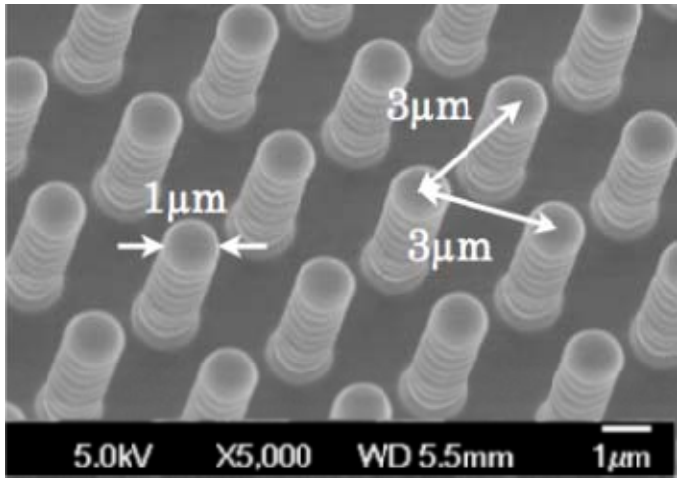


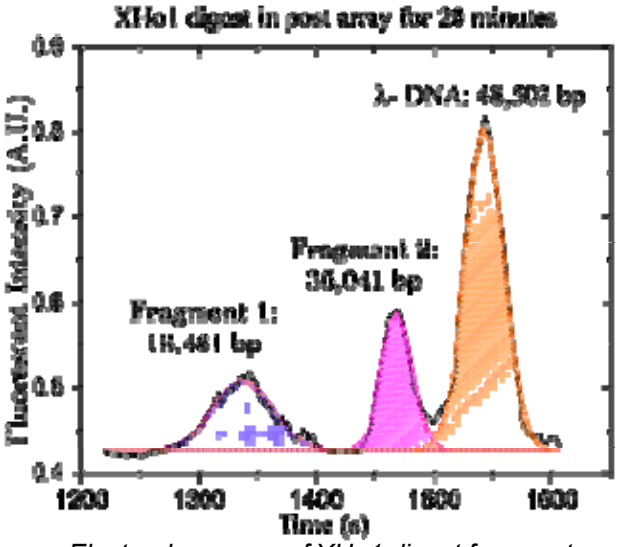
Tianhong Cui, University of Minnesota.
Work performed at the Nanofabrication Center, University of Minnesota

DNA Separation In Sparse Ordered Micropost Arrays

Agarose gels are the standard medium for separating DNA by size, but the separations are slow, require large amounts of DNA, and do not give quantitative results. Microfabricated post arrays, such as the one in this figure, reduce the separation time from hours to minutes while using only microliters of sample.

DNA separations between 10 kbp to 165.5 kbp were achieved in ordered micropost array. DNA mobility shows linear function to sizes in given post array geometry.





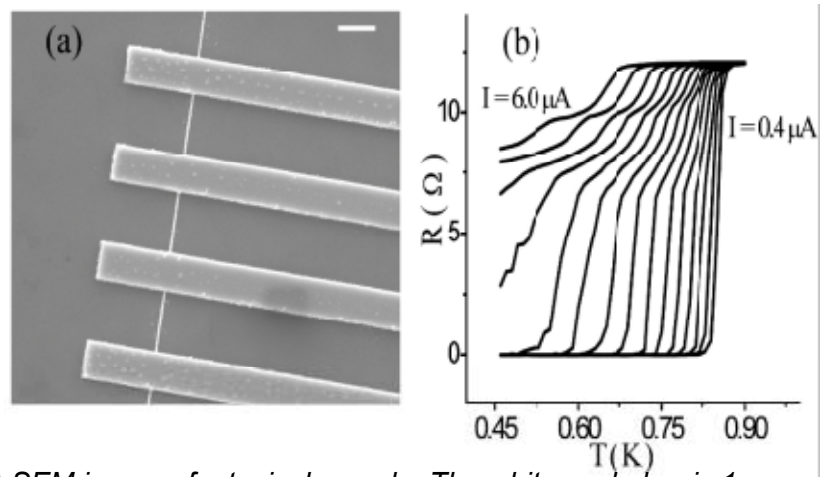
Electropherogram of XHo1 digest fragments and λ- DNA under E=10V/cm

Kevin Dorfman and Jia Ou, University of Minnesota. Work performed at the Nanofabrication Center, University of Minnesota.

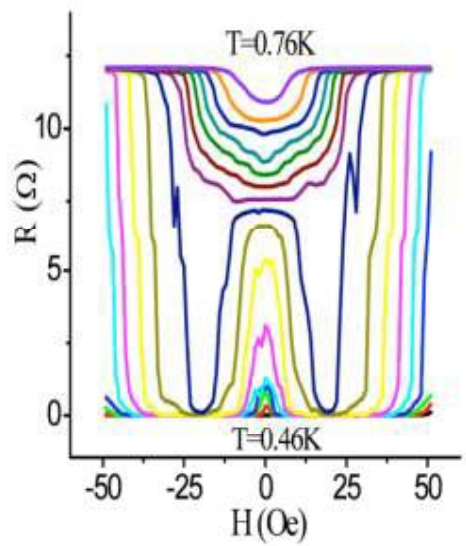
Field-Induced Re-entrant Superconductivity

This work involves the fabrication of Zinc nanowires by electron beam lithography and liftoff, the measurement of resistance as a function of current below the transition temperature of 0. 85 K, and the application of magnetic field.

Wires re-enter the superconducting state upon the application of small magnetic fields. A detailed investigation of orientation dependence of the effect leads to the conclusion that it is controlled by the effect the magnetic field has on the wide electrodes. The effect appears to be associated with the dampening of phase fluctuations by quasiparticles generated in the electrodes.



(a) SEM image of a typical sample. The white scale bar is 1 mm in length. (b) R(T) at different currents with a spacing of 0.4 mA.



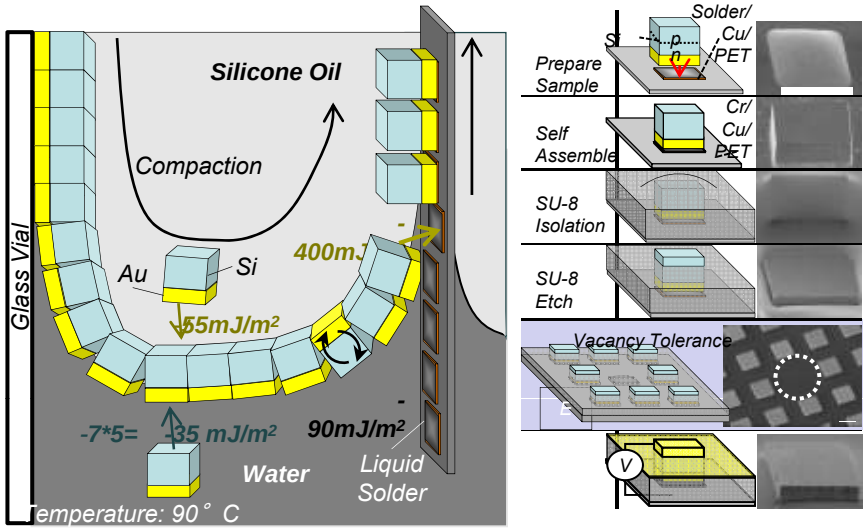
Magnetic field dependence of the wire resistance at a current of 4.4 mA with temperatures ranging from T = 0.46 K to T= 0.76 K with intervals of 0.02 K. The magnetic field is applied perpendicular to theplane of the structure.

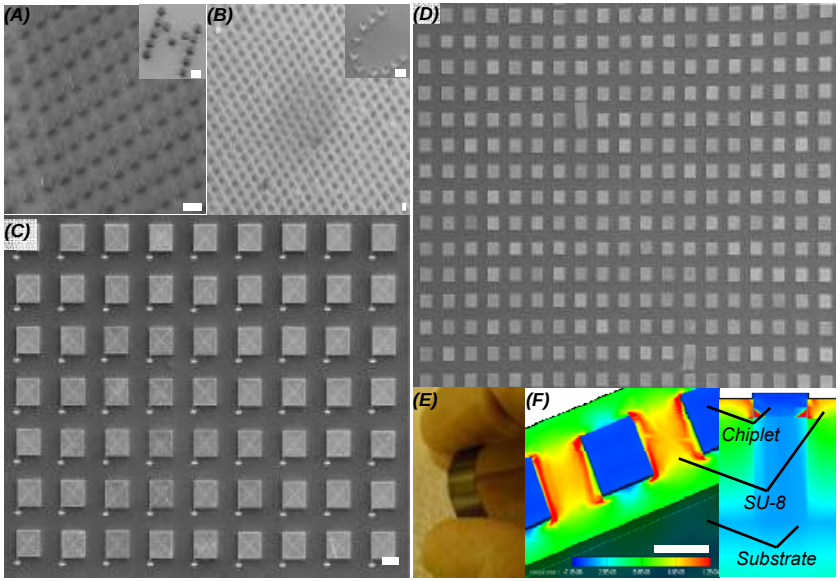
Allen Goldman, Yu Chen and Steven Snyder, University of Minnesota.
Work performed at the Nanofabrication Center, University of Minnesota.

Self-assembly of Microscopic Chiplets at a Liquid-liquid-solid Interface Forming a Flexible Segmented Monocrystalline Solar Cell

This work focuses on self assembly and integration of active semiconductor chiplets on flexible substrates. It seeks to develop an integration strategy to combine monocrystalline Si solar cells into a flexible, fault tolerant solar module.

Very small active components can be pre-oriented and assembled at arbitrary locations from a silicone oil - water interface. A flexible, monocrystalline solar cell was successfully fabricated.



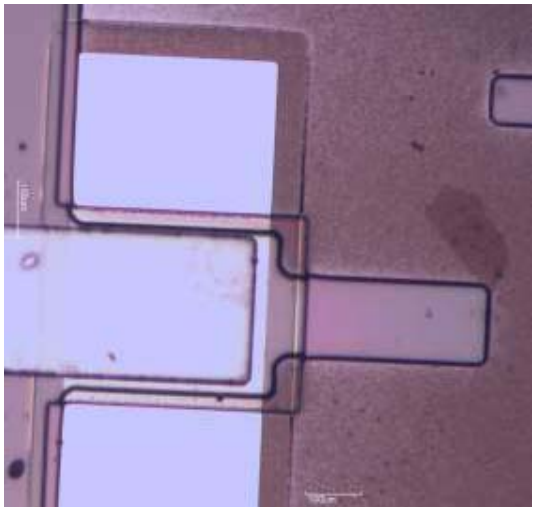


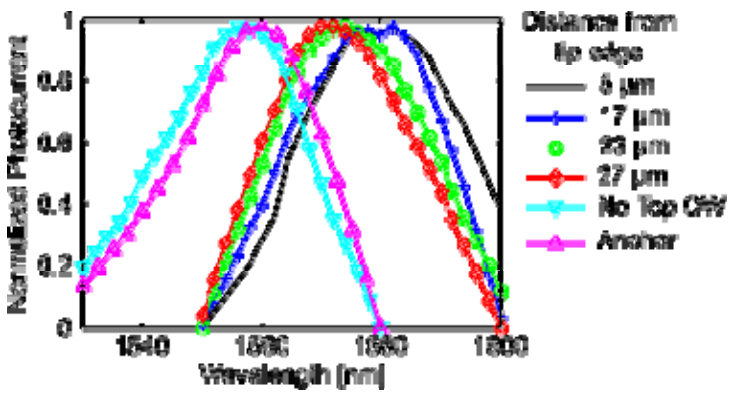
Zhihong Tang and Brian Glesson, Iowa State University and University of Pittsburgh.
Work performed at the Nanofabrication Center, University of Minnesota.

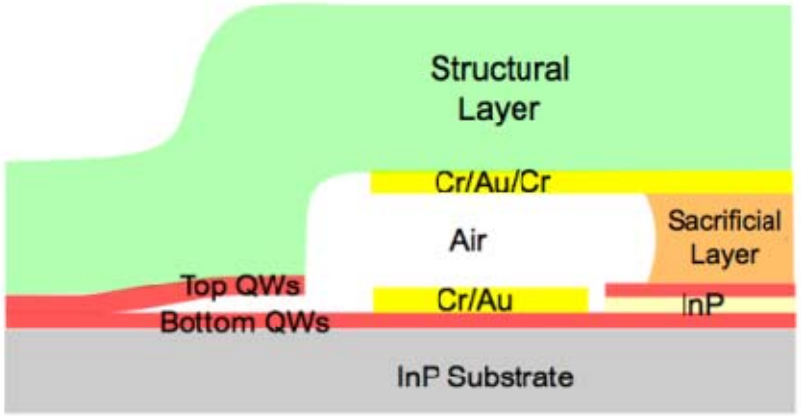
Nanomechanical Tuning of Electron States

Coupling between quantum wells can alter electron statess. The coupling strength can be changed by physically drawing quantum wells closer together. A nanomechanical actuator is being fabricated to tune the distance between two quantum wells and thereby tune the electron states.

Photoluminescence wavelength decreased as laser excitation moved from the collapsed tip of a cantilever towards the anchor. A 5-mask process is being used to fabricate the actuator.





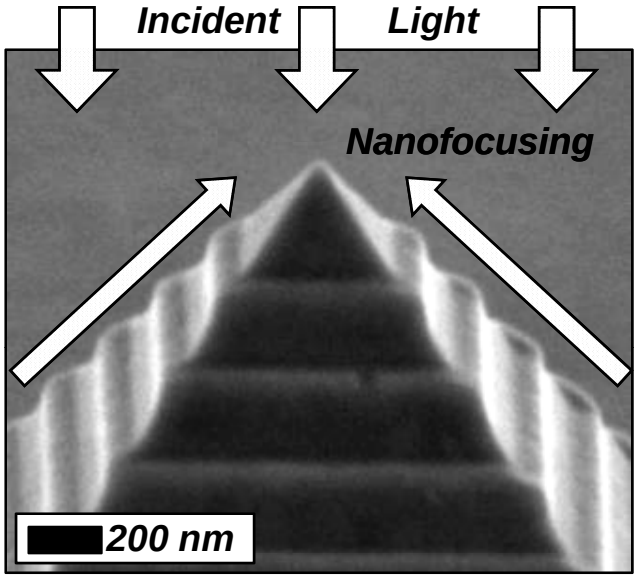


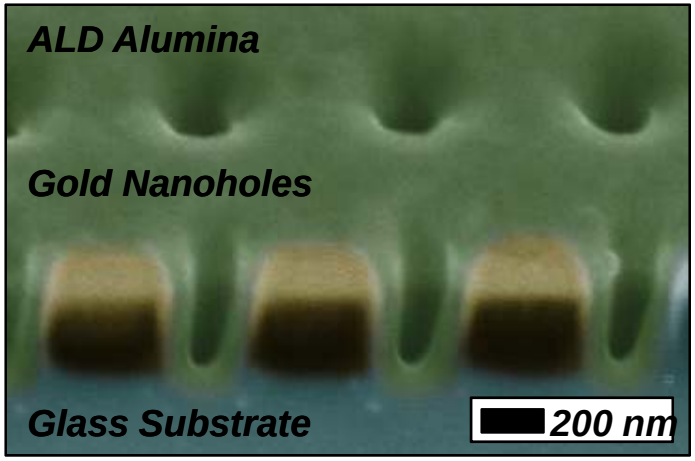
Joseph Talghader and Wing Chan, University of Minnesota.
Work performed at the Nanofabrication Center, University of Minnesota.

Plasmonic Structures for Biosensing and Nanofocusing

Surface plasmons are very sensitive to the surface properties of metals. They are also not limited by diffraction, allowing tight localization of optical energy. We are developing high-resolution sensors using novel fabrication methods.

Through template stripping for ultrasmooth surfaces, we are able to precisely control the resonances of surface plasmons using atomic layer deposition (ALD). Ultrasharp tips are obtained for nanofocusing of light.





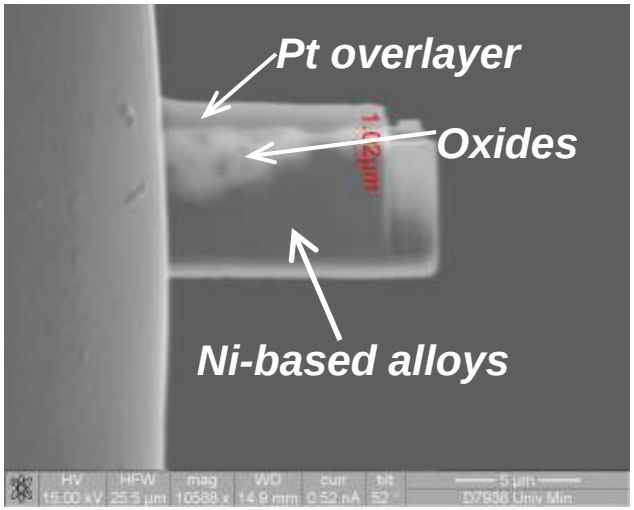
Sang-Hyun Oh and David Norris, University of Minnesota. Work performed at the Nanofabrication Center, University of Minnesota.

Preparation of Cross-sectional TEM Foils by Focused Ion Beam

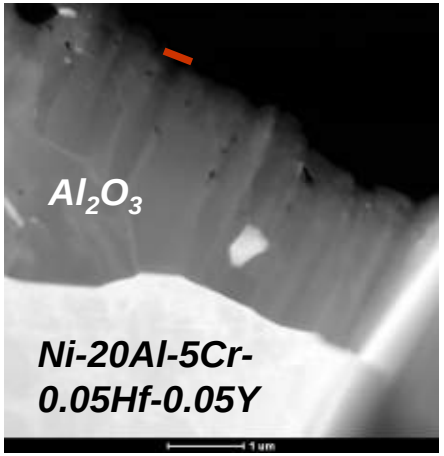
Major observations in cross-sectional TEM foils include:

Both Hf and Y segregating to Al_2O_3 grain boundaries

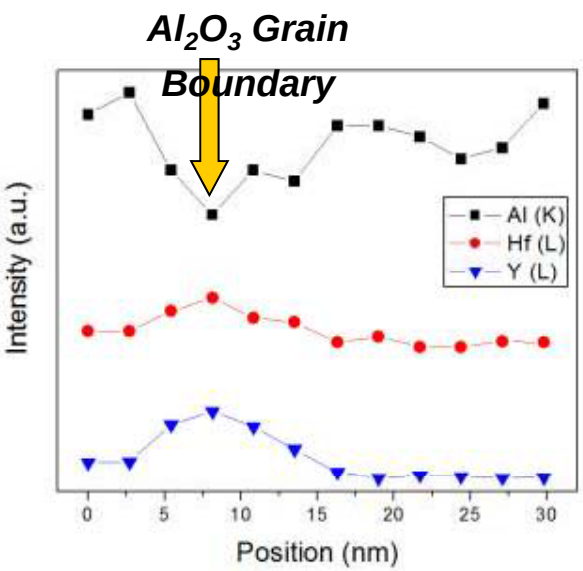
Segregation of Hf and/or Y at Al_2O_3 GB resulting in slower outward transport of Al^{+3} and slower oxidation rate.



Preparation of TEM foil for thermal grown Al2O3 on Ni-20Al-5Cr-0.05Hf-0.05Y



STEM images

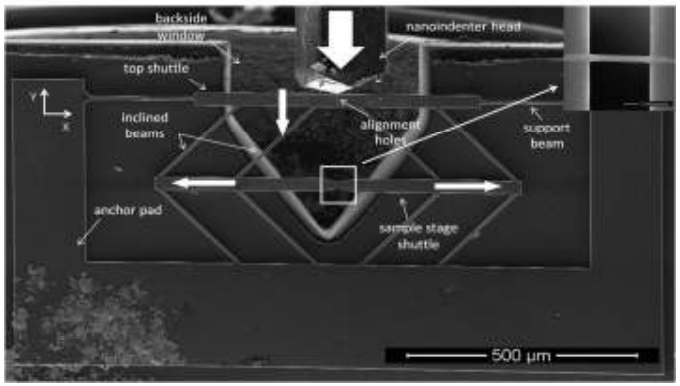


Segregation of Hf and Y at Al_2O_3 grain boundary

Zhihong Tang and Brian Glesson, Iowa State University and University of Pittsburgh.
Work performed at the Nanofabrication Center, University of Minnesota.

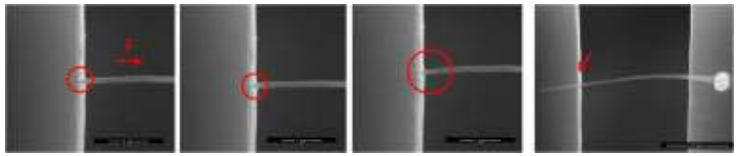
Novel Microfabricated Device for in situ Nanomaterial Testing

We have developed the design for a novel microfabricated device that can be used to perform in situ tensile and single fiber pullout experiments on nanomaterials and nanocomposites respectively within an SEM/TEM chamber. Load application (and measurement) and deformation measurement for the specimens are performed with the aid of a nanoindenter. The design converts a compressive nanoindentation force applied to a shuttle to uniaxial tension on a specimen attached to a sample stage.



