Deep Dielectric Etching

NNIN Etch Workshop 2013

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Outline

- Overview of RIE and stuff
- Masking options
- Making a good deep etch
- Chamber condition, cleaning
- Results
- Conclusions and future work

RIE – the Basic Technology

- Reactive Ion Etching is a gaseous, low pressure etch process whereby material is directionally removed via ion driven chemical reaction
- Anisotropy is achieved by balancing etch and etch resistance or passivation such that the etch only proceeds where the most energetic, normal ion collisions occur
- Originally used and developed for pattern definition in very thin CMOS materials – depth and aspect ratio minimal concerns
- Adapted by MEMS and nanofabrication for machining purposes

Why Deep, High Aspect Ratio?

- MEMS and Nanofabrication are often concerned with three dimensional structures
- Depth becomes a consideration when materials are used for mechanical or optical applications
- High Aspect ratio allows maintaining resolution and a tight package when deeper etches are required – results in less material waste and more devices per wafer – may be critical for optical gratings and lenses

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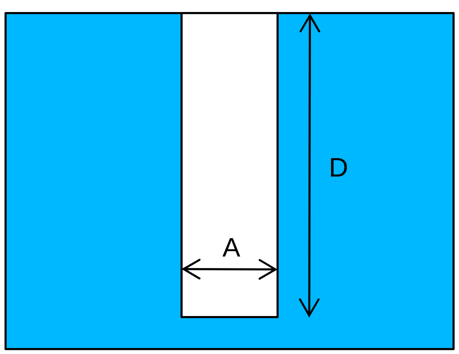
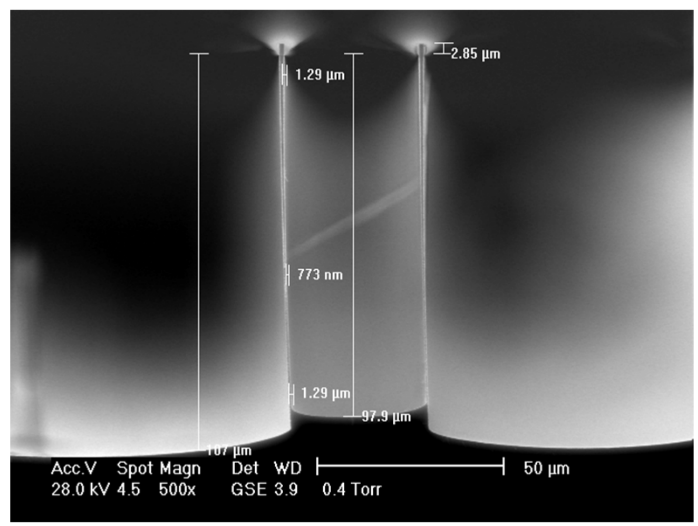
Deep, High Aspect Ratio Defined

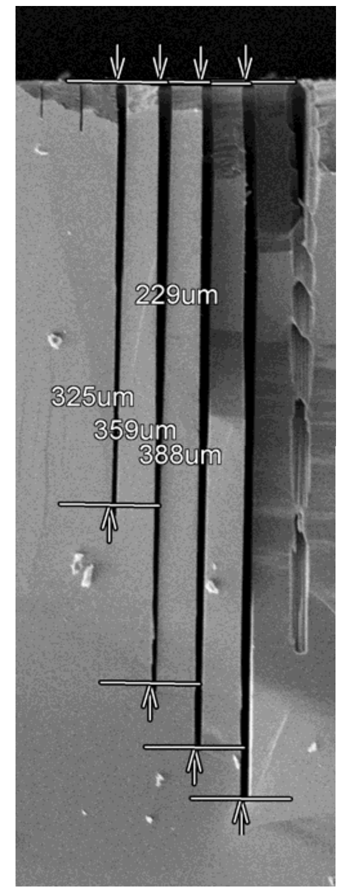
- Deep = anything greater than a few microns
  - Depends on material
  - 5 microns is deep for diamond
  - 500 microns is routine for silicon
- Aspect Ratio – Depth divided by width for trenches
- Aspect Ratio limitations generally refer to the area etched, not the area remaining



D/A:1 = AR



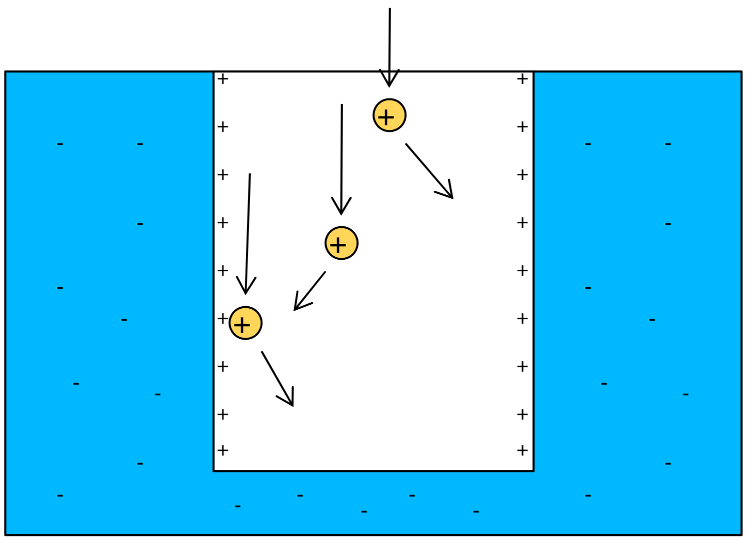
Easier



Harder

Why Deep is Difficult

- Time consuming and expensive
- Process development slow
  - Very deep etches may take several hours to a full day
  - A multiple parameter DOE may take weeks or months
- Thicker, more resistant masking requirements
- Ion redirection by non-perpendicular electric field, side-wall charging



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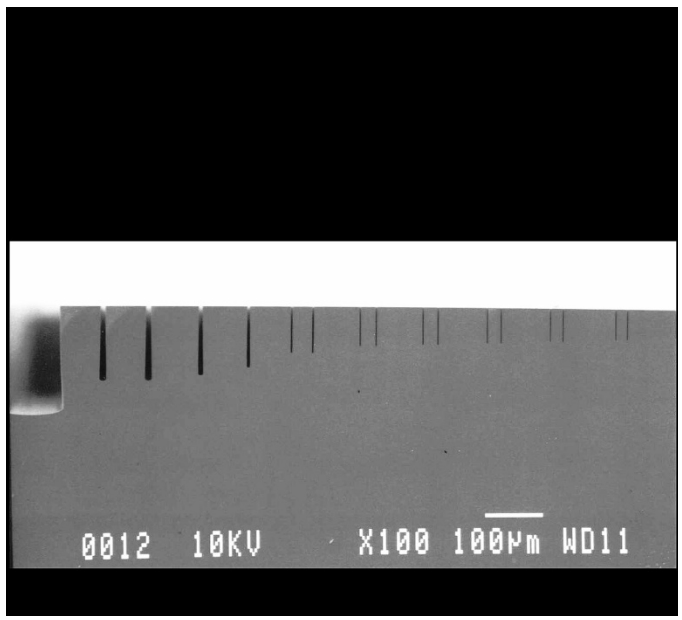
Why High Aspect Ratio is difficult

- Ion penetration
  - Ions that are not adequately normal to the substrate will not make it to the bottom of the feature
  - Ions may be redirected within the trench toward the center or into the sidewalls
- Mass transport
  - Long, tortuous path for reactive species to get into the feature and for reaction byproducts to get out of the feature
- Result is ARDE and etch stop