SEM image of the micro-device and its components; block arrows show the direction of movement of the indenter tip and the shuttles during the experiment; (Inset) close up view of a nickel nanowire tensile specimen

Dimensions of the device are 3 mm x 2mm x 0.5 mm

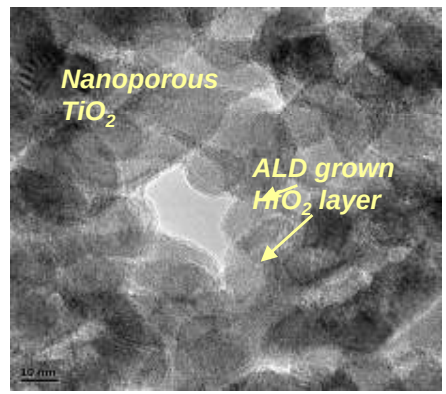


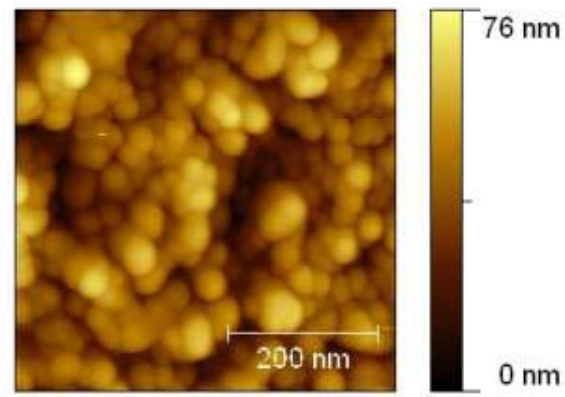
Single fiber pullout test: Multi-wall carbon nanotube gets gradually pulled out of an epoxy matrix

Jun Lou, Yogeeswaran Ganesan and Cheng Peng, Rice University.
Work performed at the Nanofabrication Center, University of Minnesota.

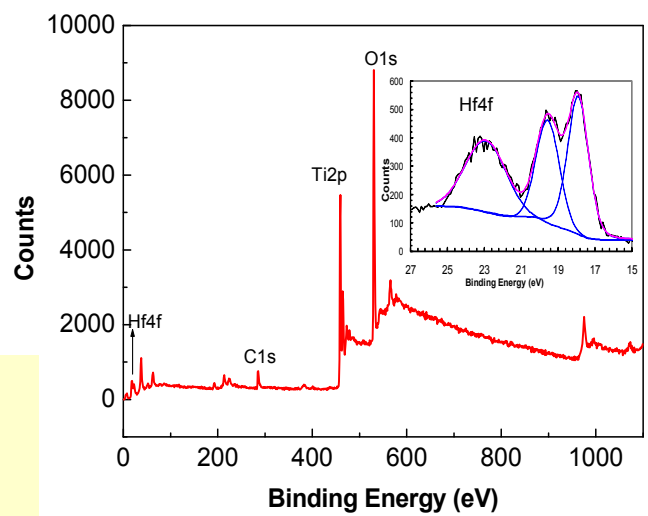
Engineering Organic-inorganic Interfaces for Dye Solar Cell Application

Ultra thin layers of hafnium oxide (HfO_2) were grown by atomic layer deposition method on the surface of nanoporous TiO_2 network to modify the density and activity of the trap states at the TiO_2/organic dye/liquid interfaces and treat the TiO_2 surface in dye solar cell (DSC). We also assess the effect of ALD oxides on the performance of DSCs.





Conformal growth of ultra thin metal oxides was obtained deep inside the nanoporous TiO_2 network. Multiple DSCs were made using ultra thin metal oxides as the interfacial layer at TiO_2/dye/electrolyte interface. A significant efficiency enhancement (E) was observed for DSCs treated with HfO_2 layers grown by 5 ALD cycles.

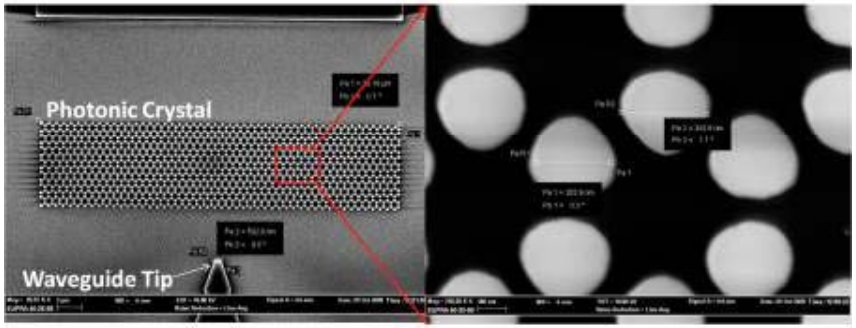


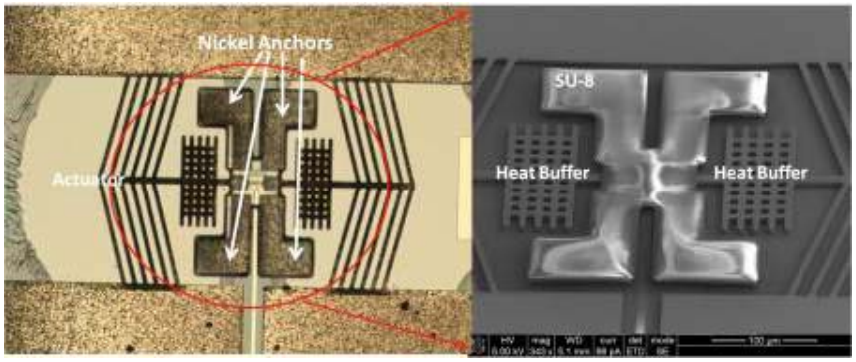
M. Farrokh Baroughi, M. Shanmugam and B. Bills, South Dakota State University.
Work performed at the Nanofabrication Center, University of Minnesota.

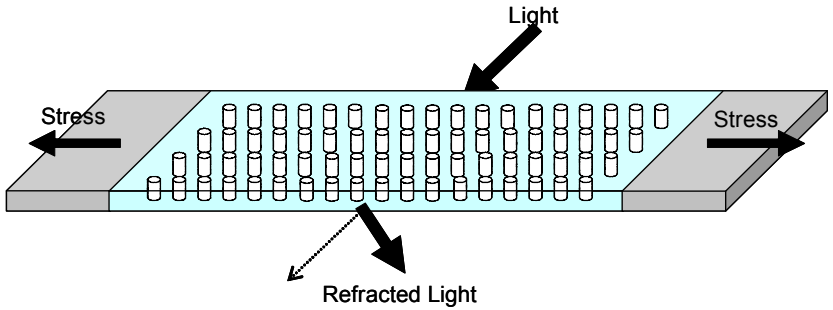
Mechanically Tunable Photonic Crystal

A new pathway to tunable photonic devices allowing much greater tunability than conventional electro-optic tuning. These devices combine nanophotonics technology with MEMS for greatly expanded applications for photonic crystal devices.

We observed negative index imaging in a silicon based photonic crystal structures and experimentally demonstrated tuning of negative index imaging by mechanical stress.





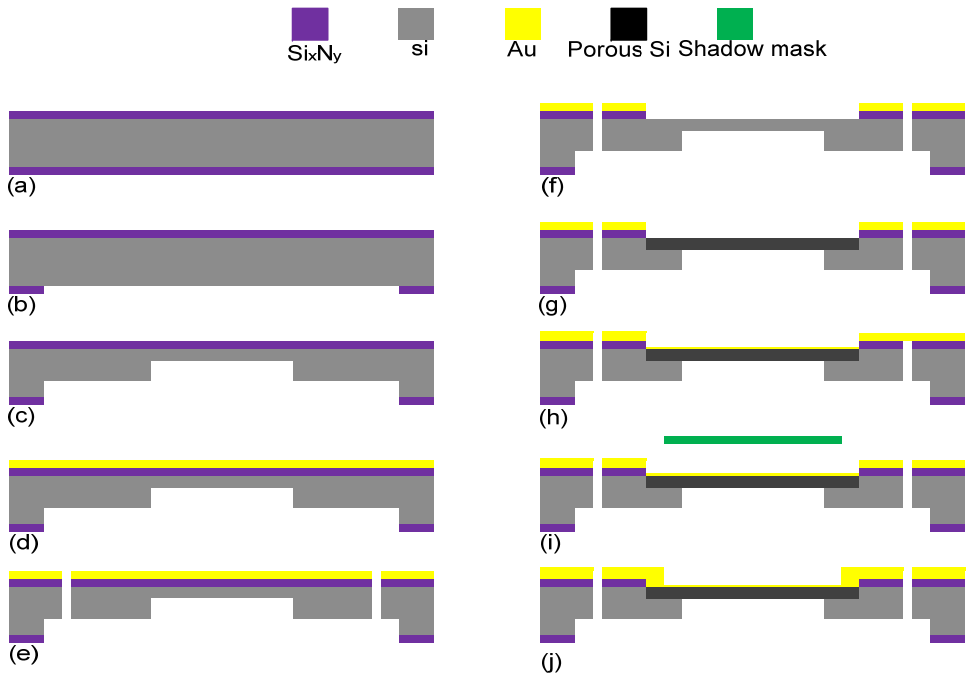


Wounjhang Park, University of Colorado. Work performed at the Nanofabrication Center, University of Minnesota.

Electrochemical Multiphase Microsensor for Detection of Organophosphates

We are working to develop an electrochemical microsensor to detect organophosphate (OP) compounds. The detection mechanism is based on the reaction of a hydroxamic acid with OP to yield cyanide ions that can be detected electrochemically. COMSOL simulation shows submicron holes etched in silicon gives the most sensitive sensor response. Here, we attempt to fabricate porous silicon with nanometer holes as gas-liquid interface.

By tuning HF concentration, wafer properties, time, and potential, the porous silicon nanopores would be achieved as a gas-liquid interface layer. The figure at right shows the schematic of the fabrication steps.



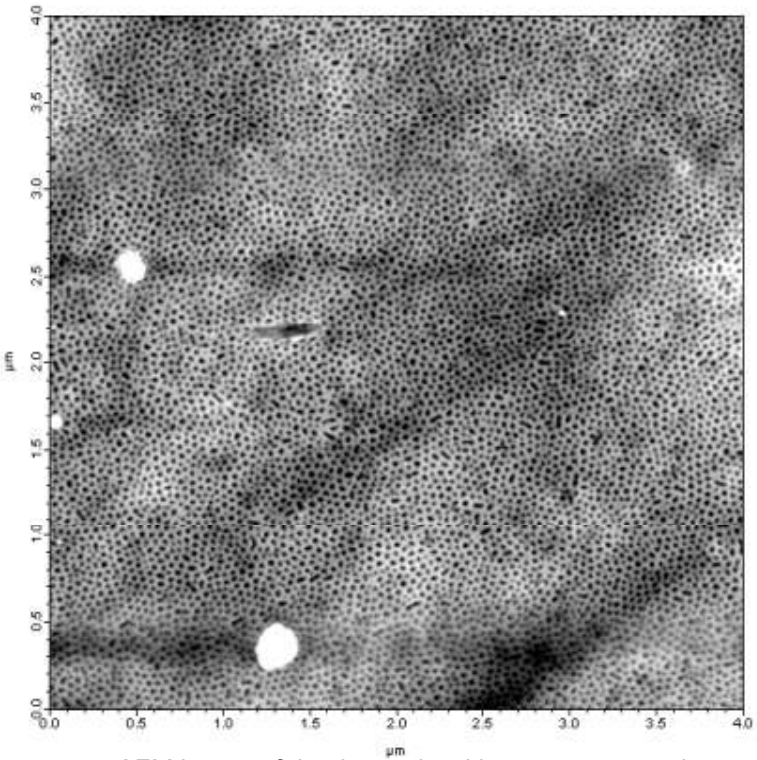
R. Masel, M. Sayyah, A. Salehi-Khojin, K.Y. Lin, University of Illinois at Urbana-Champaign.
Work performed at the Nanofabrication Center, University of Minnesota.

Nanoroughness for Osteoblast Enhancement

This work is inspired by literature observations of enhanced osteoblast growth and adhesion on surfaces with nanoscale topography. This topography is typically achieved through non-templated acid etching and is largely random in feature shape and distribution. The long-term goal of this work is the improved adhesion and growth of osteoblasts on medical implant surfaces.

Observing the grain boundaries of resulting mineral depositions, it is speculated that a 60 nm spacing would be optimum for templating this deposition.

Ion milling is used to etch titanium coins, both bare or masked with a nano-structured block-copolymer, creating nanoscale topographies on a typical implant material. Cell culture trials on these coins are currently underway.



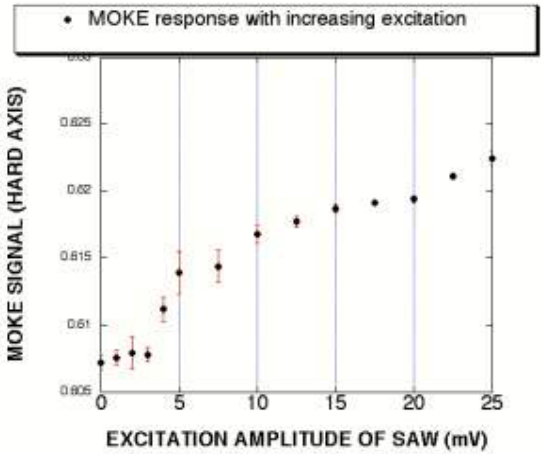
AFM image of titanium coin with nano-structured block copolymer template spin-coated on surface.

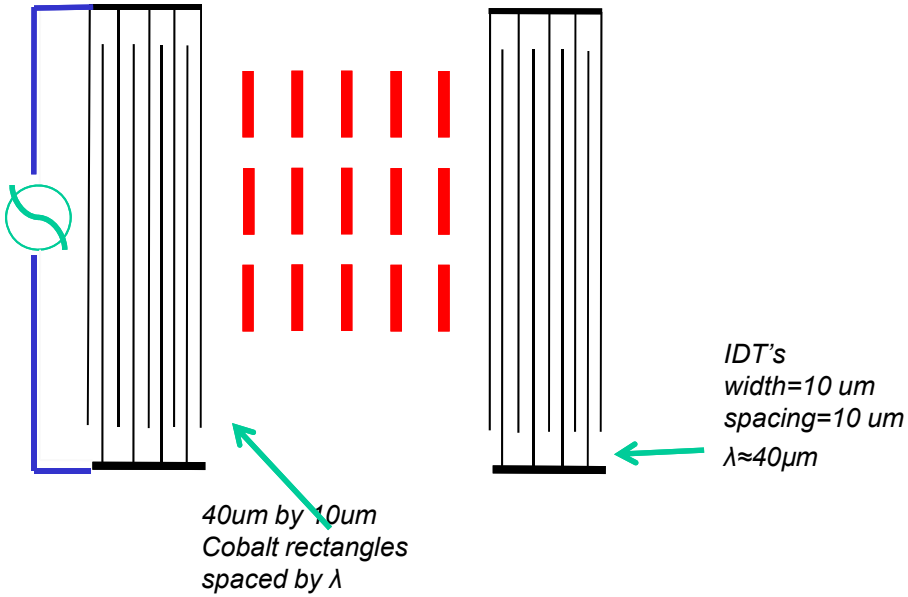
Eric Nuxoll, University of Iowa.
Work performed at the Nanofabrication Center, University of Minnesota.

Surface Acoustic Wave Induced Magnetic Switching

We look at the dynamics of magnetic switching at short time scales. To do this we create a strain wave by applying an RF voltage to an Inter-digital transducer patterned on a piezoelectric substrate [$LiNbO_3$]. This strain wave causes magnetization in patterned cobalt bars to rapidly switch direction from the geometric long to short axis at frequencies of up to ≈642 MHz.

We observe a distinct turn on point for the onset of magnetic switching at 4 mV followed by a saturation of magnetic signal at ≈45mV.

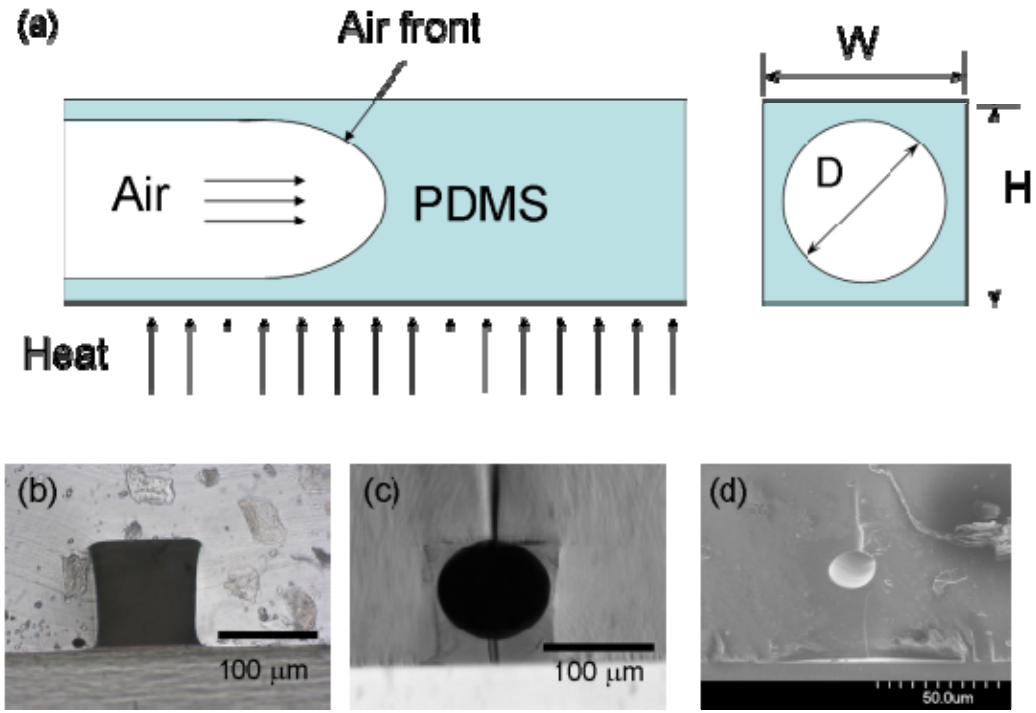




Shireen Adenwalla and Sam Davis, University of Nebraska, Lincoln.
Work performed at the Nanofabrication Center, University of Minnesota.

Fabrication of Circular Microchannels in Polydimethylsiloxand (PDMS)

We have developed a new technique to make circular microchannels very quickly and simply. We can produce microchannels 5mm to 500 mm in diameter. Potential applications include cell culture inside microchannels to mimic the microvasculature and cell trapping for single cell analysis.



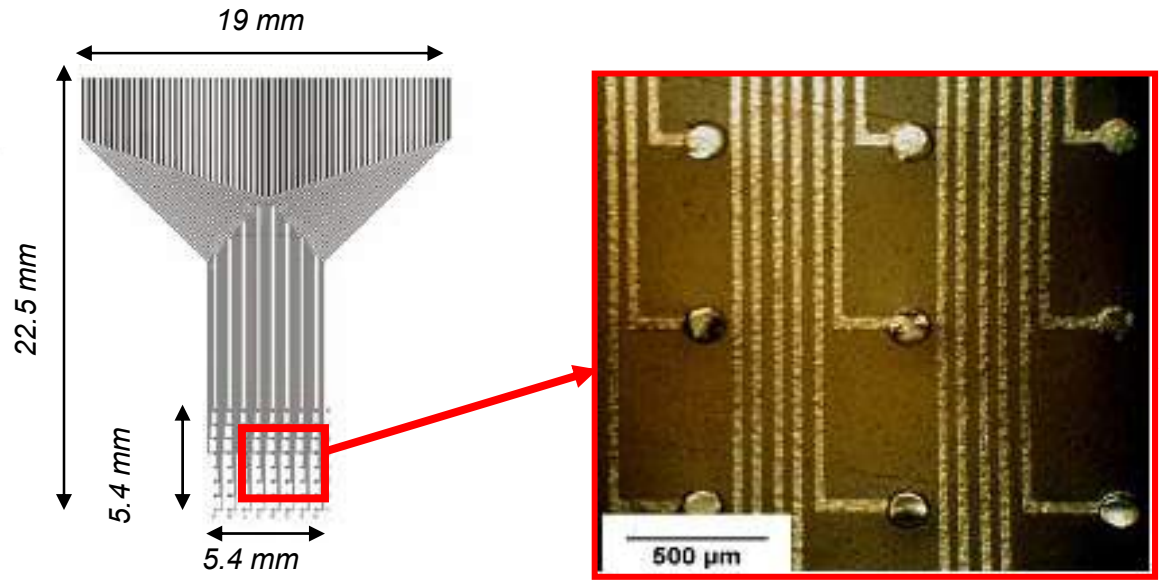
(a) Schematic of the coating process. (b) & (c) Picture of a 100 mm × 100 mm microchannel before and after coating, respectively. (d) Picture of a 100 mm × 100 mm channel after coating it three times. The resulting microchannel is 31 mm in diameter.

Y. Sun and M. Abdelgawad, University of Toronto.
Work performed at the Nanofabrication Center, University of Minnesota.

Development of Flexible Electrodes for Cortical Recording in Rats

Our work involved the fabrication of a mask used for developing gold on kapton flexible electrode to implant between the skull and dura in rats for recording electrical activity in the brain during whisker activity in the rat.

The mask was successfully fabricated at University of Minnesota's Nanofabrication Center. Adhesion testing and subsequent implantation was successful and the array was used for over one year.