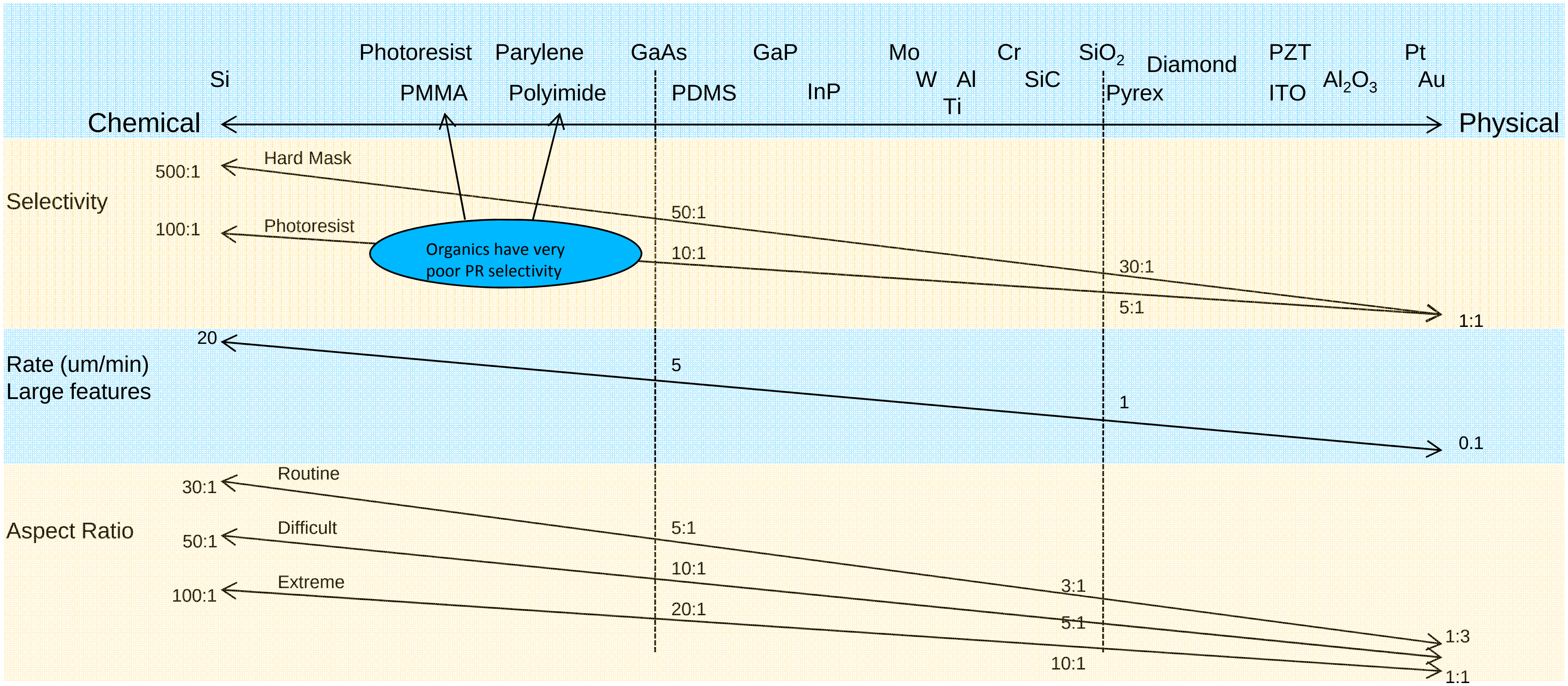
Aspect Ratio Dependent Etching

- Also called RIE lag
- Higher aspect ratio features etch slower
- Typically insignificant below 1:1



What can I etch deep?

- Silicon etching is a very special case, perhaps unique – there is no 'Bosch-like' process likely for most other materials
- Most other materials are significantly more difficult to etch



Silicon Carbide, Silica, and Diamond

- Silica, Silicon Carbide, and diamond etching have seen advances in recent years with significant recent focus on silica in particular
- All of these materials etch slowly, but unique material properties and lack of viable alternative machining mechanisms continue to drive efforts
- Silicon Carbide typically etches faster with cleaner chemistry, primarily SF6, and lower bias energies
- Silica typically etches with fluorocarbon chemistry which deposits around chamber and requires frequent cleaning
- We have little experience with diamond etching, but published data suggests potential rates similar to SiC and SiO_2 – primary etch gas is O_2 and byproducts are CO and CO_2
- Due to slow etch rates, development is extremely slow for deep etches – It may take a full day of processing and chamber maintenance to obtain a single data point
- Metal mask is commonly used with all of these materials, but has significant problems

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Pyrex

- SiO_2, the primary component of glass etches similar to SiO_2, however the doped impurities cause problems
- Boron, sodium, and aluminum oxides make up around 20% of the material - These oxide are non-volatile and must by physically sputtered away
- Very high bias voltage is required to drive this etch deep making mask selectivity difficult
- Redeposition and sloped sidewalls are common
- Chamber mechanical clean requirements are very frequent limiting the depth that may be achieved in a single etch
- Etches of 200 microns at rates nearing 1 micron per minute may be achieved, but at very high cost

Dielectrics and inert metals

- PZT, Al2O3, and ITO are very difficult to etch with a high percentage of non-volatile material that must be sputtered away
  - These materials are not appropriate for deep, high aspect ratio etching and RIE in general should be approached with caution
- Plasma inert metals including Platinum, Gold, and Nickel are removed entirely by sputtering
  - The sputtered material ends up back on the sample or on the walls of the chamber
  - These materials should be patterned by plating, lift-off, or wet etch whenever possible
  - Ion beam etching is an alternative for vertical features

How do I etch SiO_2?

- Typically use fluorocarbon based chemistries
  – Fluorocarbons also deposit on sample (teflon)
- How do we counteract deposition?
  – Sputter it off (high power)
  – Noble gas dilution (e.g. Ar, He)
- Typically, this results in very low selectivity
- Low pressure is necessary, particularly for high aspect ratio etching

Masking Options

- Hard masks
  - Metals (e.g. Ni)
  - Silicon
- Polymer masks
  - Standard photoresist
  - Epoxies (e.g. SU-8)

Metal Masks

Pros

- High selectivity (up to 30:1)

Cons

- Difficult to pattern
  - Thick, usually plated
  - High stress
- Can disrupt plasma
- Can cause micro-masking due to re-sputtering
- Very “dirty”

Problems With Metal Mask

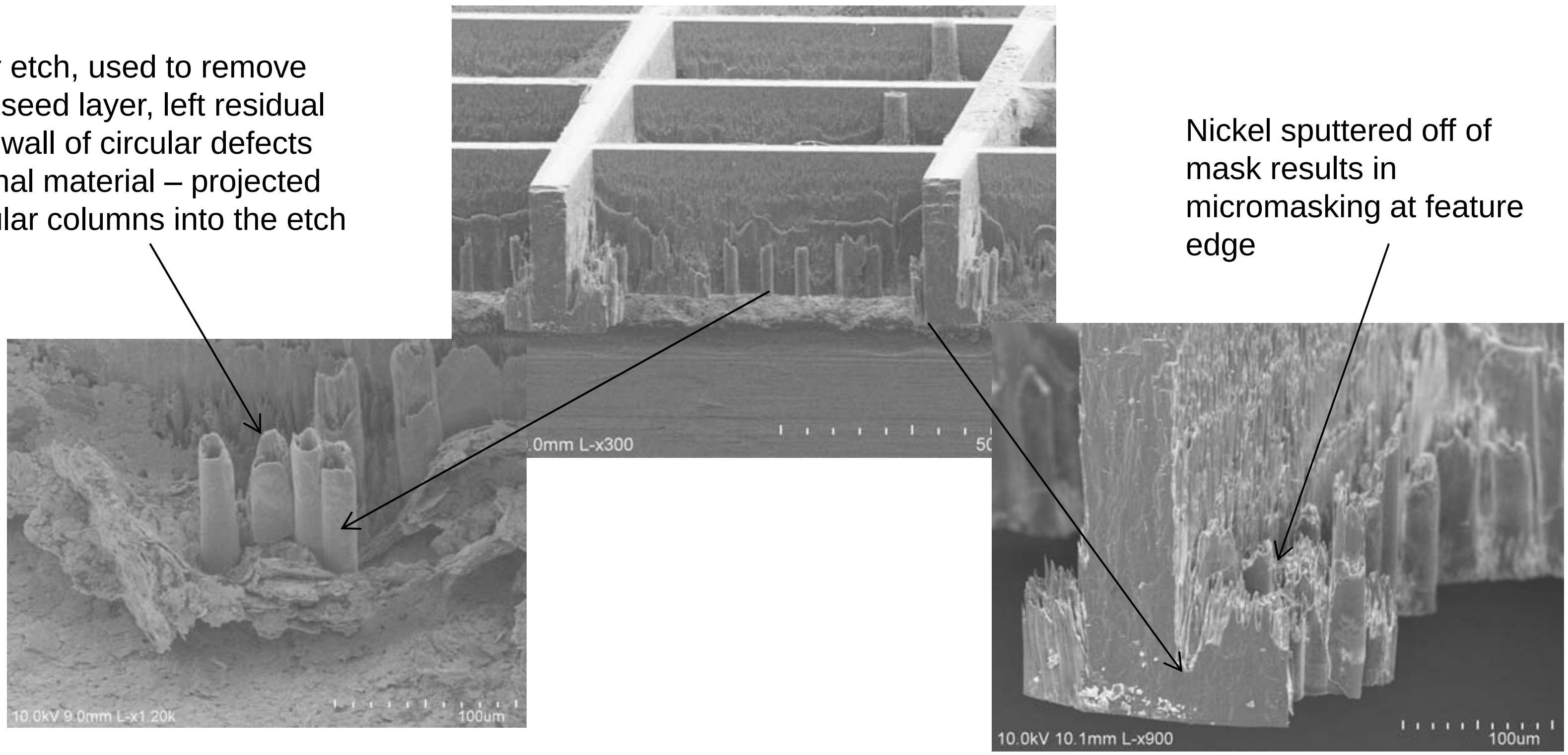
- Metal masks are chosen because they are not reactive with the etch chemistry and are physically sputtered away, maximizing selectivity
- This non-volatile sputtered material contaminates the sample and the chamber
  - Very low pressure must be used to extend the mean free path and minimize redeposition within the features
  - Chamber ceramics coated with conductive metal may result in a shift in plasma properties, plasma instability, or even failure of the ceramics
  - Frequent chamber cleans are required

Problems With Metal Mask 2

Silicon Carbide Etch performed at LNF Using a Plated Nickel Mask

Sputter etch, used to remove plating seed layer, left residual on sidewall of circular defects in original material – projected as tubular columns into the etch

Nickel sputtered off of mask results in micromasking at feature edge



Avoid Metal Mask Whenever Possible

- After early problems, efforts at the LNF have shifted away from metal masking
- Primary focus has been on silicon and KMPR
- Silicon is useful in etching silica and glass
    - The fluorocarbon chemistry typically used passivates the silicon and minimizes etching
    - Silicon is, however, still reactive with the chemistry and much of what is removed is exhausted via the pumping system
    - It is easy to make very thick masks by bonding a full thickness silicon wafer and etching via Bosch process
    - It is more difficult to make thinner masks when attempting to optimize resolution
- KMPR is a negative tone resist that may be patterned up to 100 micron in a single spin and is stable at much higher temperature than standard resist