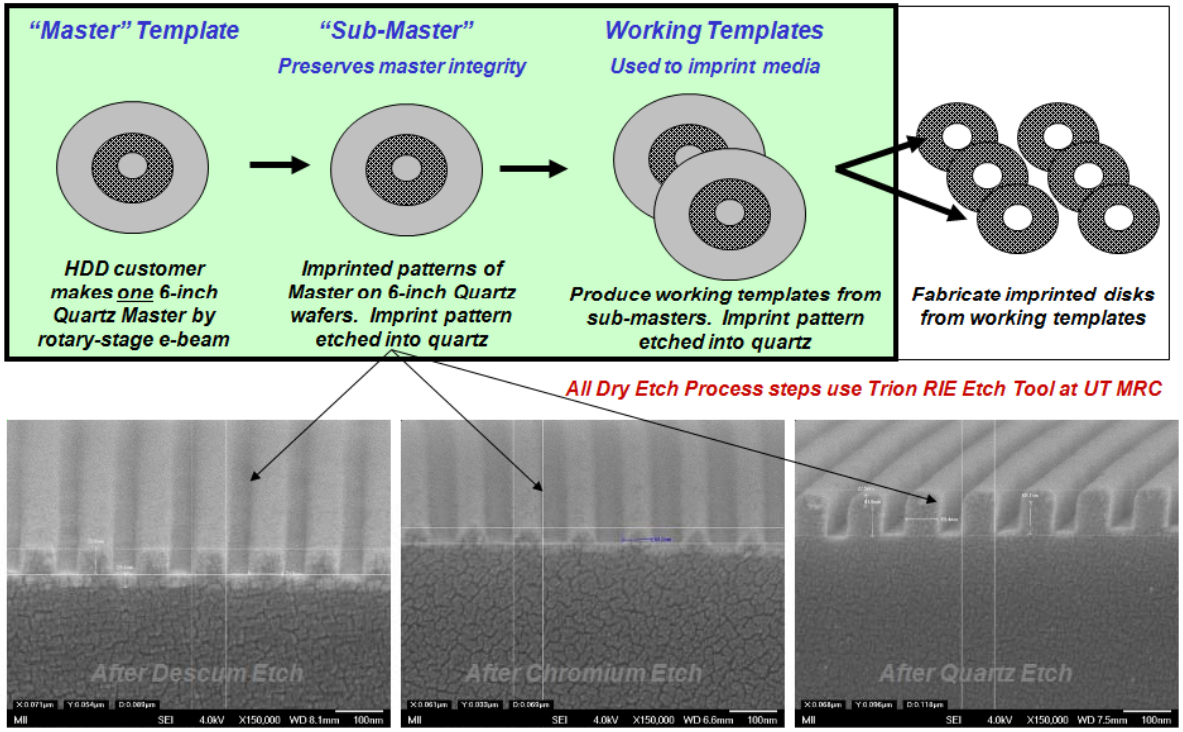
David Bahr, David Rector, Yoonkap Kim and John Yeager, Washington State University.
Work performed at the Nanofabrication Center, University of Minnesota.

University of Texas

Template Replication for Hard Disk Drive Industry

The ever-growing demand for hard drives with greater storage density has motivated a technology shift from continuous magnetic media to patterned media hard disks, which are expected to be implemented in future generations of hard disk drives to provide data storage at densities exceeding 10^{12} bits/in^2.

Step and flash imprint lithography (S-FIL) technology has been employed to pattern the hard disk substrates. Template Replication Method for SFIL-mediated imprinting of disks is demonstrated with substrate throughput currently as high as 180 disks/h (dual sided). These processes are applied to hard disk substrates with both discrete tracks and bit-patterned designs.

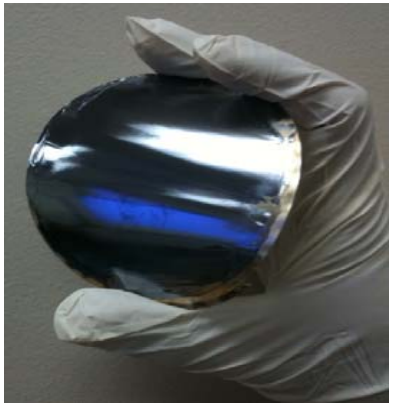


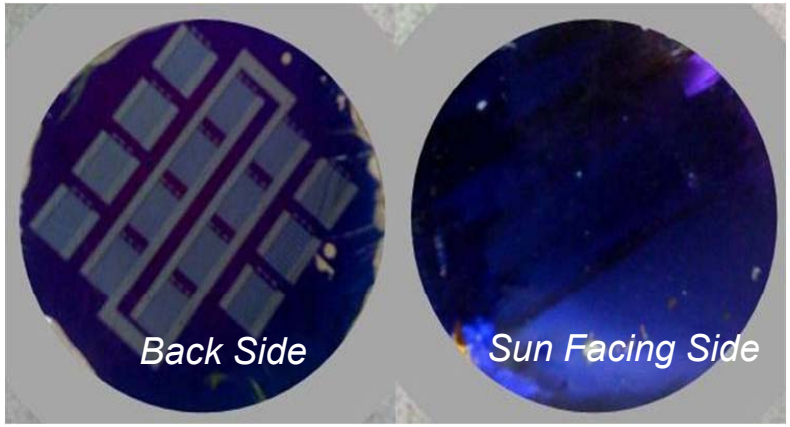
S.V. Sreenivasan, C. Brooks, DJ Resnick, Molecular Imprints™
Work performed at Microelectronics Research Center Facility at Univ. of Texas

Thin Crystalline Silicon Solar Cells

Crystalline Silicon Solar cells comprise the largest segment of the PV market. Using optimal silicon thickness can reduce costs substantially and enable new applications due to flexibility of thin crystalline silicon.

A novel cost-effective process has been developed to make flexible 30um crystalline silicon wafers. This technology has also been demonstrated for other substrates such as Germanium and GaAs. Back-contact and hetero-junction solar cells have been fabricated on these foils. The cells can be mounted flat or with curvature.





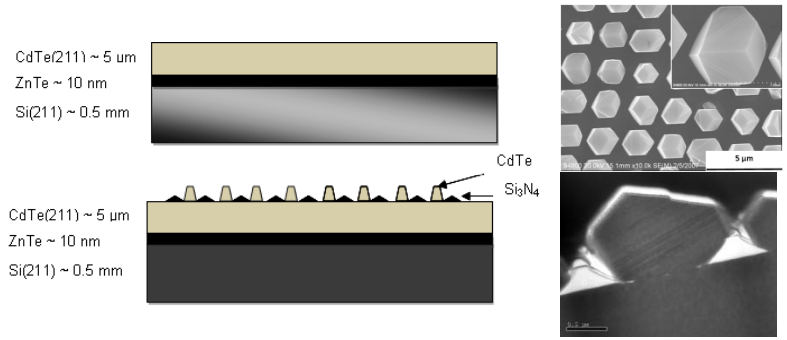
***1**. Flexible Crystalline Silicon foils. **2.** Heterojunction Solar cells using thin crystalline silicon. **3**. 30um crystalline silicon Back Contact solar cells*

Leo Matthew, Dharmesh Jawarani; AstroWatt Inc
Work performed at Microelectronics Research Center Facility of The University of Texas

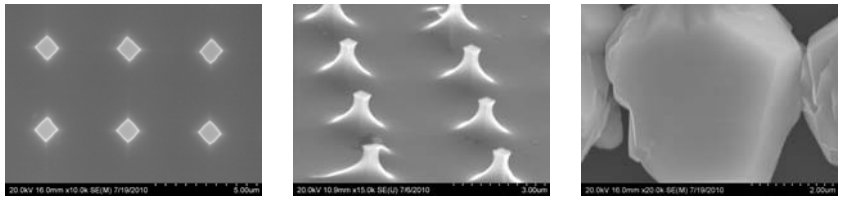
Selective CdTe Single Crystal Deposition with High-Areal Density

CdZnTe bulk material is commonly used as a substrate for the growth of HgCdTe, the most prominent material used for infrared detector applications. Although excellent HgCdTe material has been demonstrated using bulk CdZnTe substrates, the size and production requirements for future FPAs has led to an increased interest in using composite Si substrates for HgCdTe growth.

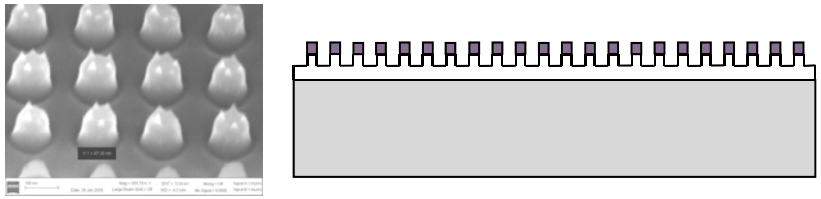
Advances in the technology associated with epitaxial CdTe film growth on Si(211) substrates have produced HgCdTe films with dislocation densities between 10^5 - $10^6/cm^2$, which are acceptable for optoelectronics applications, but are too high for long-wavelength infrared performance. Nanoheteroepitaxy is being explored as a method to grow low defect CdTe regions for subsequent HgCdTe growth. It is expected that defects will be minimized for selective growth at the nanoscale as a result of dislocation migration to the side walls and/or localization at the interface. Imprint Lithography was exploited to create a large areal-density template for single-crystal pillars.



1 µm CdTe Crystal on CdTe/ZnTe/Si(211) Window: *CdTe deposited by close-spaced sublimation (CSS) on MBE grown CdTe. Si(211) wafer patterned by optical lithography using Si_3N_4 as a mask.*



500 nm - 1 µm CdTe Crystal on Si(100): *CdTe deposited by CSS on Si pillars. Si(100) wafer patterned by optical lithography. CdTe deposited preferentially on Si pillars without use of a mask.*



100 nm CdTe Crystal on SOI: *CdTe to be deposited on Si pillars. SOI wafer patterned using Imprio 100 Nano-Imprint Lithography*

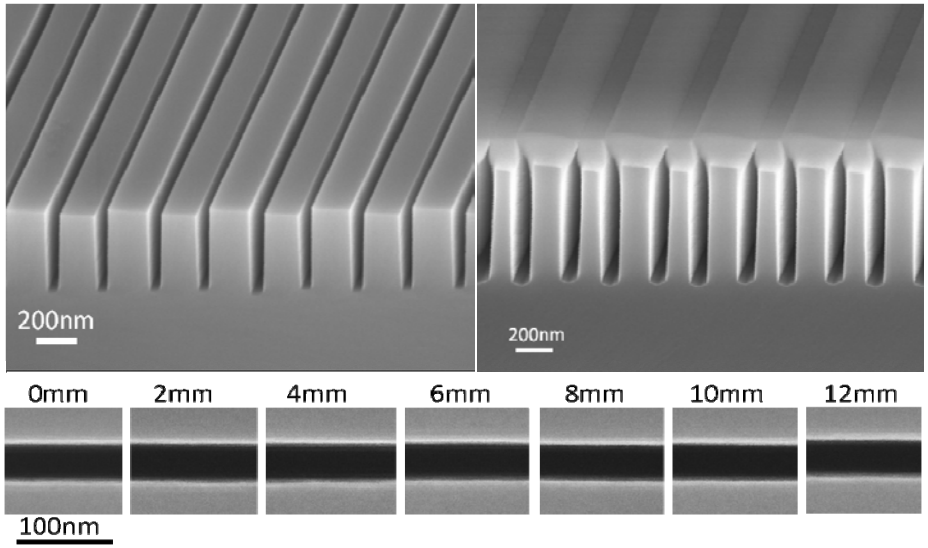
Stella Quiñones, The University of Texas at El Paso, Electrical and Computer Engineering

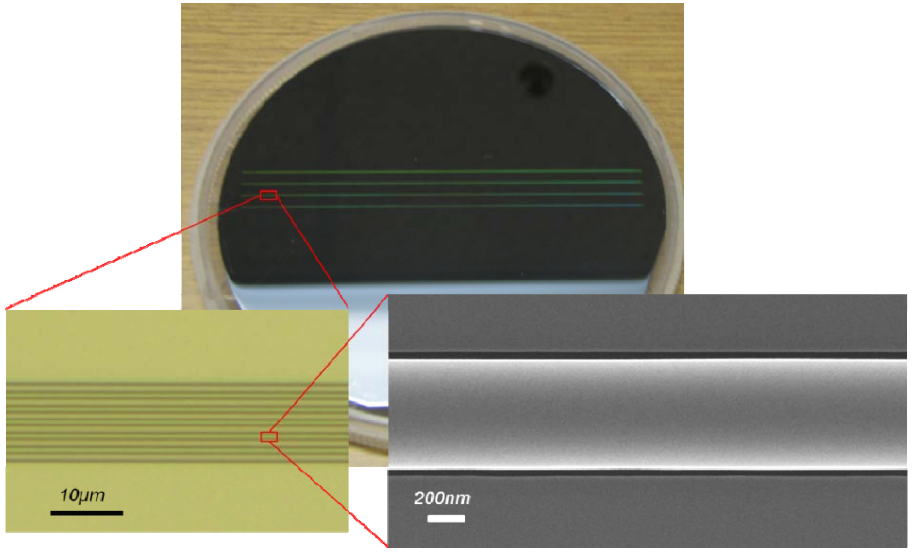
Work performed at Microelectronics Research Center in UT-Austin, TX and The University of Texas at El Paso

Self-Aligned Sub-lithographic Nanochannels

Nanochannels have wide applications in bio analysis, molecule separation, drug delivery *etc.*.

At MRC of UT-Austin, we developed a highly reliable self-aligned sub-lithographic masking method to fabricate silicon nanochannels. This method is applicable to standard optical lithography. Due to the wet anisotropic etching of silicon, the nanochannels have ideal rectangular shape. The atomically smooth sidewalls provide extremely uniform surface properties. The channel width can be tightly controlled within 2nm. With this method, arrays of 9cm-long nanochannels have been demonstrated.





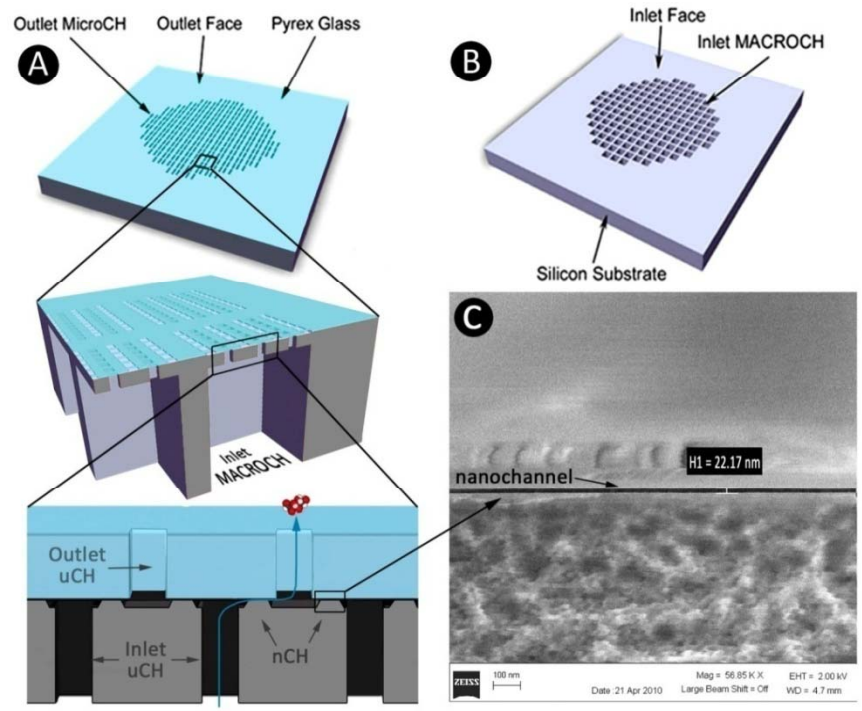
Zhuojie Wu and Paul S Ho,
Microelectronics Research Center (MRC) at The University of Texas at Austin

Nanochannel Delivery System (nDS)

A Solid-State mechanically robust nanofluidic membrane with tunable zero-order release for implantable dose specific drug delivery has been fabricated. Current capabilities allow continuous release of 100 µg/day of Leuprolide.

Components of research performed at MRC at UT-Austin, CNF at Cornell University, CNS at Harvard University, SNF at Stanford University, in addition to several non-NNIN facilities

(A,B) Schematic representations of a nanoscale delivery system (nDS) membrane.



(C) Scanning Electron Micrograph of the nanochannel outlet of the nDS. Imaged obtained by fracturing an nDS membrane using a mechanical clamp.

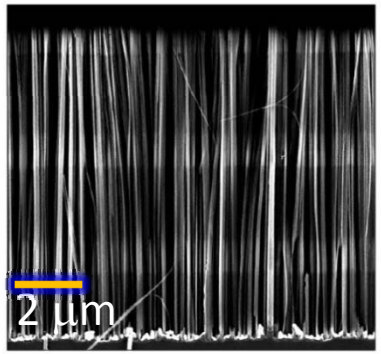
Daniel Fine, Alessandro Grattoni, Sharath Hosali, Arturas Ziemys, Enrica De Rosa, Jaskaran Gill, Ryan Medema, Lee Hudson, Milos Kojic, Miljan Milosevic, Louis Brousseau, III, Randy Goodall, Mauro Ferrari, Xuewu Liu; *The University of Texas Health Science Center.* Work achieved at *Microelectronics Research Center (MRC) at The University of Texas at Austin (UT-Austin)*

Porous Silicon Nanowires as Nanobarcodes

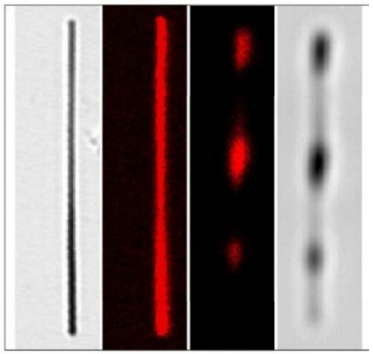
Vertically-aligned nanowires were synthesized by metal assisted electroless etch. Segments with different porosity along nanowire axis were revealed. Tunable photoluminescence and color was confirmed for different geometries and dimensions.

Nanowires can load nanoparticles to engineer functionality. Their biodegradable nature enables applications for drug delivery and biolabeling. Applications for resorbable electronics are also envisioned for these nanostructures. These nanowires display a shallow volume, which also permits role as nanoneedle.

Nanobarcodes



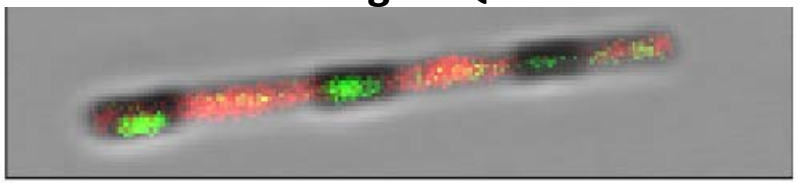
Photoluminescence



Segment-specific porosity

Reflection

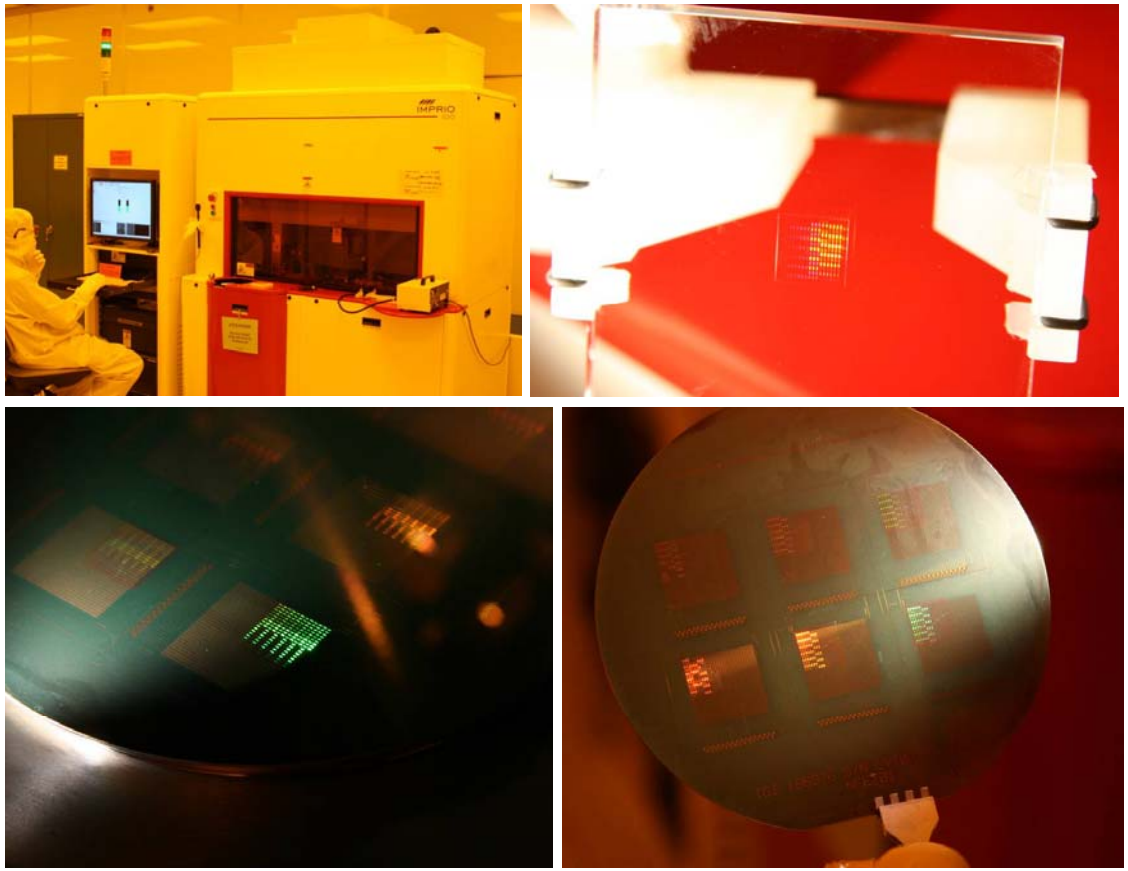
Differential loading of Q-dots



C. Chiappini, X. Liu, J.R. Fakhoury, M. Ferrari, The University of Texas Health Science Center.
Realized at Microelectronics Research Center (MRC) at The University of Texas at Austin

Molecular Imprinting of Semiconductor Nanotracers

Step-and-Flash Imprint Lithograohy has been exploited for the fabrication of semiconducting nanotracers for use in direct electrical detection of target reagents. Targets include both solution nucleic acids, where the target hybridizes with complementary sequences coupled to the nanotrace surface. As well as direct detection of volatile organic compounds (VOC) for multiplex vapor signature identification applications. High-throuput, reliable and atomic sized nanotraces can pinpoint different molecules and medicines.

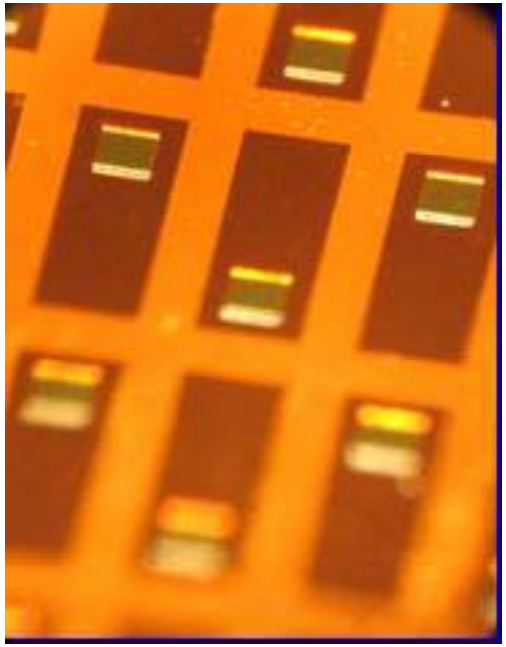


Imprint lithography at the MRC. A template is used to imprint a pattern on electrode arrays with registration at the nanoscale

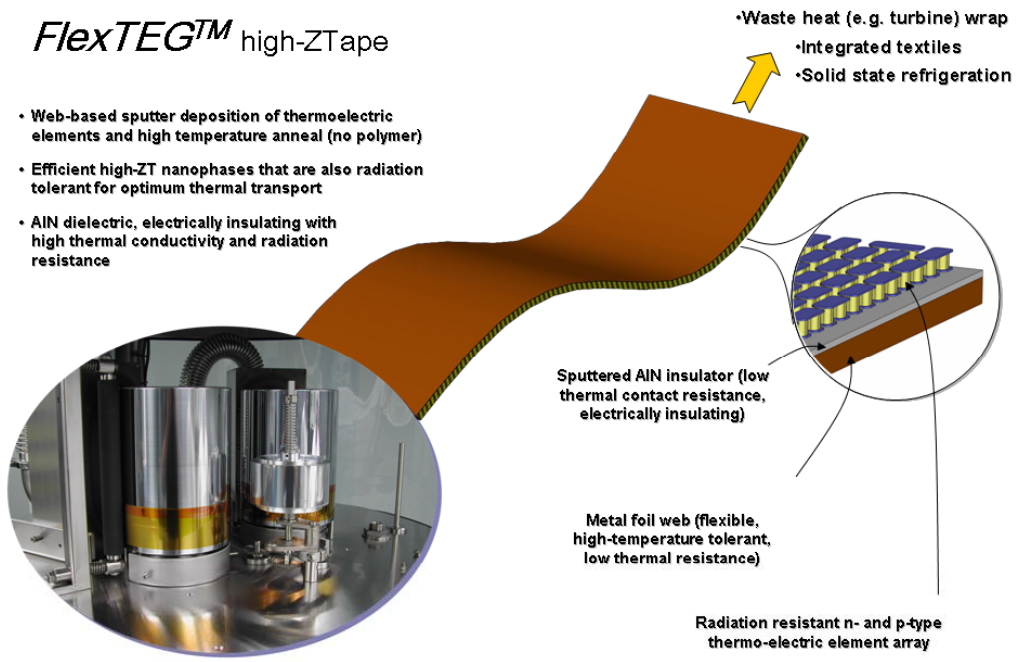
Steve Savoy and Jeremy John,
Nanohmnics, Inc.

Fabrication performed at University of Texas at Austin Microelectronics Research Center

MicroThermoElectric Devices



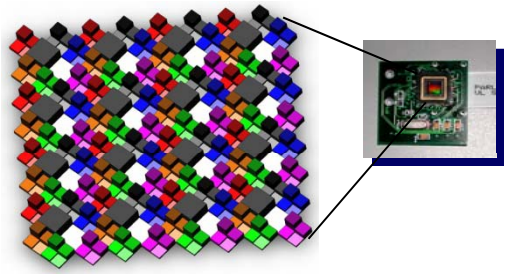
Bi_2Te_3 filled cavity molds



The unique lithographic processing capabiltiies of the MRC enabled the fabrication of a mold for patterning flexible thermoelectric cooler devices composed of a consolidated nanophase microdice. Solid state heating or cooling devices that can be made more efficient by virtue of increasing the thermoelectric Figure of Merit hold promise in small device heat dissipation (detectors, microchips) as well as larger scale heat recovery process (thermoelectric generators).

Steve Savoy- Nanohmnics, Inc. Kevin Stokes- University of New Orleans
Rhonda Willigan- United Technologies. Work performed at University of Texas at Austin Microelectronics Research Center.

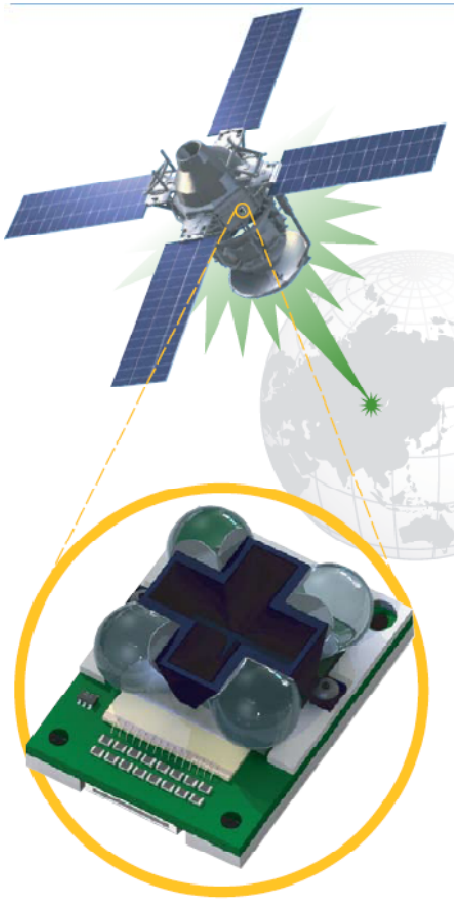
Laser Threat Assessment



Expanded color filter mosaic schematic. Two methods are employed t o make the filter including lithography and nucleic-directed immobilization

An expanded color filter mosaic was developed to enable broader spectroscopic definition on image sensors and to detect wider threat spectral range and enhanced background rejection (e.g. a Laser Warning Mosaic (LWM) from visible to near-IR). Defense systems benefit from this high-sensitivity sensor fabricated using Imprint Lithography.

Argus Laser Threat Assessment System



Argus™ is a sophisticated laser threat warning and assessment system with state-of-the-art electro-optical and signal processing capability. The Argus™ laser threat assessment system detects visible and near-infrared laser radiation over a hemispherical field-of-view and provides measurements of angle-of-arrival, wavelength, and irradiance. The system consists of a compact optical detector module connected to a controller card. Applications include satellite situational awareness, and laser threat discrimination and detection for aircraft, vehicles, and individuals.

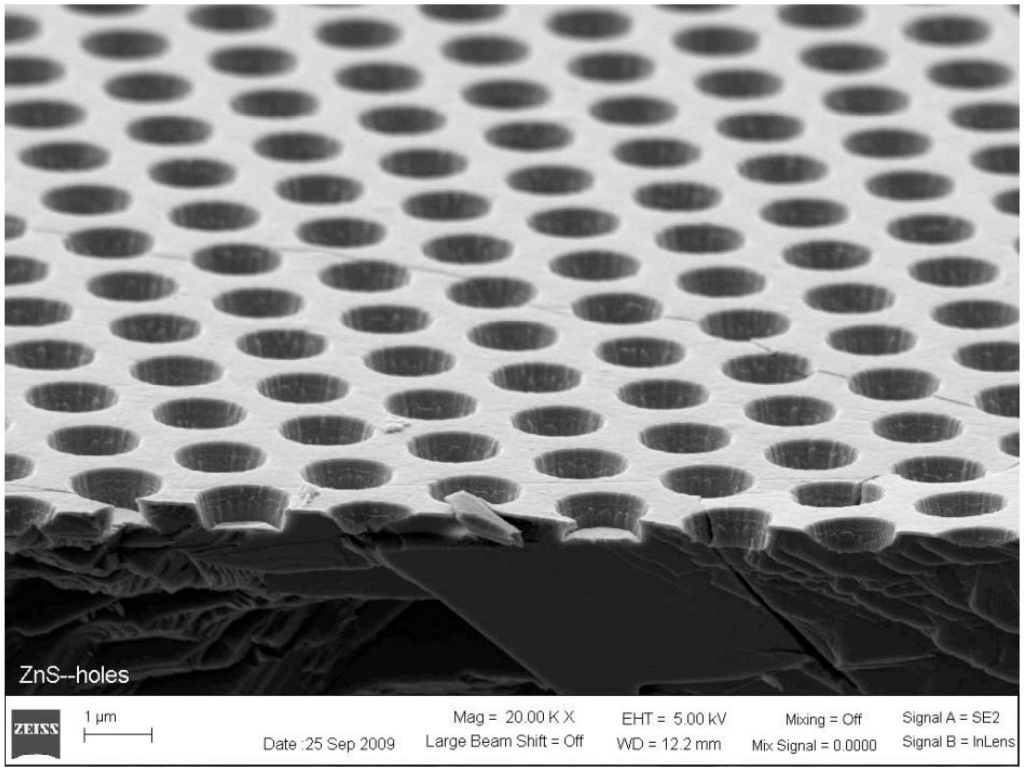
Key Features

- Unique optical system collects light over full hemisphere
- Threat radiation is focused onto an image sensor, spot position related to angle-of-arrival
- Transmission through custom color filter array determines wavelength, provides a means for rejection of broadband sources
- Controller card collects and assesses laser threat information, provides simple messages to host
- Low battery power consumption and thermal dissipation compatible with micro-satellite applications
- Simple serial interface for command and communication with host
- Provides space assets with ability to monitor, assess, and report laser irradiation

Steve Savoy, Byron Zollars, and Dan Mitchell- Nanohmnics, Inc.
Work performed at University of Texas at Austin Microelectronics Research Center.

Hyperspectral Infrared (IR) Windows

New methods and materials to coat zinc sulfide windows based on thermal evaporation were designed and successfully tested. Such Zn_2S windows serve as primary protection for sensitive multi-band electro-optic instrumentation or sensors in aerospace platforms. It is critical in most of these applications that the hyperspectral window resist erosion from raindrops and dust encountered during flight, and that spectral transmittance is not degraded as a result. Zinc sulfide windows have poor erosion resistance and so a protective coating is required for applications where impact with sand, dust, or raindrops is anticipated. Nanohmic's work has been creating and characterizing a patterned surface for windows that reduces optical reflections, in addition to providing enhanced protection from rain and sand erosion.

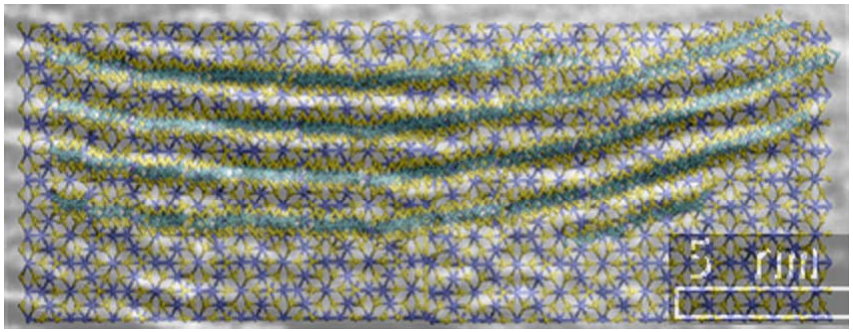


SEM micrograph showing zinc sulfide windows patterned by Imprint Lithography.

Steve Savoy, Byron Zollars, Nanohmnics, Inc.
Work performed at University of Texas at Austin Microelectronics Research Center as outside member

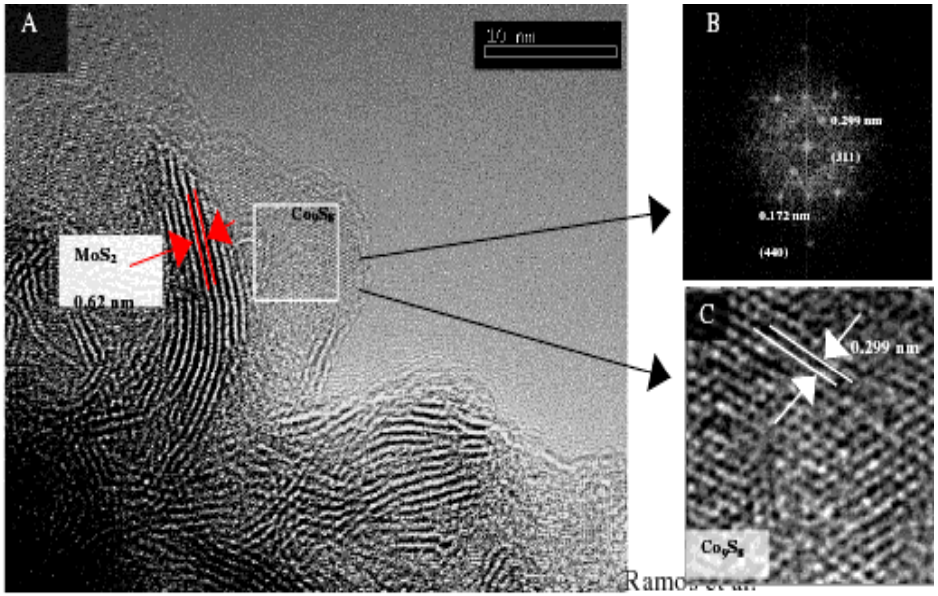
Mapping Co Promoters in MoS_2 Catalytic Nanostructure Material

The goal of this study is to understand catalysis promoters location when MoS_2 is combined with Co_9S_8. This promoter location will determine the structure/function relationship of catalytically active materials. It is known that MoS_2-Co has a strong catalytic activity specially when used on Hydrodesulphurization reaction for sulfur removal in crude oil.



Molecular model of MoS_2 growth on Co_9S_8 (111) to depict TEM images and prove hypothesis.

Manuel Ramos, Brenda Torres, Russell R. Chianelli
The Materials Research and Technology Institute of Univ. of Texas El Paso.
Gilles Berhault
IRCELYON, University of Lyon France
Work performed at University of Texas at Austin, MRC

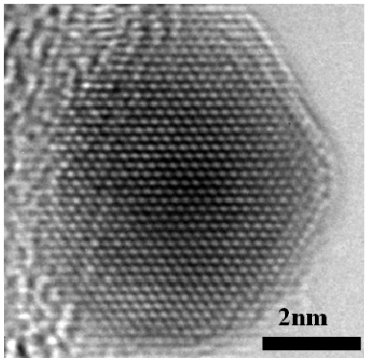


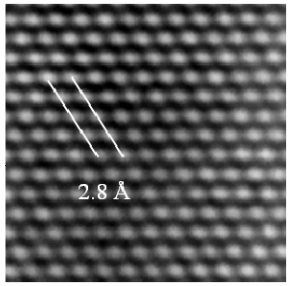
MoS_2 characteristic of fringes at 0.62nm, from TEM images one can observe the epitaxial contact with Co_9S_8 (111) principal plane.

On the Structure of “star-shaped” Au Nanoparticles

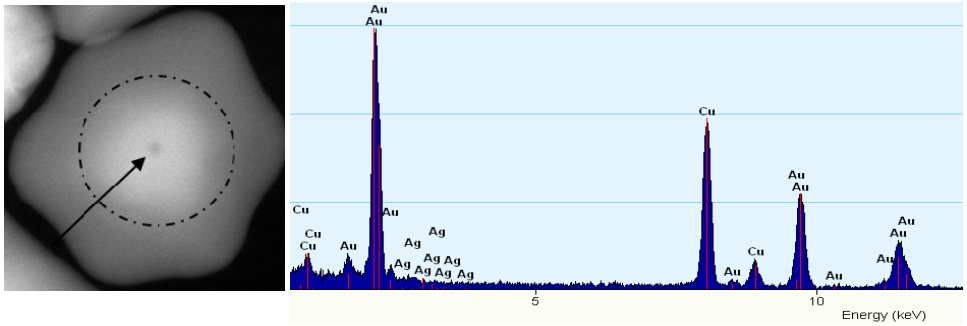
Depending on size, shape, composition and internal distribution, materials can exhibit a huge range of different properties and therefore a wide range of applications can be exploited. Gold reflects particularly well this effect as when it is in its bulk form it behaves as an inert metal; however, it becomes very reactive when it is manipulated at a very small size.
Au nanoparticles have been successfully employed for cancer detection and treatment among other applications related to their unique optical properties. In the present work ‘star-shaped’ Au nanoparticles have been synthesized by the seed mediated technique using silver as a starting point and CTAB as capping agent.

The nanostructures were fully characterized by different advanced electron microscopy techniques. These gold stars can be functionalized for selective attachment on cancer cells for early-detection and localized therapy.

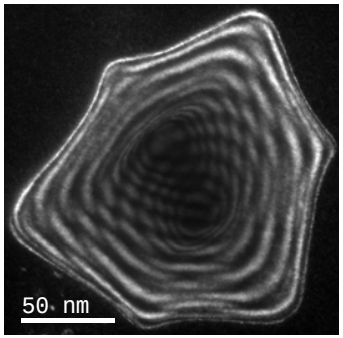




High resolution TEM image of the Ag seeds



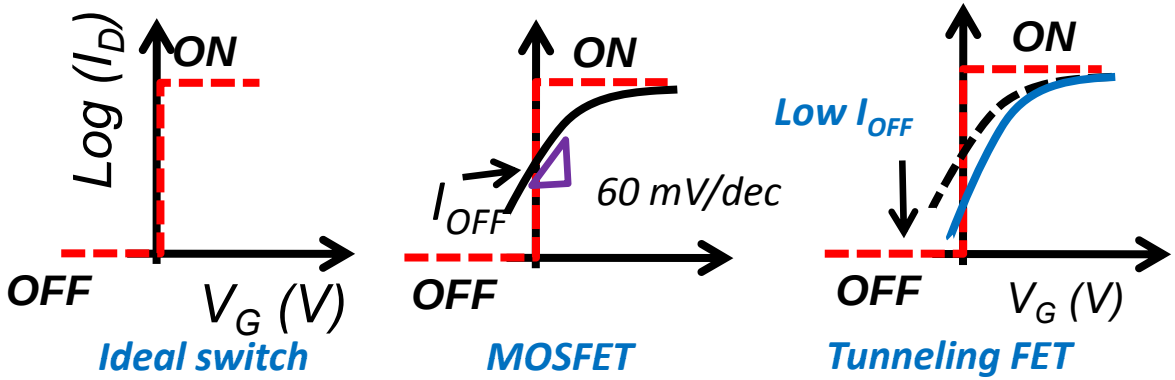
STEM-HAADF image of a Au nanoparticle with the Ag seed pointed by an arrow together with the EDX analysis



Weak beam dark field image (WBDF) of a Au nanostar.

Alvaro Mayoral and Miguel Jose-Yacaman; The University of Texas at San Antonio (UTSA). Work performed at Microelectronics Research Center of The University of Texas at Austin.