Si Masks

Pros

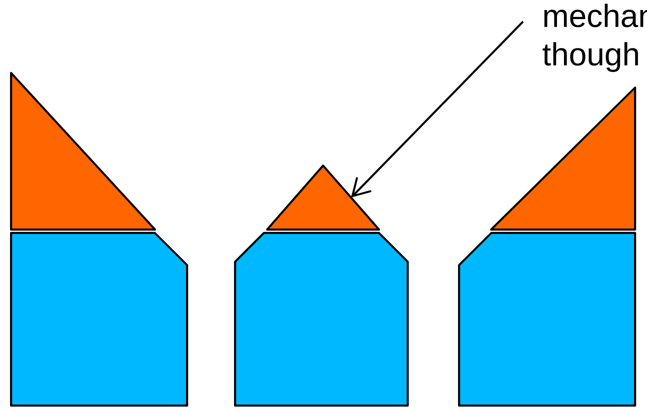
- Can have good selectivity (up to 15:1)
- Easy to pattern
  - Can use Bosch process

Cons

- Difficult to create
  - poly-Si has high stress
  - For deep etching, requires bonding a thin wafer
- Mask faceting lowers selectivity

Notes on Selectivity

- Quoted selectivity numbers almost always reference bulk material to bulk material
- Slower etch rate of high aspect ratio features result in much lower selectivity
- Faceting of the mask can reduce selectivity much further still
- We have achieved bulk selectivity between silica and silicon of 15:1, to KMPR of 7:1, but effective selectivity of KMPR is higher due to less faceting
- Effective selectivity for 10 micron silica trenches approaching 5:1 aspect ratio are around 4:1 for KMPR and 2:1 for silicon thus far



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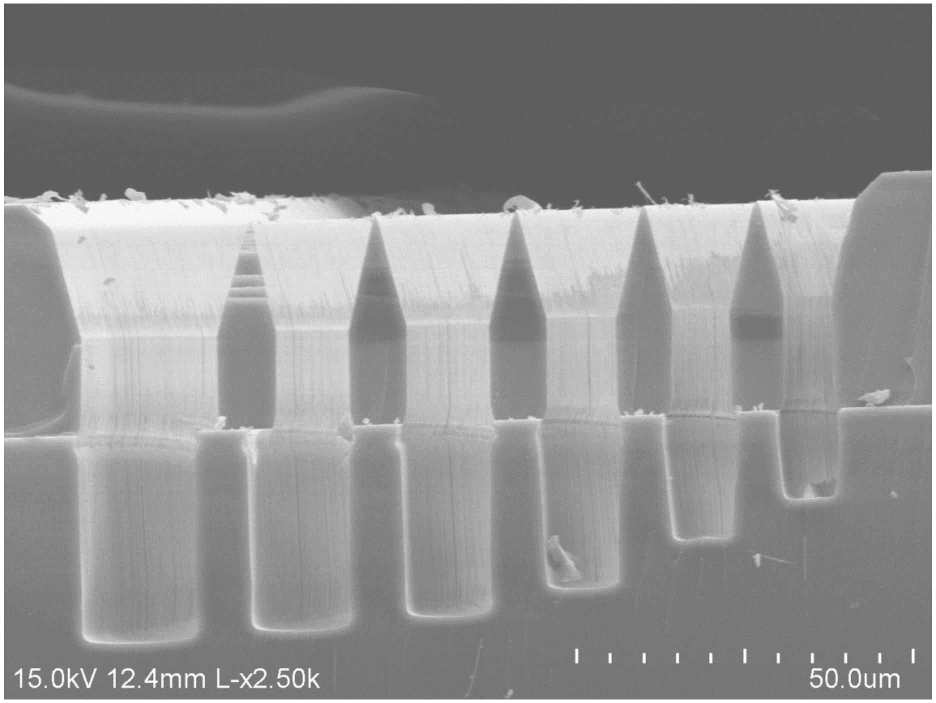
Si Masks

- Generally we see good bulk selectivity (>15:1)
- Mask faceting is a serious issue



Polymer Masks

Pros

- Easy to pattern
- Easy to remove, clean
- Post-process chamber clean is simple

Cons

- Thickness limitations
  - Standard PR limit ~20um
  - SU-8, KMPR can be patterned much thicker
- Typically low selectivity
  - ~2:1 for standard PR
- Low temperature tolerance

KMPR/SU-8 as a Mask

- Standard PR has low temperature tolerance
  - Can easily burn due to heat generated by plasma and ion bombardment
- SU-8 and KMPR are much more stable
- Slightly higher selectivity
- Both can be stripped using an O_2/CF_4 plasma