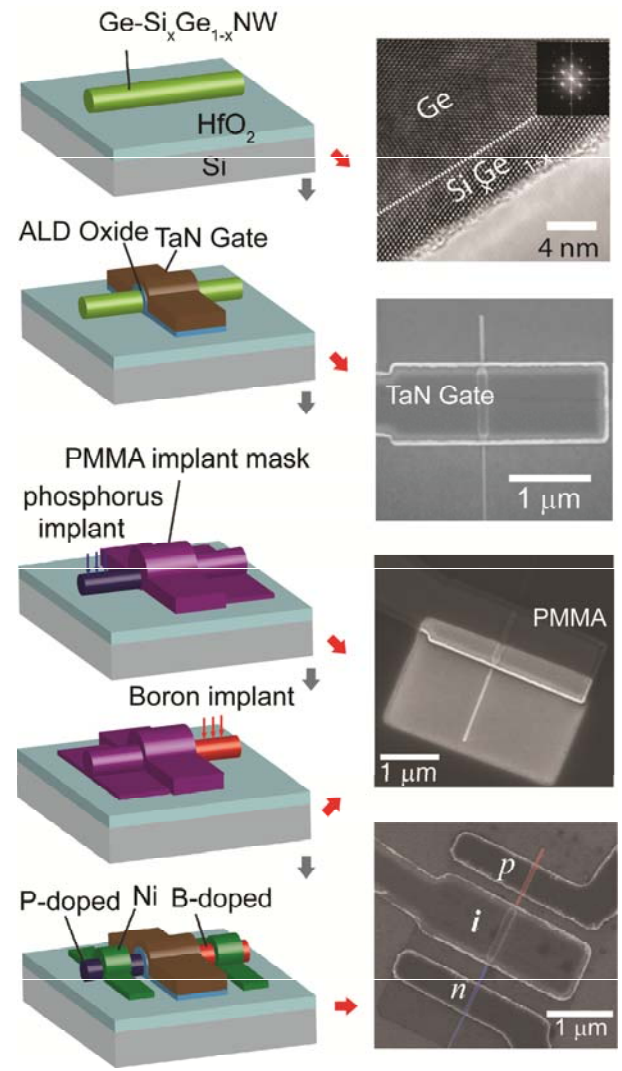
Tunneling Field-effect Transistors for Low-power Electronics



Ideal switch should be turn on/off steeply and completely turned off at standby mode. However, metal-oxide-semiconductor field-effect transistors can only be turned on/off with a minimum slope of 60 mV/dec due to fundamental physical limit and dissipates the energy even at standby mode. Tunneling field effect transistors have a potential to operate as close as an ideal switch, such that steep turn on/off as well as low off-state current can be achieved. Therefore, TFETs have a potential as low power consumption electronic devices.

Using germanium nanowires, GeNW TFETs are fabricated using atomic layer deposition, e-beam lithography, ion implant, rapid thermal process, and metal deposition process.

J. Nah, K. Varahramyan, S.K. Banerjee and E. Tutuc;
Univ. of Texas. Work performed at UT-Austin Microelectronics Research Center

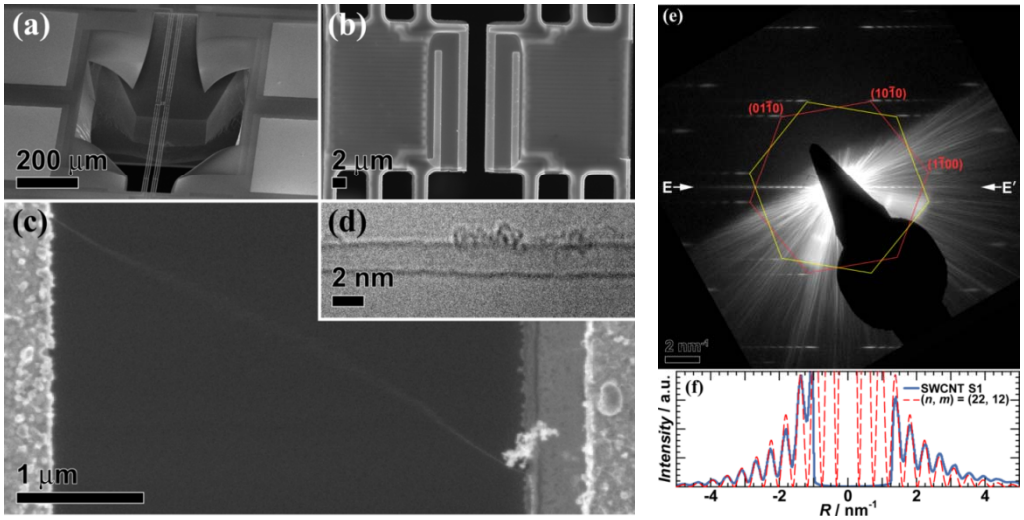


Fabrication of a germanium nanowire tunneling field-effect transistor

Structure-Thermal Relationships of Carbon Nanotubes

In CNTs, high axial thermal conductivity and electron mobility is expected for defect-free nanotubes, as long-range crystalinity along the axial direction and negligible boundary scattering in unconstrained nanotubes allow heat and charge carriers to flow with ease.

We have been able to demonstrate a capability for establishing the structure-thermal property relationship of different types of individual CNTs using a suspended microthermometer device fabricated at MRC to allow for a fundamental understanding of thermal transport processes in these materials.



Pettes, M.T., and Shi, L., *Adv. Funct. Mater.* **19**, 3918 (2009).

- Defect concentration appears to increase with number of walls
- Thermal contact resistance per unit length obtained for three as-grown multi-walled carbon nanotubes (MWCNTs) is in the range of 78 – 585 mKW^{-1} at room temperature
- Intrinsic thermal conductivity for three MWCNTs is in the range of 42 – 343 $Wm^{-1}K^{-1}$; the calculated phonon mean free path correlates well with the TEM observed defect concentration
- Large thermal contact resistance limits effective κ for as-grown SW and DW CNTs to ~ 600 $Wm^{-1}K^{-1}$ at room temperature

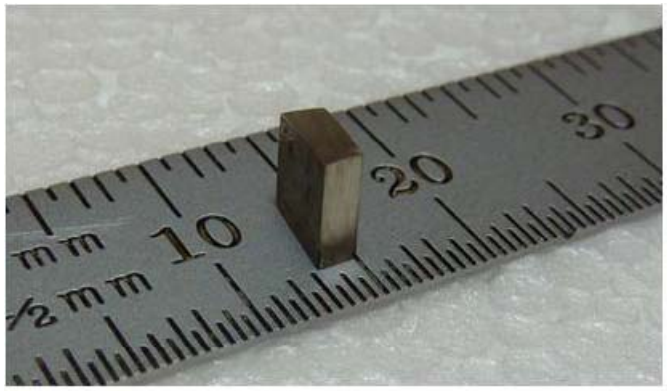
(a) SEM image of the suspended micro-device for thermal conductance measurements of carbon nanotubes. (b) SEM image of the two central membranes of the micro-device. (c) SEM and (d) transmission electron microscopy (TEM) image of SWCNT sample S1 bridging the two membranes. (e) Nanoarea Electron Diffraction pattern for S1 The diameter and chiral angle are determined to be 2.33 ± 0.02 nm and 20.44 ± 0.2°, respectively. (f) Equatorial oscillations (solid line) along EE' in (e) and calculation (dashed line) for a (22, 12) SWCNT are in good agreement.

M. Pettes, Li Shi. Univ. of Texas.
Work performed at U. Texas Austin MRC

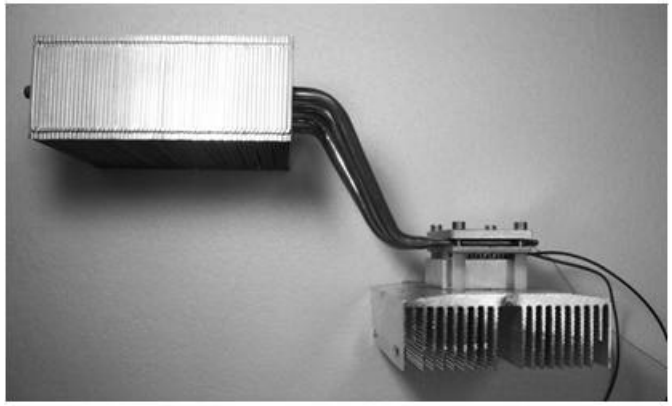
NEAT Energy Converters

The goal of our research is to realize high-efficiency electronic energy converters that exploit nonequilibrium transport effects and energy selective tunneling at semiconductor-metal interfaces. These NEAT devices are an enhanced version of thin film thermoelectric coolers, and will be incorporated in the cooling engines designed by Sheetak for compact refrigerator and air-conditioner OEMs in US and India. The NEAT project has been recently selected for funding by the ARPA-E for improving air conditioners in buildings and homes.

We use advanced PVD and CVD methods to deposit bismuth chalcogenides and fabricate cooler elements with phonon-blocking tunneling layers that reduce the thermal conductance without affecting the electronic conduction processes.



Consolidated thin film thermoelement of Sheetak's energy converter



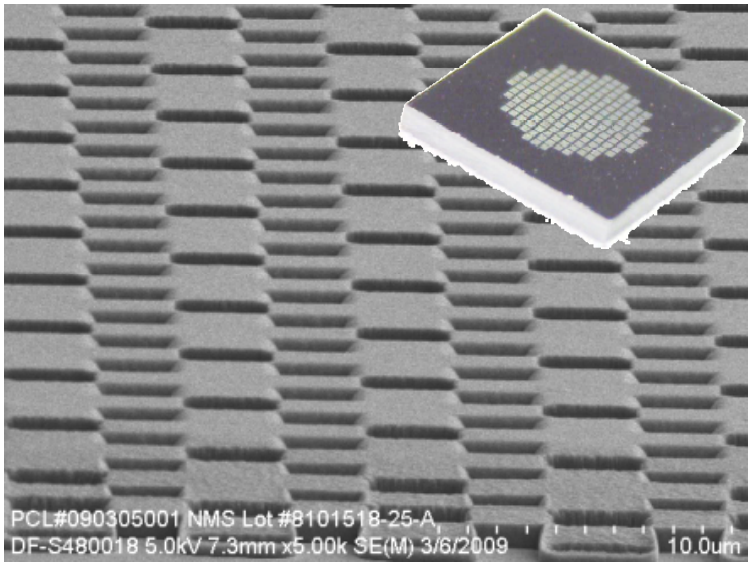
Sheetak's solid-state cooling engine for refrigerators

Uttam Ghoshal, Ayan Guha, and Anthony Stautzenberger,
Sheetak Inc.
NNIN facility at MRC, University of Texas at Austin

Personalized Molecular Drug-delivery System

Many existing/new therapeutics are limited by effects related to delivery. A family of small implantable drug delivery devices called nanochannel delivery system (nDs) have been created for slow release of therapeutic agents from a reservoir over a period of months. These micron-sized platforms adapt to wide variety of drug/application configurations. Constant and controlled delivery rate is set by advanced silicon semiconductor processing technologies.

Our nDS tools are embodied on a silicon chip that regulates the diffusion of therapeutic molecules from the implant. The use of extensive and novel cleans procedures were needed to reduce the number of defective devices.

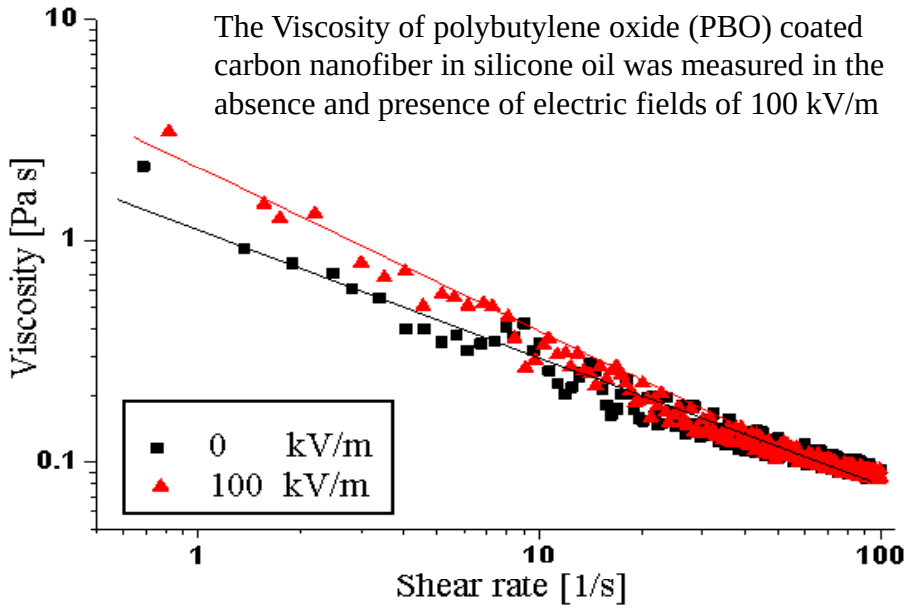


SEM micrograph of solid-state drug delivery system. Inset sketches the high-areal density of the pattern.

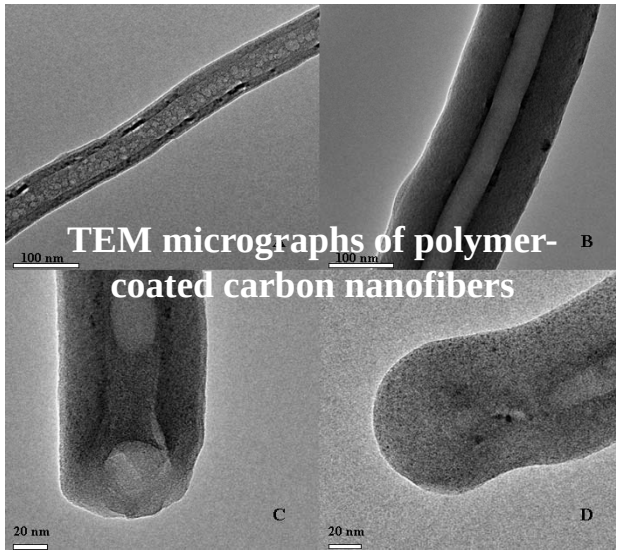
Theresa Mathews, Nanomedical Systems. Performed at MRC/NNIN Univ. of Texas for 2 years and 2 current users.

Carbon Nanofiber-mediated Electrorheology

These experiments involved the synthesis and characterization of polybutylene oxide-grafted carbon nanofibers for electrorheological applications. This project possesses a strategic technological importance owing to the designed electrorheological fluids could potentially be used in flexible electronics for portable devices with electronic circuits of conformable shapes. Carbon nanofibers (CNFs) were coated with polymers such as polybutylene oxide (PBO) for enhanced viscosity. Bare CNFs showed short circuit at very low applied electric field. Outstanding electrorheological response was demonstrated for PBO-coated CNFs.



The Viscosity of polybutylene oxide (PBO) coated carbon nanofiber in silicone oil was measured in the absence and presence of electric fields of 100 kV/m



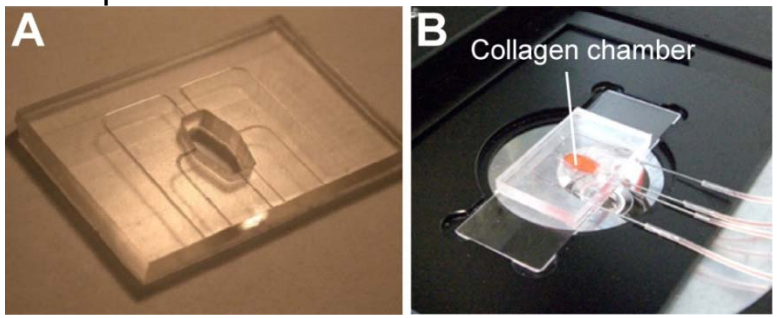
TEM micrographs of polymer-coated carbon nanofibers

Karen Lozano, University of Texas Pan American, Edinburg, TX
Work achieved at *Microelectronics Research Center (MRC) at The* University *of Texas at Austin (UT-Austin)*

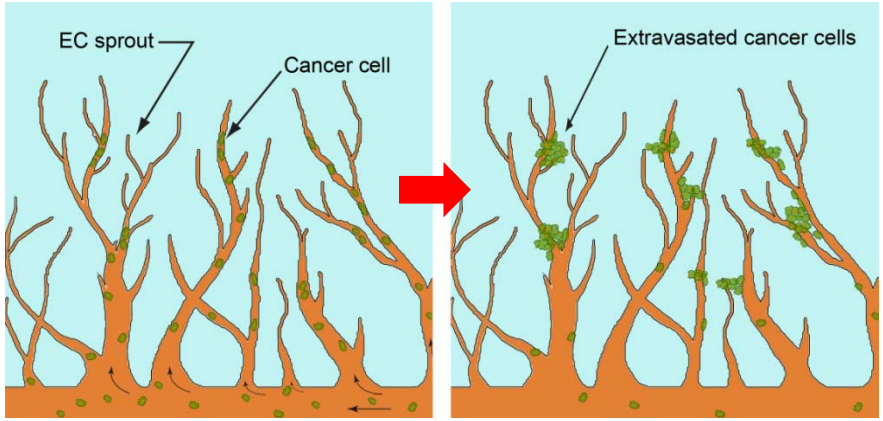
Univ. of Washington

Vascularized In-Vitro Model of the Tumor Microenvironment

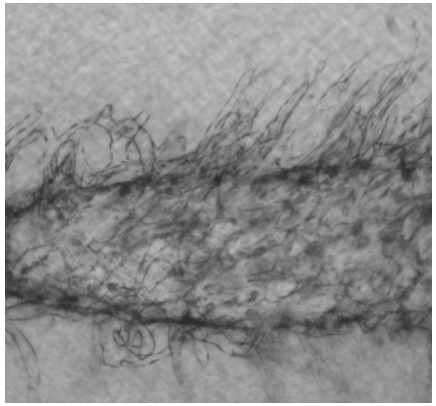
The focus of this work funded in the past by NIH R21 and currently by NIH SBIR phase I grants is the development and optimization of an In-Vitro Angiogenesis System, which includes growing of perfusable humanized artificial capillary-like microvessel networks in a 3-D extracellular matrix. Currently we are expanding this method to develop a model to study cancer cell invasion (extravasation) in vitro, one of the key phenomena in tumor metastasis. Understanding of the cellular and molecular events underlying cancer cell extravasation is critical to development of successful treatments.



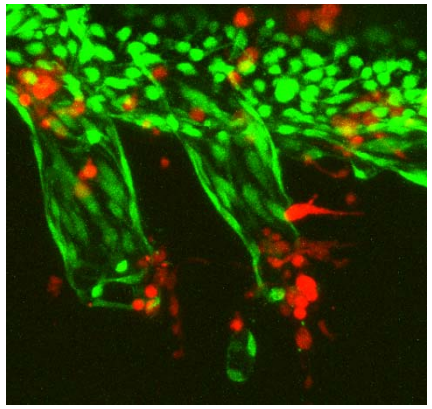
Microfluidic devices for creating microvessels. *(A) Photograph of a molded PDMS device for angiogenesis studies, (B) Assembled angiogenesis device on a microscope tray.*



Tumor cell extravasation. *(A) In this schematic drawing, tumor cells (green) have entered the blood stream (i.e., intravasated) and settled (chemotaxed, or became mechanically trapped – mechanism is unknown) in microcapillaries (orange). (B) Tumor cells penetrated endothelial cell walls and invaded extracellular matrix.*



Sprouting of endothelial cells in engineered micro-vessels. *Phase contrast image showing a parent vessel with outgrowing sprouts. The construct is embedded in collagen matrix.*

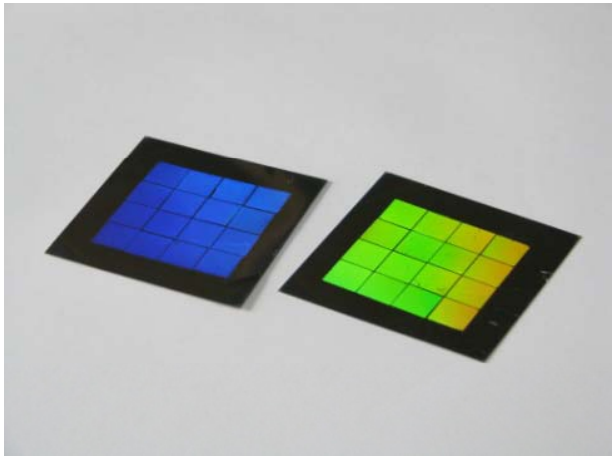


Extravasation of metastatic prostate cancer cells (PC3) in engineered micro-vessel sprouts. *Confocal microscopy image of PC3 cells (red) and endothelial cells (green).*

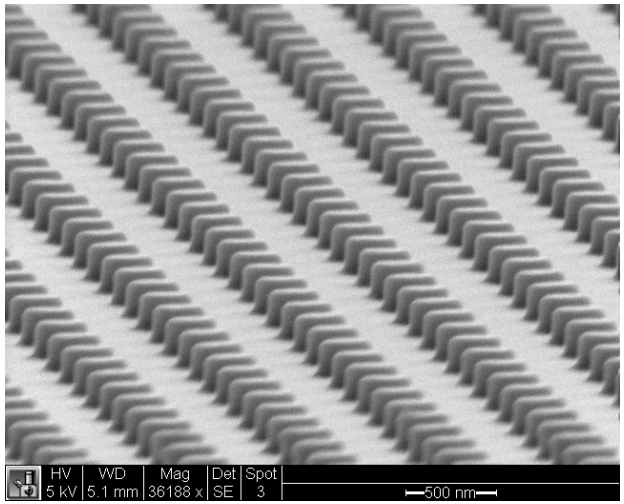
VisionGate, Inc.
Work performed at U. Washington

Nanoimprinted Ceramic Gratings

Nanoimprinting is an attractive tool for patterning large substrate areas with nanometer-sized features. We have developed imprinting techniques for all-inorganic ceramic precursor materials. These films have numerous applications, such as photonic back reflectors in flexible solar cells, moth-eye antireflection structures, or catalyst supports for fuel-cell and battery applications. We have recently demonstrated a significant improvement for the efficiency of thin silicon solar cells using imprinted diffractive structures on the backside of the absorber layers (Presentation at 54th EIPBN Conference, Anchorage, AK , 3 June 2010).



Two-dimensional grating structures on flexible substrates (35mm x 35mm patterned area each). Top: photograph. Bottom: SEM micrograph.

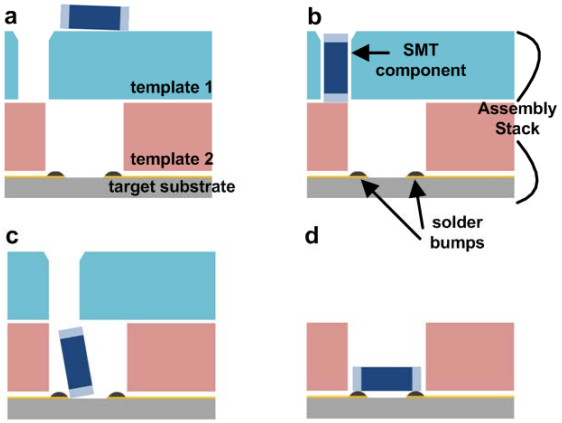


Dirk Weiss and Dustin Richmond, Washington Technology Center

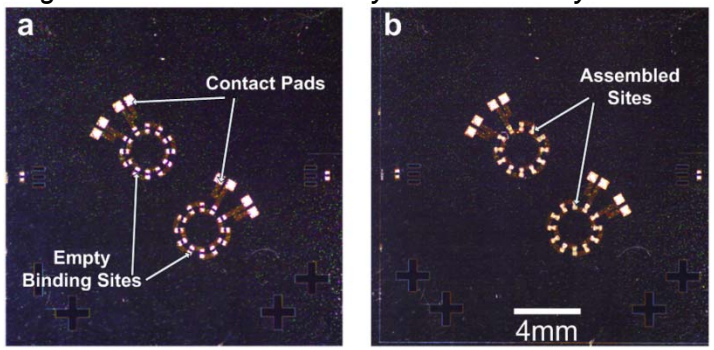
Work performed at U. Washington

Parallel Assembly of SMT Components

The purpose of the Parallel Assembly of Surface Mount Technology (SMT) Component Project is to investigate novel methods to perform the delivery and assembly of standard 01005 format (0.016” × 0.008”, 0.4mm × 0.2mm) thin-film resistors and monolithic ceramic capacitors with a programmable batch assembly process that leads to 100% yield within tens of seconds, that is high volume manufacturing compatible. We make use of assembly templates and target substrates fabricated on silicon wafers.



Assembly process: a. component delivery; b. a single component is captured by template 1 near the binding location; c. component is allowed to drop into template 2; d. slightly agitating the system aligns the component to the orientation of the aperture on top of the binding location on the target substrate. After step d, solder reflow is performed to bond the component to the target substrate mechanically and electrically.



SMT assembly at arbitrary in-plane orientations: a. empty circuit – binding sites are oriented at various in-plane orientations; b. assembled circuit.

Intel Corporation
(in collaboration with Karl F. Böhringer, UW)
Work performed at U. Washington

MEMS Accelerometers

Silicon Designs, Inc.'s miniature accelerometer technology combines additive micro machining and integrated circuit technology to produce a highly reliable, exceptionally rugged, capacitive sensor to detect shock, vibration, and acceleration. SDI specializes in commercial-grade accelerometers such as those used in automobile crash detection and stability testing, identifying unusual vibrations in race cars and airplane engines, and monitoring structural integrity in bridges, hydroelectric power generators, and wind farm turbines.

These accelerometers operate to specification after sustained exposure to up to 10,000 g and limited exposure above 200°C.

Silicon Designs is developing its next generation devices in the UW-NNIN Microfabrication Laboratory in an effort that combines materials and systems in new ways to result in a five-fold improvement in certain parameters.

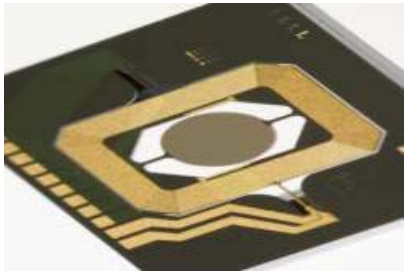
Silicon Designs, Inc.
Advanced Accelerometer Solutions for Demanding Applications

http://silicondesigns.com

Silicon Designs, Inc.
Technology developed at U. Washington

Pico Projectors - PicoP™

Microvision provides a powerful technology platform that enables next generation display and imaging products. High performance MEMS scanning mirrors are fabricated using common bulk silicon etch techniques. A robust, reliable, high angle, high frequency MEMS device has been successfully transferred to an external manufacturing partner. The technology is developed within a long-term collaboration with the UW NNIN site.



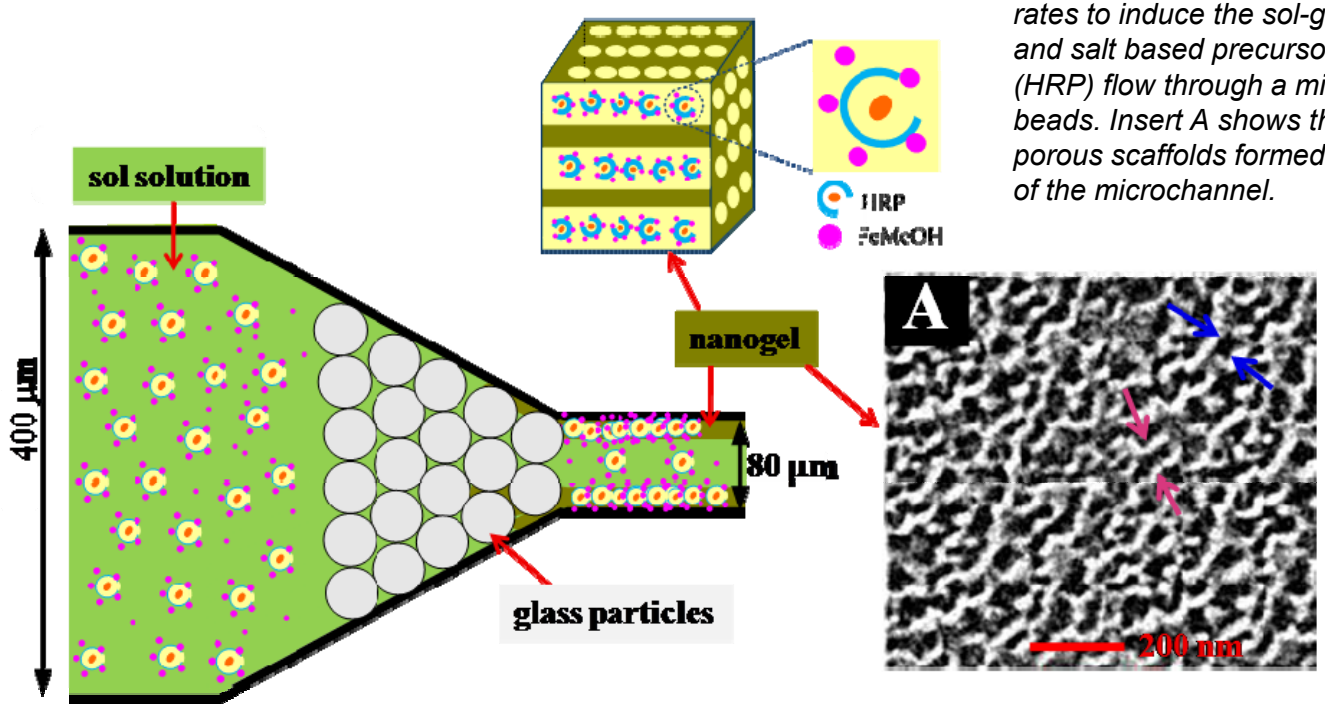
Microvision MEMS Mirror

SHOWWX™ Laser Pico Projector
http://www.microvision.com

Microvision, Inc.
Technology and prototypes developed at U. Washington

Microfluidics Enhanced Biocompatible Nanoporous Scaffolds Synthesis for Biosensing

Our microfluidics approach is able to facilitate the single throughput, in-situ process to immobilize enzymes in a nanoporous scaffold that can retain enzymes' native stabilities and reactivity. The nanogel based sensor has demonstrated high sensitivity, stability and selectivity. This flow induced immobilization technique opens up new pathways for designing simple, fast, biocompatible, and cost-effective process for enhanced sensor performance.



Microfluidics provides a high shear and extension rates to induce the sol-gel transition after a surfactant and salt based precursor solution containing enzymes (HRP) flow through a microchannel packed with glass beads. Insert A shows the TEM image of the nano-porous scaffolds formed (i.e. nanogel) at downstream of the microchannel.

Amy Shen, UW Mechanical Engineering

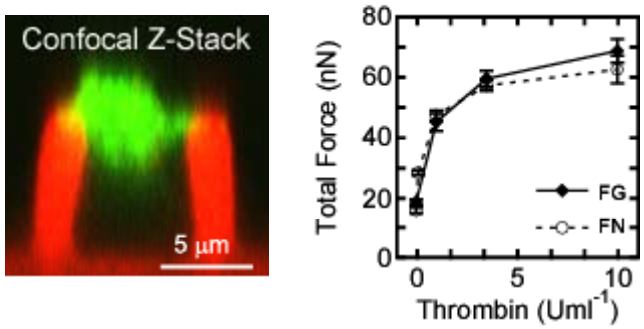
Work performed at U. Washington

M. Vasudevan et al., Nat. Mat., ***2010;***
D. Lu, J. Cardiel, G. Cao, A.Q. Shen
Advanced Materials, in press, ***2010***

Measurement of Platelet Forces

The purpose of the Platelet Force Project is to investigate the biomechanics of blood clotting by measuring the contractile forces that platelets generate on arrays of flexible, microfabricated posts. Each post acts as a force transducer because it deflects in proportion to the contractile force that platelets apply at the tip. The confocal microscope at the UW's NanoTech User Facility was used to measure the size of the platelet clots and the deflections of the post. This novel biomechanical assay can be used to evaluate hemostasis, thrombosis, and embolization.

Platelet clotting forces measured using arrays of flexible microposts.



Confocal microscopy was used to measure platelet forces on the microposts. Thrombin concentration increased platelet forces on fibrinogen (FG) and fibronectin (FN) coated posts

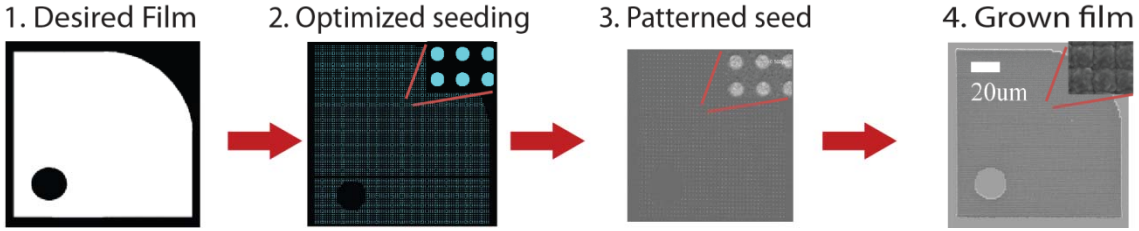
Xin Liang and Nathan Sniadecki, UW Mechanical Engineering

Work performed at U. Washington

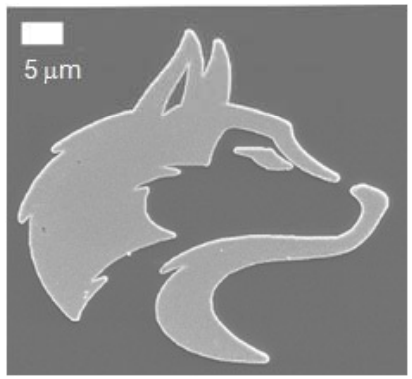
Orchestrated Structure Evolution (OSE)

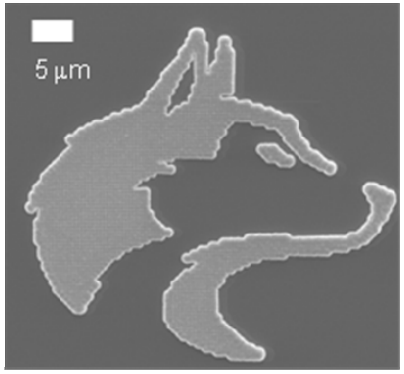
In nanomanufacturing, both "top-down" (tool-directed) and "bottom-up" (molecular self-assembly) approaches create a tension between the precision that one seeks in the build process, and the time, cost, and flexibility that must be traded off to achieve the needed quality. Here we seek to create the molecules, algorithms, and hierarchical growth processes that will integrate protein self-assembly with tool-directed growth to minimize cost and build time while providing flexibility and high quality nanomanufactured products.

Electron beam lithography (EBL) is used to illustrate OSE concept. The desired object (1) is evaluated to determine the optimal seeding locations (2), taking into account the trade-offs between write-time and geometric accuracy (a measure of quality) expected. The seed locations are transferred into a CAD program and patterned by EBL on the PMMA coated substrate (3). The final object (4) is grown using copper electrodeposition from the developed EBL "seeds"



OSE demonstration with EBL defined "seeds" and electrodeposition



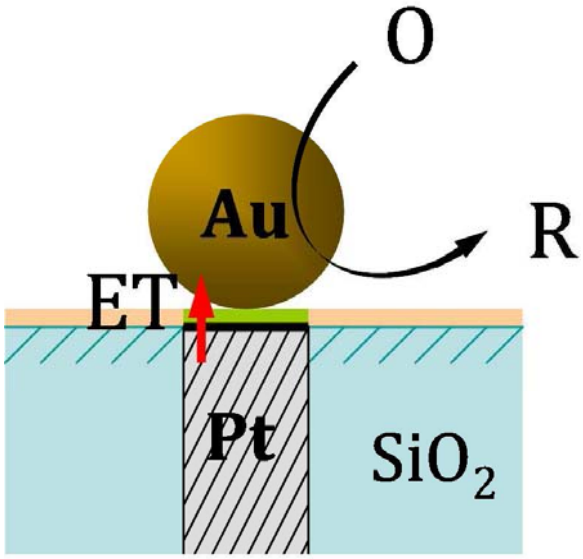


E-beam lithography is used to define a mask for electrochemical growth of copper. Top: a traditional e-beam raster drawing takes 25 seconds to prepare the "husky" pattern. Bottom: The e-beam is used to pattern discrete locations that seed copper growth, reducing the e-beam drawing time to 5 seconds.

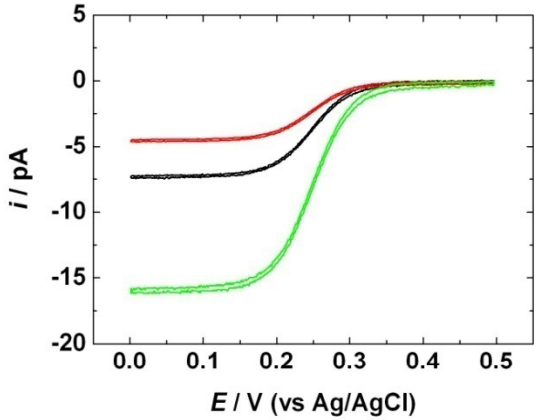
Sathana Kitayaporn, Shaghayegh Abbasi, Weibin Zhou, François Baneyx, Karl F. Böhringer, and Daniel T. Schwartz, UW
Work performed at U. Washington

Single-Nanoparticle Electrocatalysis

The goal of the project is to study electrocatalysis at individual Au nanopaticles (NPs). Molecular-scale Pt nanoelectrodes have been developed to accomplish this goal. Single Au NPs are chemically attached at the surface of a nanoelectrode. Electrochemical response and electrocatalytic activity are obtained at single-NP level directly from the nanoelectrode.



A schematic drawing of a single NP electrode

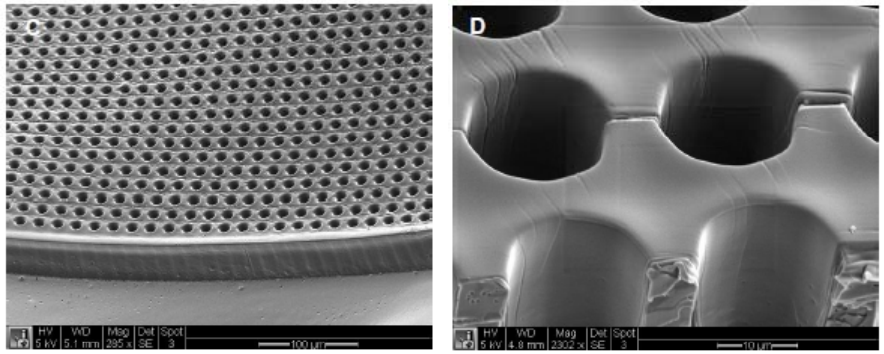


Voltammetric response measured from a single Au NP (green), as compared to that from a Pt nanoelectrode (black), and silane-modified Pt (red)

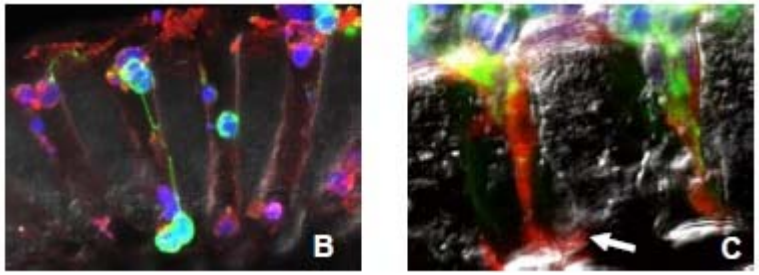
Yongxin Li, Jonathan T. Cox, Bikash K. Jena, Stephen J. Percival and Bo Zhang, UW Chemistry
Work performed at U. Washington

Microchannel Scaffolds for Retinal Tissue Engineering

This project aims to develop and characterize degradable microchannel scaffolds designed for engineering retinal tissue from stem cells. We make the scaffolds using soft lithography techniques to mold a degradable polymer into the desired shape. When seeded inside the microchannels, the dissociated retinal cells re-orient into columns just like in a natural living retina, with rod photoreceptors (green) extending processes on top of glial support cells (red). Being able to generate 3D, bio-mimicking artificial retinal tissue from stem cells is an exciting prospect that could open up a host of possibilities, including patient-specific retinal pathology assessment and drug screening.



Z-oriented microchannels, 15 microns in diameter and 75 microns deep.

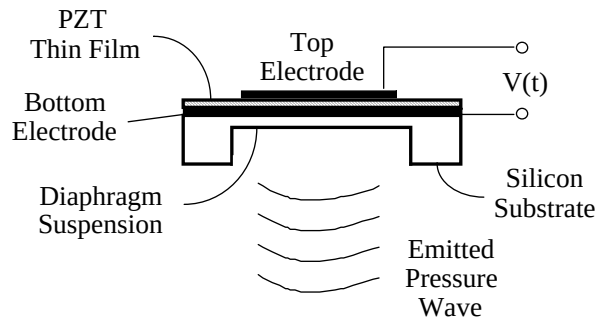


Cross-sections of dissociated mouse retinal cells in microfabricated microchannel scaffolds.

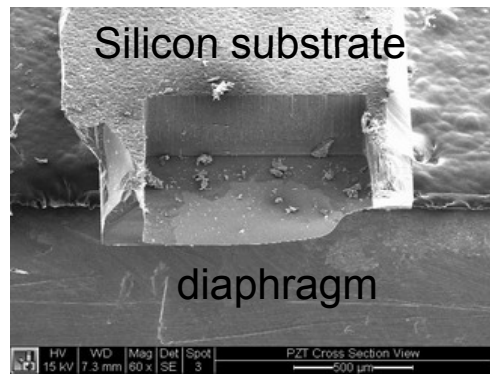
Andrew McUsic and Thomas Reh, UW Biological Structure
Work performed at U. Washington

PZT Thin-Film Microactuators

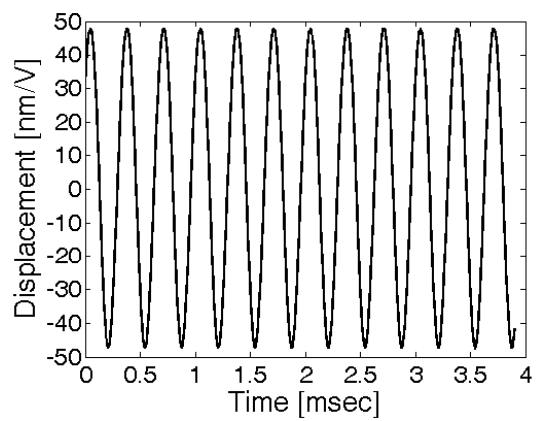
PZT is an oxide made from lead, zirconium and titanium. As a piezoelectric material, PZT deforms under an applied electric field. If made in the form of a thin film with thickness less than 10 microns, PZT can serve as tiny actuators for advanced applications, such as minute hearing aids and miniaturized diagnostic tools. In this research, we propose to enhance performance of PZT thin-film microactuators via multi-scale and multi-domain approaches that encompass nanotechnology and mechanics. For example, we use seeded PZT nano-particles and nano-textured electrodes to enhance PZT properties. We use grooves and secondary electrodes to relieve stresses enhancing actuator performance.