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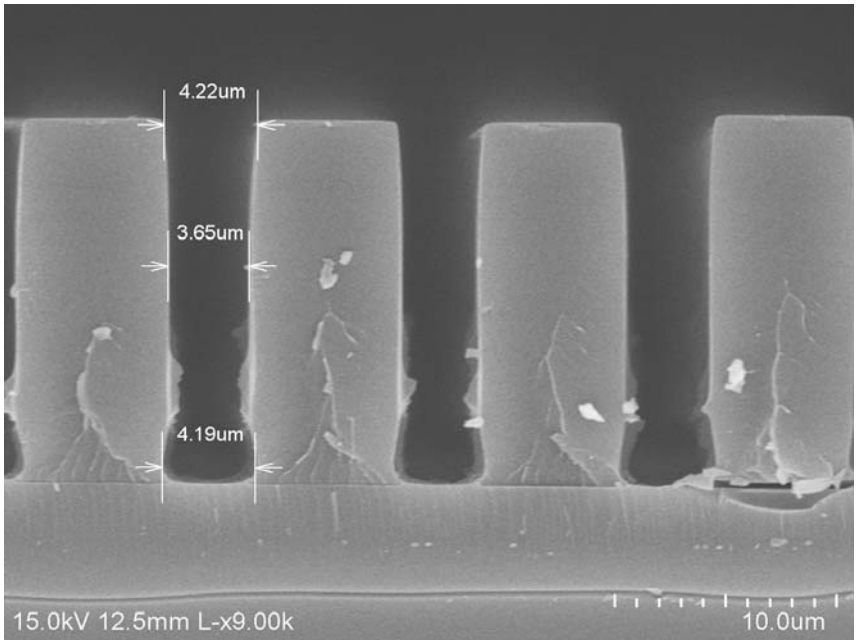
KMPR Patterning

- Can easily pattern up to 25µm
  - Thicker is harder, but very possible
- Develops in AZ 300
- Good resolution
  - 2µm features in 18µm of resist
- Vertical profile
  - Less risk of faceting
  - …



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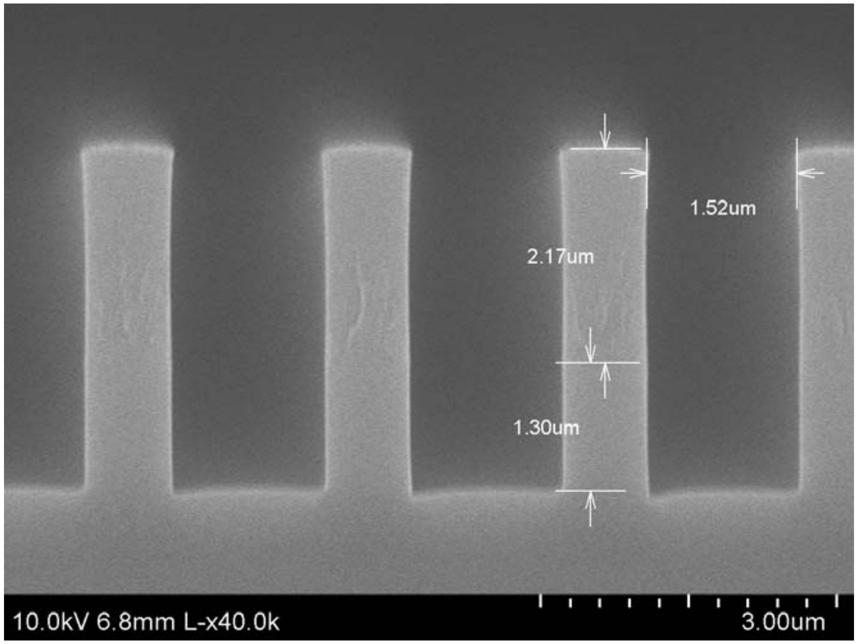
uk submicron etch