Actuator Design



SEM Image



Experimental Results

I.Y. Shen and G. Cao, UW MSE
Work performed at U. Washington

Self-assembly of Microchips

We have developed a process to accurately assemble very small CMOS circuits with aluminum pads. First, the exposed aluminum pads are electrolessly plated with Ni/Au (CVInc). Secondly, the pads are wetted with a 60ºC, lead-free solder alloy (Indium). (Fig. 1)

Next, we fabricated a template with complementary pads for electrical connection. The template is composed of a wettable metal layer (Cr/Ni/Au), electrical insulation to selectively inhibit wetting (SU-8 2), and a thick polymer that acts as a rough alignment mechanism (SU-8 25). Exposed pads are coated with solder. (Fig. 2)

Lastly, in a slightly acidic ethylene glycol environment, we roughly place the microchip and heat the solution. The capillary force of the solder facilitates very accurate chip alignment. The reliability is greatly improved by soldering both the chip and the template. (Fig. 3)

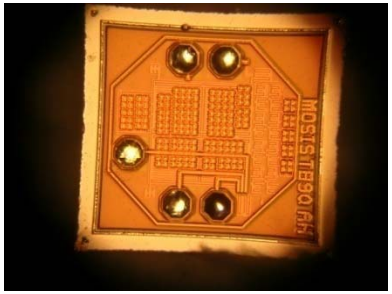


Fig. 1

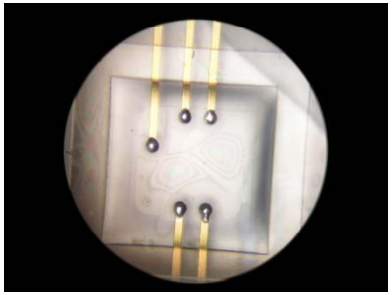


Fig. 2

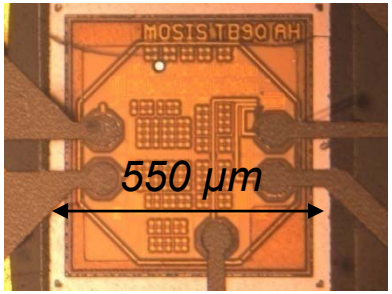


Fig. 3

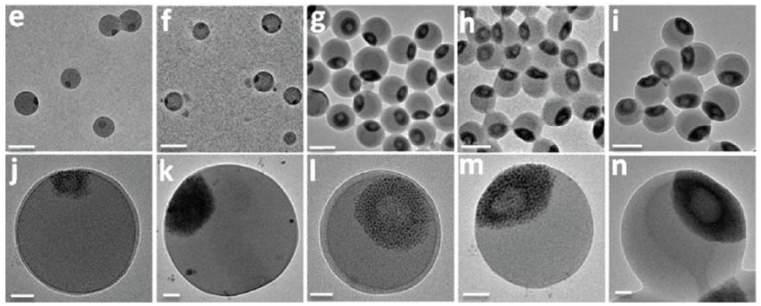
B. Parviz, UW EE

Work performed at U. Washington

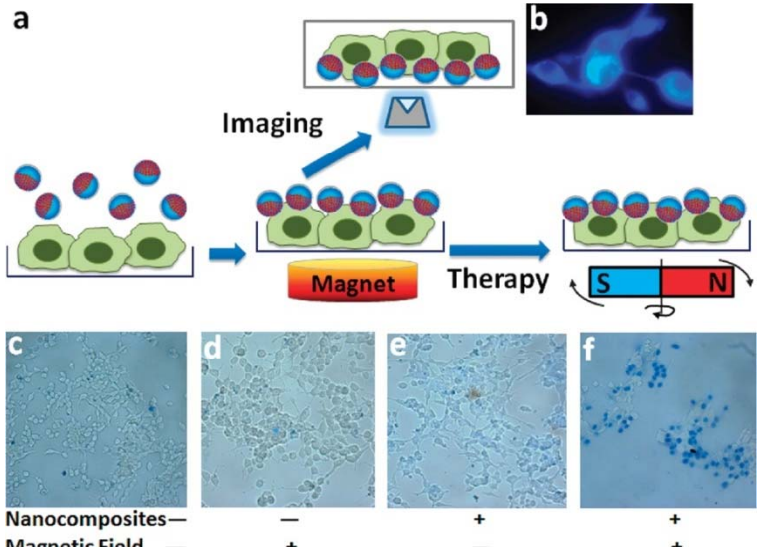
Multifunctional Nanocomposites

Compact nanostructures with highly integrated functionalities are of considerable current interest to drug delivery, multimodality imaging, and electronic devices. A key challenge, however, is how to combine individual components together without interfering or sacrificing their original electronic and optical properties. We recenlty demonstrated a new class of nanocomposites with spatially separated functionalities, and further showed magnetic field modulated imaging and magnetolytic therapy of cancer, based on magnetically controlled mechanical damage to cell membranes.

J. Am. Chem. Soc. 2010



Nanocomposites with phase-separated functionalities



Tumor cell imaging and therapy using the composites

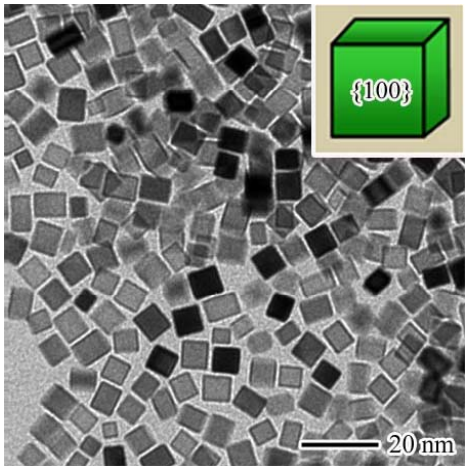
Shang-Hsiu Hu and Xiaohu Gao, UW Bioengineering

Work performed at U. Washington

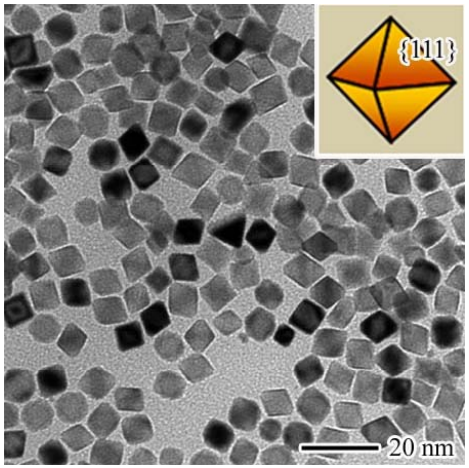
Washington University in St. Louis

Active Pharmaceutical Ingredients (API)

In this project, Covidien/Mallinckrodt, a leading pharmaceutical company aims to employ well-tuned Pd nanocrystals as catalysts and improve catalytic activity in the synthesis of active pharmaceutical ingredients (API) – active chemicals used in the manufacturing of drugs, which can in turn reduce the impurity level in drugs. Inductively coupled plasma mass spectrometry (ICP-MS) is used to monitor the concentration of catalysts in API and optimize synthetic process in manufacture.



Pd nanocubes with {100} facets.

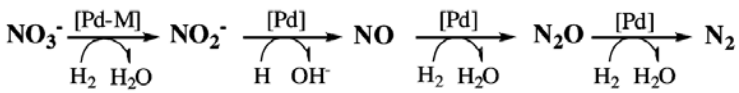


Pd nano-otahedrons with {111} facets.

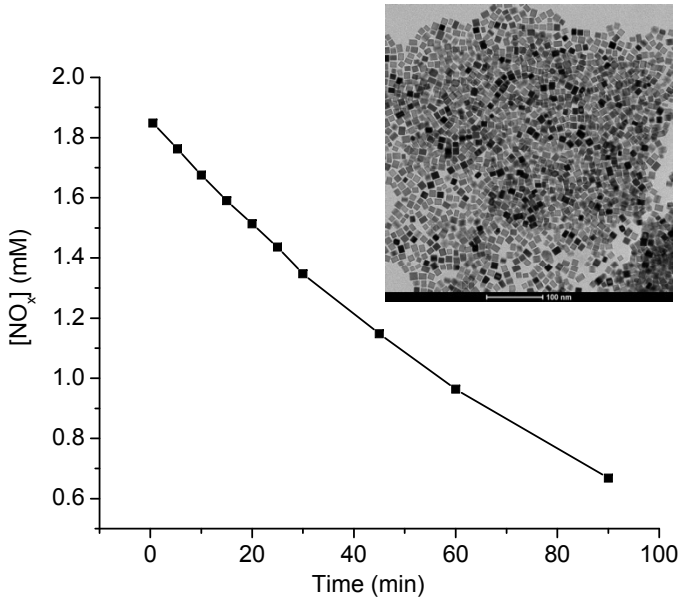
Tao Jiang, Covidien/Mallinckrodt
Work performed at the Nano Research Facility at Washington University in St. Louis

Catalytic Nitrate Reduction in Drinking Water

To reduce the possibility of adverse health effects, such as methemoglobinemia in infants, the EPA and various governmental agencies have set limits on the amounts of nitrate and nitrite in drinking water. A promising approach is through catalytic reaction with Pd-based catalysts. In this project, the Werth research group aims to investigate the selectivity of Pd nanocrystals with different facets in the catalytic reduction of nitrate to dinitrogen in drinking water treatment, and eliminate the side reaction from nitrate to ammonia.



Reaction path for catalytic nitrate reduction with Pd.

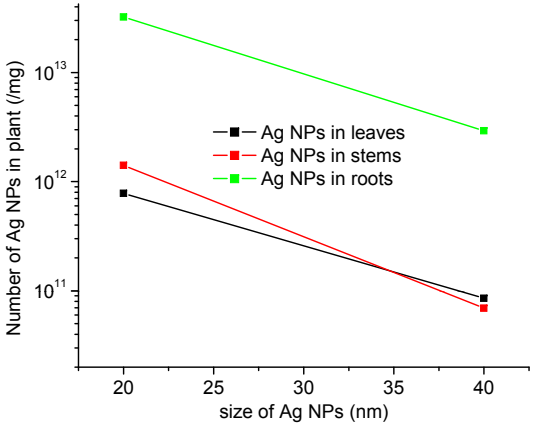


Kinetics curve of nitrite reduction with Pd nanocubes as catalysts.

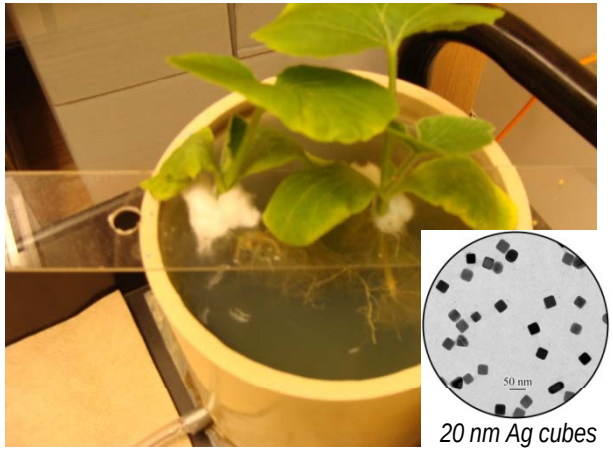
Danmeng Shuai and Charles J. Werth, University of Illinois at Urbana-Champaign
Work performed at the Nano Research Facility at Washington University in St. Louis

Ecological Implication of Nanotechnology

As nanotechnology progresses from research and development to commercialization and use, it is imperative to explore the associated implication to the ecology. In this project, the effects of size and shape on nanoparticle uptake by model pumpkin and watermelon plants are examined and toxicological symptoms assessed. Nanoparticle uptake is assessed quantitatively by inductively coupled plasma mass spectrometry (ICP-MS) and qualitatively by transmission electron microscopy (TEM). This study will contribute to understanding the transport and fate of nanoparticles in an ecological system.



Size-dependence of Ag nanoparticle uptake by pumpkin.



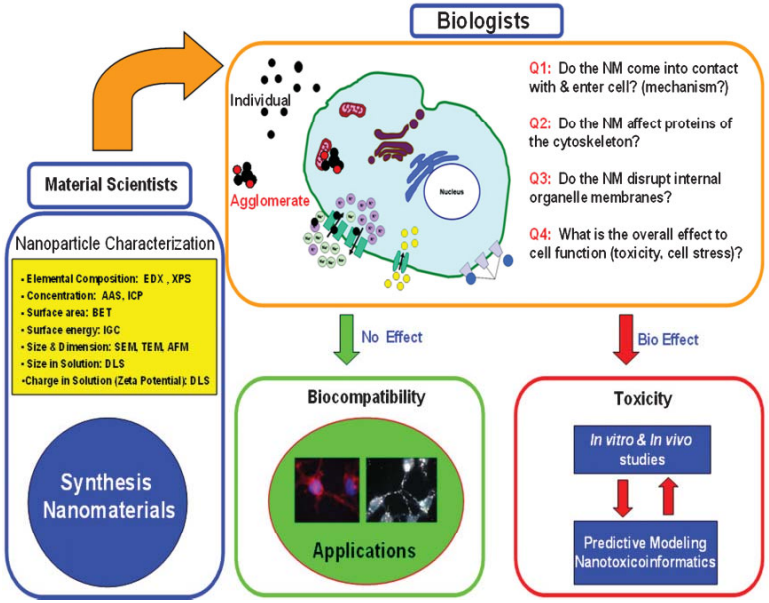
20 nm Ag cubes

Pumpkin plant after Ag nanoparticle uptake.

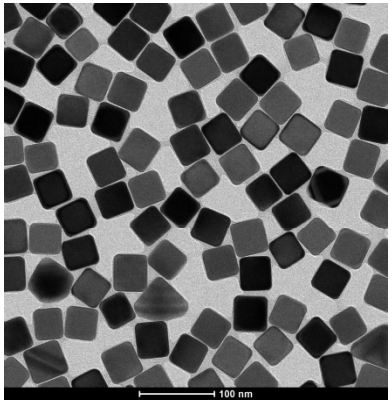
J. C. Tarafdar and Uday Burman, Central Arid Zone Research Institute, India
Work performed at the Nano Research Facility at Washington University in St. Louis

Toxicological Studies on Silver Nanostructures

It has been commonly assumed that the small size of nanoparticles allows some to easily enter tissues, cells, organelles, and functional biomolecular structures. To assess the safety of nanomaterials, it is necessary to establish reliable sources of nanomaterials, and understand the significance of interactions of these nanomaterials with relevant biological systems. In this project, a systematic and reliable method of evaluating the toxicity of nanoparticles will be developed to address the related environmental, health and safety (EHS) issues, by using nanoparticles with well-controlled size, shape and surface group.



Investigation approach of nanotoxicological studies.



Well-controlled 40-nm silver nanocubes used in toxicological studies.

Saber Hussain, Air Force Research Lab, Dayton OH
Work performed at the Nano Research Facility at Washington University in St. Louis

Gold Nanocages for Smart Drug Delivery

Smart drug delivery – releasing medications only at the site of tumor or infection – has presented great challenge in disease treatment. Xia research group has developed a system with gold nanocages covered with a smart polymer poly(N-isopropylarcylamide) that can seal the chemicals that are loaded to the hollow nanoparticles up to a critical temperature of 39 °C. When triggered by infrared light, polymer coated gold nanocages can absorb light strongly, heating the polymer above the critical temperature so that it undergoes a phase change, contracts, exposes the nanocages' tiny holes and releases the drug. When laser is turned off, the polymer returns to its previous state, resealing the contents.

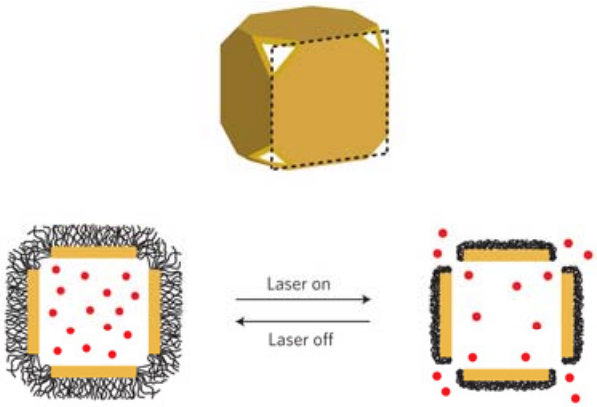
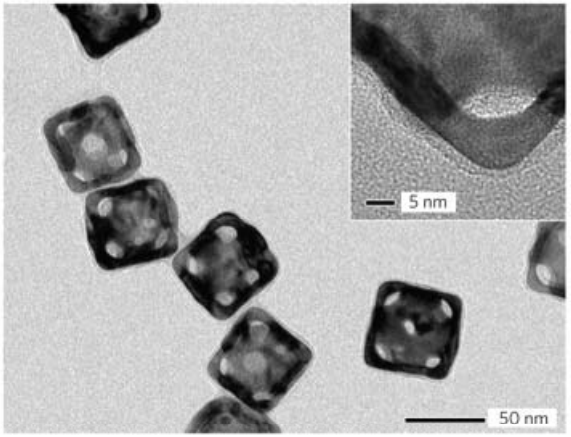


Illustration of gold nanocages for smart drug delivery.

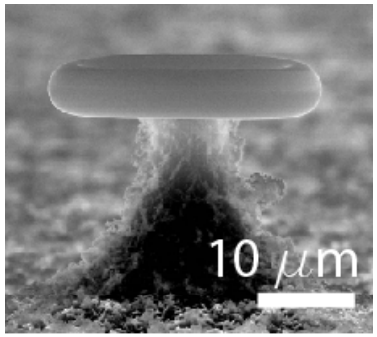


Gold nanocages used for drug delivery.

Younan Xia, Washington University in St. Louis
Work performed at the Nano Research Facility at Washington University in St. Louis

Single Nanoparticle Detection and Measurement

The purpose of the Single Nanoparticle Detection Project is to achieve a portable optical device capable of real-time, in situ detection and measurement of single nanoparticles and pathogens which would offer unprecedented benefits to environmental monitoring, clinical diagnostics, pharmaceutical studies, and homeland security applications. The mode-splitting technique developed in Yang's lab provides a novel self-referencing and position-independent sensing technique that overcomes the limitations of current resonator-based sensors while keeping the advantages of ultra-sensitivity offered by resonant structures.



Ultra-high-quality optical microtoroid resonator on a silicon wafer.

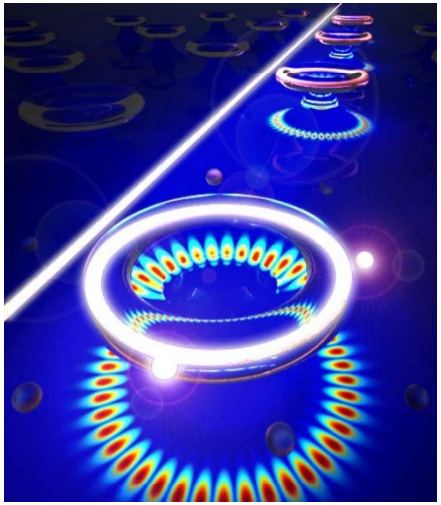
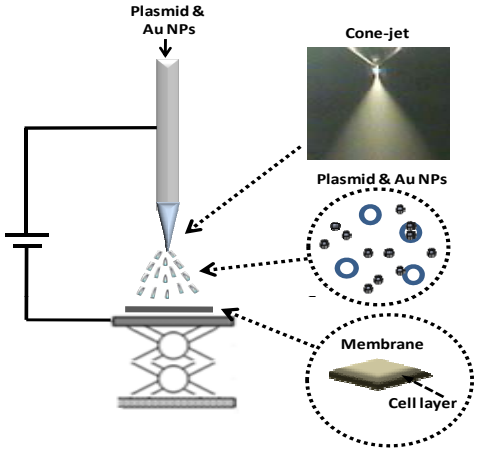


Illustration for single nanoparticle detection and measurement.

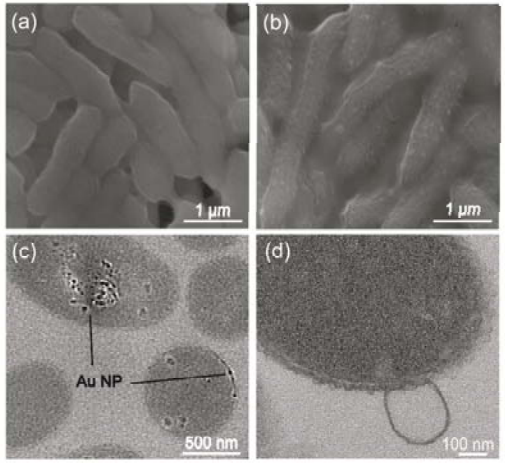
Lan Yang, Washington University in St. Louis
Work performed at the Nano Research Facility at Washington University in St. Louis

Nanoparticle-Facilitated Gene Delivery

In this project, a technique has been developed for delivering genes to microorganisms via electrospray of gold nanoparticles. During the electrospray process, a mixture of pET30a-GFP plasmid and nano-sized gold particles is deposited on a thin layer of non-competent Escherichia coli cells. Electron microscopy has been employed to image the morphological changes of plasmids and cellular membranes after being electrosprayed with gold NPs. The observed temporary damage on cellular membranes creates channels that allow plasmid DNA to cross the cell envelope. This gene delivery method has the potential to work universally for different genetic materials in both prokaryotic and eukaryotic cells.



Electrospray system employed to delivery gene into non-competent cells.

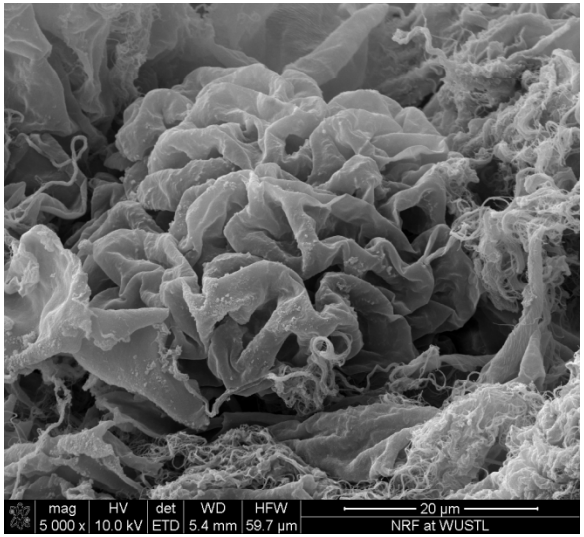


Morphological changes of cells and interactions of NP-plasmid complex with cells.

Yinjie Tang and Daren Chen, Washington University in St. Louis
Work performed at the Nano Research Facility at Washington University in St. Louis

Structure of Kidney Glomerular Podocytes and Basement Membrane

The architectures of podocytes, a specialized epithelial cell in the kidney glomerulus, and the extracellular glomerular basement membrane (GBM) that it helps to synthesize are critical for kidney function. In this project, the mouse models of human kidney diseases are investigated to exhibit abnormalities in the GBM and in the adjacent podocytes. A better understanding of how the fine structure of podocytes and basement membranes are affected by GBM protein defects could lead to new treatments for diverse kidney diseases.



Glomerular basement membrane from a normal mouse.

Jung Hee Suh and Jeffrey H. Miner, Washington University School of Medicine
Work performed at the Nano Research Facility at Washington University in St. Louis

NNIN Education Highlights

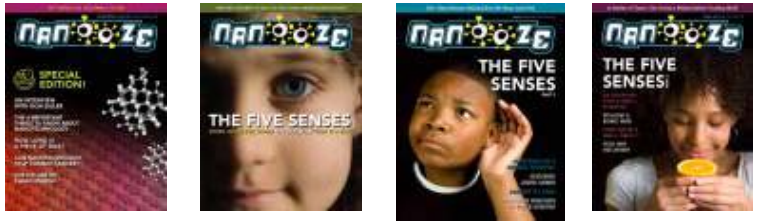
The NNIN Science News Magazine for Kids

Exciting, Educating, and Challenging both Students and their Teachers about Science and Nanotechnology in Today's World.

How many "pixels" are in your eye?

What is nano about your sense of smell?

Up to 100,000 printed copies of each issue distributed to classrooms



Many young students have heard about "nano" but don't really know what it is. "*Nanooze*" is a vehicle to take advantage of that natural interest, bringing the excitement of science and nanotechnology to young children at a level they can understand and in a language and style they relate to. Content draws on science in the news and science in everyday lives, and relates, as enrichment material, to standard science curriculum at the middle school level.

The target is the "post-atomic" kid, i.e. a student who knows about atoms or molecules but doesn't yet know what it all means in real life. In general that is the middle school level, although the content is adaptable across a wide range of ages and interests.

Nanooze is available on the web in English, Spanish, and Portuguese. In addition, fifty thousand printed copies are distributed 3 times per year to classrooms across the US, free of charge. Recent issues have explored nanotechnology and the five senses, a new twist on a topic which is addressed in many middle school biology classes and a topic to which students can easily relate. A total of seven issues are available. Major (>10,000 copies) distributions have been done to middle schools in suburban Atlanta and metropolitan Detroit; the rest are distributed to individual classrooms on request. *Nanooze* is produced by a team led by Prof. Carl Batt at Cornell University and distributed by NNIN.

On the web at www.nanooze.org, in English, Spanish, and Portuguese

An activity of the Education Program of NNIN, the National Nanotechnology Infrastructure Network, funded by the National Science Foundation as part of ECS-0335765, Sandip Tiwari, Cornell, PI.

Nanotechnology Undergraduate Research

An Activity of the NNIN Education & Outreach Program

Providing quality initial research experience is a critical part of undergraduate science and technology education. The **Research Experiences for Undergraduates** program provides an avenue for such research and it is particularly critical for students from "non-research" universities. For 14 years, NNIN and its predecessor, NNUN, have conducted a nanotechnology REU program, with up to 80 students at sites across the network. Our program is highly coordinated across the 14 sites with one common application and common set of procedures and expectations. Students conduct a significant individual research project in one of the state-of-the-art NNIN facilities, experience the graduate research environment, and learn a range of nanotechnology tools and processes.

Over 700 students have participated in the NNIN REU program since its inception. Because of its size and long history, our program offers a unique opportunity to gather meaningful, non-anecdotal data on the long term impact of REU on career outcomes. As a student's career choices play out only after 5-10 years, it is necessary to adopt a long term view to accurately assess program impact. NNIN has collected data from approximately 55% of the first 375 participants (1997-2004). Data show that 86% have gone on to graduate school with 47% completing or nearing completion of a Ph.D. degree. 95% remain in scientific careers. While it is not possible to compare this outcome to a control group, these results and the accompanying comments from past participants, demonstrate the importance of REU programs in the education of the next generation of nanotechnology researchers.

Longitudinal Study of REU Outcomes

Degrees		***Type of Career***	
Terminal B.S.	*14%*		
Terminal M.S.	*26%*	*Science Career*	*95%*
Ph.D.	*47%*		
J.D./MBA	*8%*	*Nanotechnology*	
M.D.	*5%*	*Career*	*48%*

An activity of the Education Program of NNIN, the National Nanotechnology Infrastructure Network. Funded by the National Science Foundation as part of ECS-335765, and as REU site award EEE-EEC-0649215, Sandip Tiwari, Cornell, PI

Research Experience for Teachers in Nanotechnology

An Activity of the NNIN Education and Outreach Program

The NNIN **Research Experience for Teachers** program introduces middle and high school teachers to nanotechnology. The program at 5 NNIN sites serves 20 teachers each year for an 8 week research and curriculum development project. Participants work in NNIN facilities along with NNIN staff and faculty learning the techniques and processes of nanotechnology research.

Middle and high school teachers have direct influence on early stages of the human resources pipeline. As a result of their RET participation, they can relate their direct research experience to the students as well as use new nanotechnology activities to enrich their curriculum content. Because each teacher interacts with hundreds of students in subsequent years, this program has a highly leveraged impact on the scientific human resources pipeline

As part of the experience, each teacher develops a nanotechnology activity suitable for use in a classroom. Each module must examine a nanotechnology concept suitable for middle or high school classrooms while also relating to National and State content standards so that it can be easily integrated into normal curriculum. These lessons and activities are refined with the help of NNIN Education staff, NNIN Technical Staff, and other participating teachers. The resultant activities are posted on the NNIN education web site and are used in other NNIN education/outreach activities. NNIN Education staff follow up with participants in subsequent years to help with classroom implementation.

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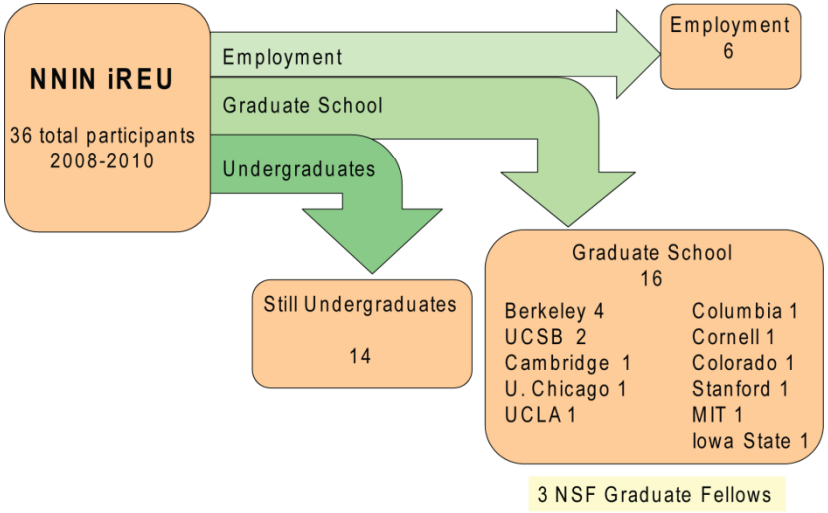
An activity of the Education Program of NNIN, the National Nanotechnology Infrastructure Network, Funded by the National Science Foundation as part of ECS-335765 Sandip Tiwari , Cornell, PI , and as RET site award EEC-0908895, Nancy Healy, Ga. Tech, PI.

Developing Globally Aware Scientists
NNIN iREU
An Activity of the NNIN Education and Outreach Program

Science in the 21st century requires a technology workforce able to compete effectively in a global environment. U.S. students are, however, in general, poorly prepared to deal with the complexity of research in an international context. Issues relate to both culture and communication. This program seeks to expose talented undergraduates to a rigorous international research experience that will have a long term effect on their careers.

Fortunately, NNIN has access to a talented and proven pool of early career researchers, the "alumni" of the NNIN REU program, both who are quite capable of advanced research and who would benefit greatly from the additional research experience. The NNIN REU program is used as a feeder program to this more rigorous 2nd summer research program in an international situation, the NNIN iREU program. Because of their introductory NNIN REU experience and our rigorous selection process, our international partners can be confident the participants will be exceptional and contribute to their research at the level of graduate researchers.

We recently completed the 3nd summer of this program, with 9 NNIN students at the National Institute of Materials Science in Tsukuba, Japan, and with 6 others at the Forshungszentrum Jülich in Germany, and 3 at IMEC in Belgium. Our partners in Japan, Germany and belgium have been very impressed with the quality of participants and are eager to continue as partners with NNIN in this exciting program. We will continue with at least 12 more students in summer 2011. This program has demonstrated that even undergraduates with as little as one year of research experience can contribute to research at a leading international laboratory. The resulting "globally aware scientists" will contribute significantly to the next generation of nanotechnology researchers.



An activity of the Education Program of NNIN, the National Nanotechnology Infrastructure Network, funded by the National Science Foundation as part of ECS-335765. Specific activity partially funded by IRES program under OISE-0727552. A portion of the 2008 activity was funded via an IREE supplement from the NSF Engineering Division.

Nanotechnology Showcase for Students

An NNIN Education/Diversity Program

Student awareness and excitement about nanotechnology is a prerequisite to a path that leads to appropriate education for a nanotechnology career. Many undergraduate institutions, however, do not have nanotechnology courses or research activities. Increasing student participation in nanotechnology thus requires new approaches to expose students to this exciting area.

The **Nanotechnology Showcase for Students** brings a nanotechnology exposition to conferences serving primarily undergraduate and minority student populations. The event, offered cooperatively by staff from all NNIN sites, consists of introductory lectures on nanotechnology and nanotechnology careers, followed by simple nanotechnology laboratory demonstrations. NNIN has a suite of portable nanotechnology instruments (AFM, STM, SEM, microscopes, spectrometers, etc) which can be brought to the conference site and quickly deployed to demonstrate key nanotechnology concepts. Staff from NNIN sites also demonstrate interesting nanotechnology applications drawing on activities in their laboratories.

To date, this event has been offered at the national conference and regional conferences of the Society of Hispanic Professional Engineers and the national conference of the National Society for Black Engineers. At each event, hundreds of students enthusiastically participated and went away with an expanded understanding of nanotechnology and their potential place in the nanotechnology world. The event also acts to promote participation in the NNIN REU program

Nanotechnology Demonstrations & Activities

- *AFM on Nanostructures*
- *STM of Graphene*
- *SEM of Familiar Microscale Objects*
- *Microfluidics*
- *MEMS*
- *Nanotechnology Products*
- *Shape Memory Alloys*
- *Optical Emission from Nanoparticles*

An activity of the Education Program of NNIN, the National Nanotechnology Infrastructure Network, Funded by the National Science Foundation as part of ECS-335765, Sandip Tiwari Cornell, PI

International Winter School for Graduate Students

An activity of the NNIN Education and Outreach Program and the NNIN Program on Social and Ethical Issues in Nanotechnology

The NNIN iWSG (International Winter School for Graduate Students) is a major new educational initiative for NNIN. The iWSG, a technical short course with a strong SEI component, is aimed at exposing a select group of graduate student users to education in a specific area of nanotechology within the context of developing world environment. Each year, ten outstanding students are selected in a national competition. They participate in a one week technical short course lead by 6 US faculty. The course takes place in a developing country where they are joined by up to 100 foreign graduate students and faculty from a major international institution. The first iWSG was held in December 2008 at IIT-Kanpur (India) on the subject of organic electronics; The second took place at IIT Bombay in Dec. 2009 on the subject of Nanoelectronics. The third will take place at IISc Bangalore in Jan 2011.

A critical and distinguishing part of the iWSG is that it endeavors to place the technology into the context of the developing world. During the 2nd week of the course, the group leaves the academic campus and travels to live and work in a rural village. In 2009, for example, the group traveled to an off-grid village with little educational resources where they will be assisting in the construction of a regional school.

An NNIN faculty member in the area of Science and Society/ Social and Ethical Issues travels with the group. The SEI faculty plays a major role in this group as the students debate and wonder about of technology and technology's implications in the context of developing world. The intention is to help the students grasp not only the international nature of science and technology, but also the social context in which science and technology exist in most of the undeveloped world.

An activity of the Education Program of NNIN, the National Nanotechnology Infrastructure Network, Funded by the National Science Foundation as part of ECS-335765, Sandip Tiwari Cornell, PI

NanoExpress

An NNIN Education/Diversity Resource Operated by Howard University

Introduced in the summer of 2006, the NanoExpress is a self-contained mobile laboratory operated by the Howard University Nanoscale Science and Engineering Facility (HNF). The NanoExpress presents the complex, fascinating world of nanotechnology to both students and the general public. With 208 sq. ft of lab space designed to facilitate hands-on experiments, it includes an AFM, an electron microscope, an evaporator, a small furnace, and photolithography equipment, enough to demonstrate a variety of nanoscale processes. Experimental activities include: Introduction to Passive Nanoparticles, Introduction to Self Assembly, Introduction to Micro and Nanofabrication, “Chips are for Kids”, Instruments for Nanoscience, Shape Memory Alloys and Soft Lithography. Undergraduate and graduate students assist the staff in setting up and supervising experiments.

The NanoExpress maintains a full schedule of visits to elementary schools, middle schools, and high schools, as well as to national conferences and local civic events. The NanoExpress is also used by several advance level college courses. Most visits are in the DC regional area, although it has made trips to Massachusetts and Georgia. The NanoExpress incorporates green technology with a built-in biodiesel tank to for its diesel generator that supplies electrical power to the the equipment.

With NanoExpress NNIN can bring high technology to schools and communities that have very little exposure to nanotechnology or to advanced science in general. It is an important vehicle to bring understanding and awareness of science and scientific careers to these communities.

The Nanoexpress is an activity of Howard University, as part of the Education Program of NNIN, the National Nanotechnology Infrastructure Network. Funded in part by the National Science Foundation as part of ECS-335765, Sandip Tiwari Cornell, PI

NNIN Laboratory Experience for Faculty

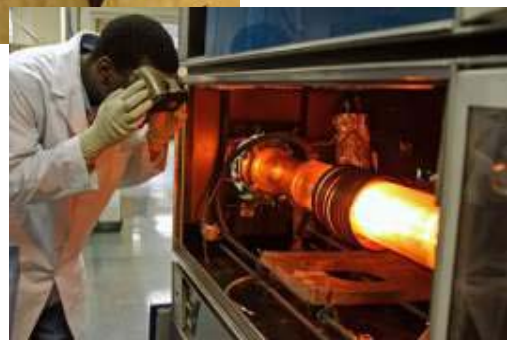
An NNIN Education/Diversity Program

Assuring the diversity of the future nanotechnology workforce requires a multi-level approach. Students at minority serving institutions often have little exposure to nanotechnology and few role models within the faculty with nanotechnology research programs. Similarly, minority faculty may have interest in nanotechnology but do not have access to appropriate resources to start or continue a nanotechnology research program.

The NNIN Laboratory Experience for Faculty (LEF) provides an REU like experience to minority faculty and faculty at minority serving institutions. Faculty are selected from across the country and spend approximately 8 weeks at an NNIN site. In come cases, the faculty have nascent nanotechnology research programs but need access. In other cases, faculty have in interest in nanotechnology but do not have sufficient background or experience to properly integrate nanotechnology into their courses. As part of the program, selected faculty receive salary support, travel and housing, as well as access to NNIN facilities.

NNIN LEF was offered in the summer 2008,2009, and 2010, with a total of 18 participants from 16 different institutions.

In the ideal case, LEF helps boost the research career of the participating faculty, leading him/her to become an NNIN user, 2) provides a nanotechnology context which can be integrated into his/her courses at the minority serving institution, and 3) develops an advocate for the NNIN REU program and thus improving the effectiveness of NNIN's REU recruitment efforts.



An activity of the Education Program of NNIN, the National Nanotechnology Infrastructure Network
Funded by the National Science Foundation as part of ECS-335765, Sandip Tiwari Cornell, PI

NNIN Professional Development Workshops for Teachers

NNIN offers workshops to secondary science teachers that are two hours to one week in duration. We provide these workshops at the annual and regional meetings of the National Science Teachers Association, at local and regional science teacher conferences, and schools/school districts. In 2010, we gave a half day workshop at the University of Virginia's Center for Diversity in Engineering Innovation Workshop**:** Teaching Nanotechnology within Virginia Standards of Learning; co-taught the Exploratorium's one week workshop N*anotechnology for Teachers;* and provided resources/lectures for the summer NanoTeach Institute at the Mid-Continent for Research in Education and Learning.

The Georgia Institute of Technology site is the lead in developing and providing these workshops. To date, we have reached at least one teacher (in most cases many more) in 43 of the 50 states (and Puerto Rico).

The workshops focus on providing ways for teachers to include standards-based nanotechnology lessons in their science classrooms. Our workshops have been designed to also tie lessons to the *Big Ideas of Nanoscale Science and Engineering: A guidebook for secondary teachers* (Stevens et.al. 2009, NSTA Press). We emphasize that teachers can include nanotechnology topics and still teach materials required in science classrooms. All of the workshops are hands-on so that teachers can experience the lessons as students would.

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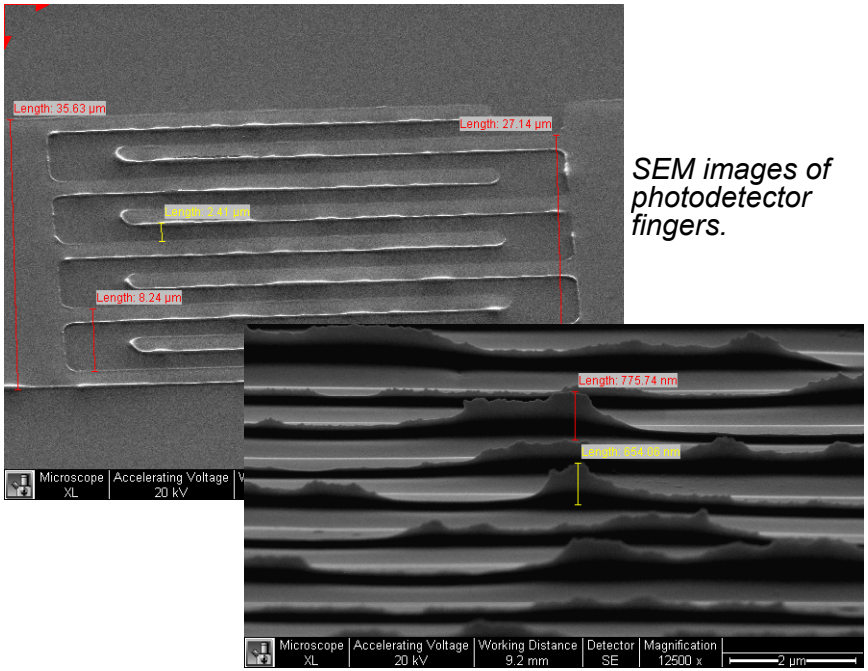
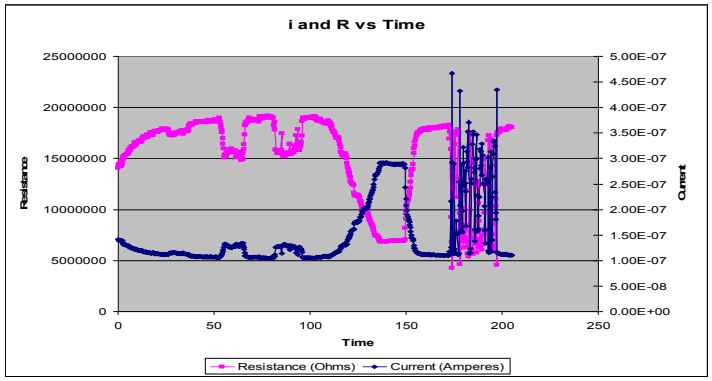
Photodetector Fabrication and Testing

North Seattle Community College Nanotech Program

North Seattle Community College's 90-credit degree prepares graduates for entry-level technician positions in the nano/micro-fabrication industry and related manufacturing industries. Students are exposed to cleanroom procedures including an understanding and maintenance of nano/micro fabrication and characterization equipment. During the lab portion of the fabrication course, each student makes and tests a micro-photodetector using the UW facilities.



SEM images of photodetector fingers.



Student data: Photodetector response to light (current high, resistance low) and darkness (current low, resistance high).

Alissa Agnello, Director
North Seattle Community College Nanotech Program
Work performed at U. Washington