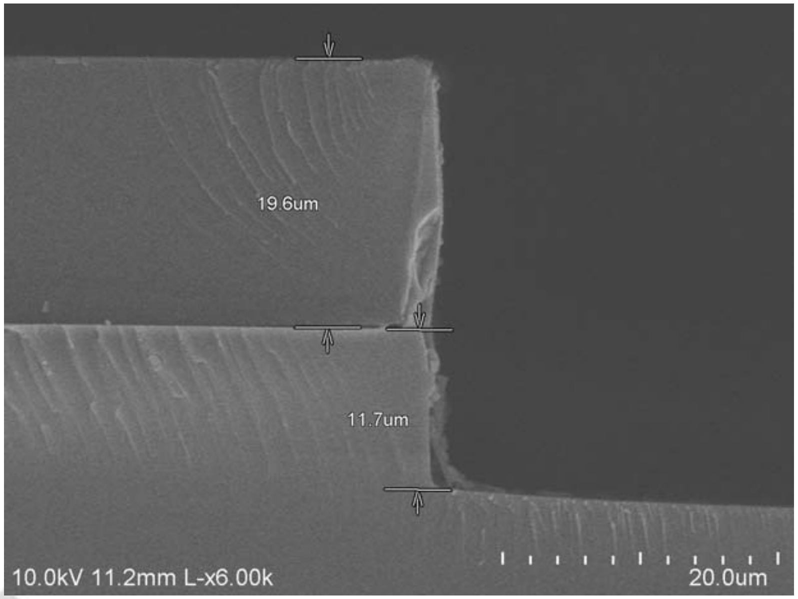
- Power
  - 1400W coil
  - 300W platen
- Pressure 4mTorr
- Gas
  - 10sccm C4F8
  - 174sccm He
- **0.24µm/min bulk etch rate**



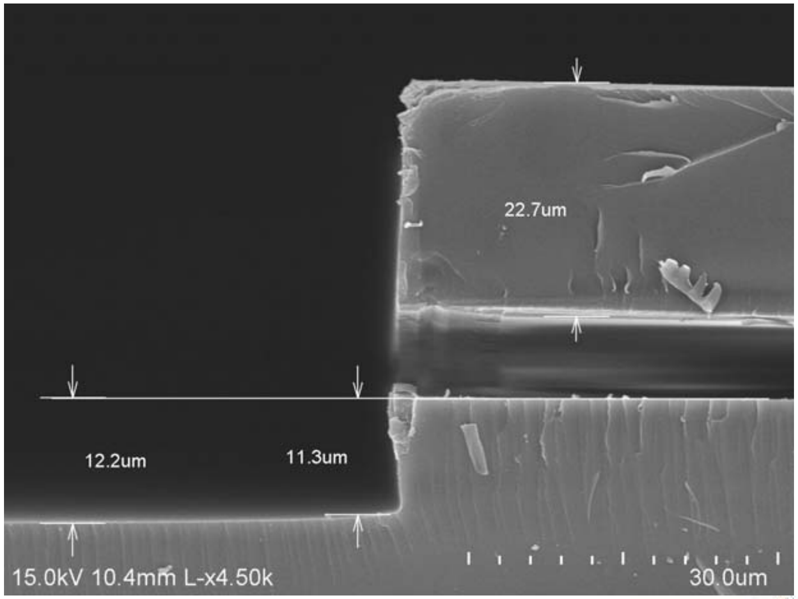
Improving Selectivity

H_2 addition can vastly improve selectivity

1400/400W
30:180 C4F8:He
Selectivity: 2:1



1400W/400W
30:20:170 C4F8:H2:He
Selectivity: ~4:1



Notes on Aspect Ratio

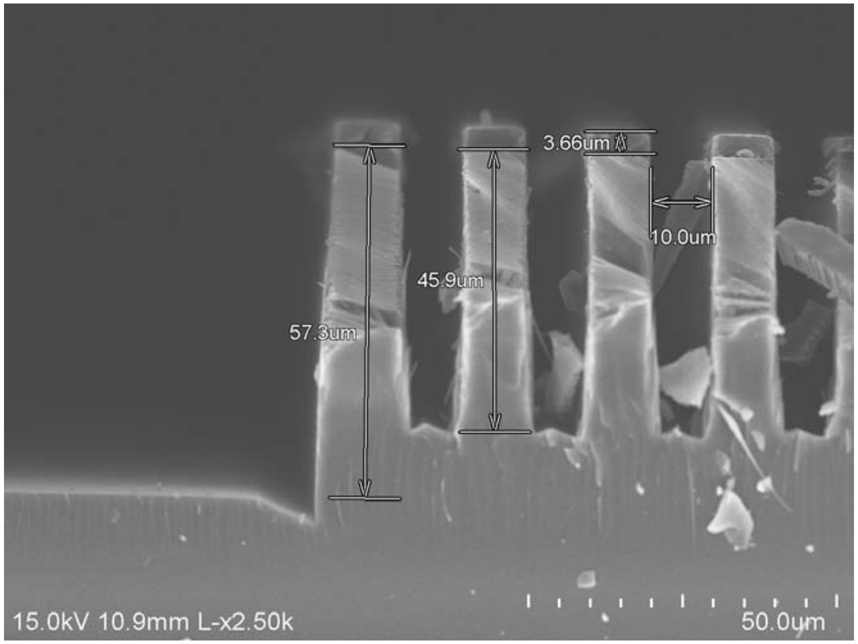
- Aspect ratio numbers are almost always quoted based on long trenches
- Holes are much more difficult to etch due to additional ion shielding and mass transport restriction
- Typically aspect ratio capability for holes is around 1/3 of that quoted for trenches
- Corners are effectively very high aspect ratio structures and they will tend to round as the etch progresses deeper

Increasing etch rate

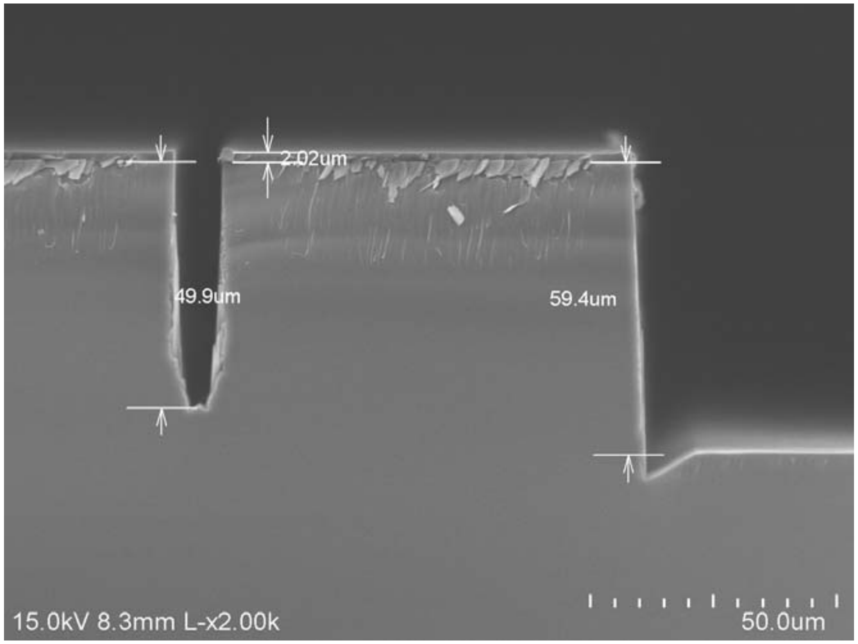
- Increased power
- Increased flow rate/ratio
  - More H_2 improved selectivity, to a point
  - With H_2, can have a larger C_4F_8:He ratio

Noble Gas Dilution

Helium



Argon



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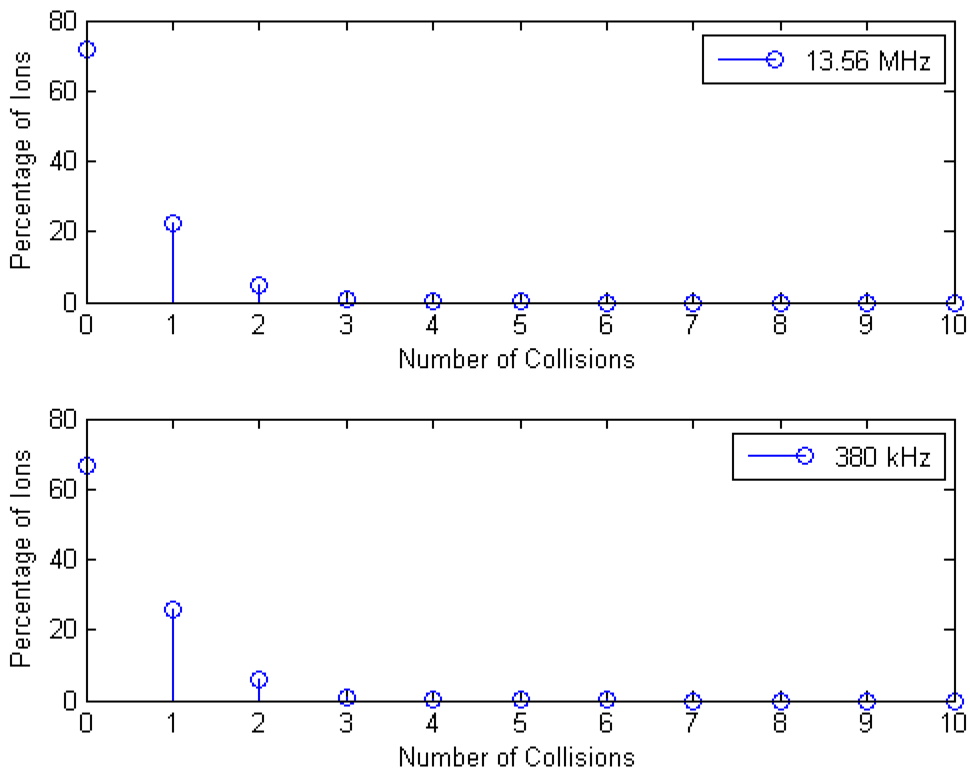
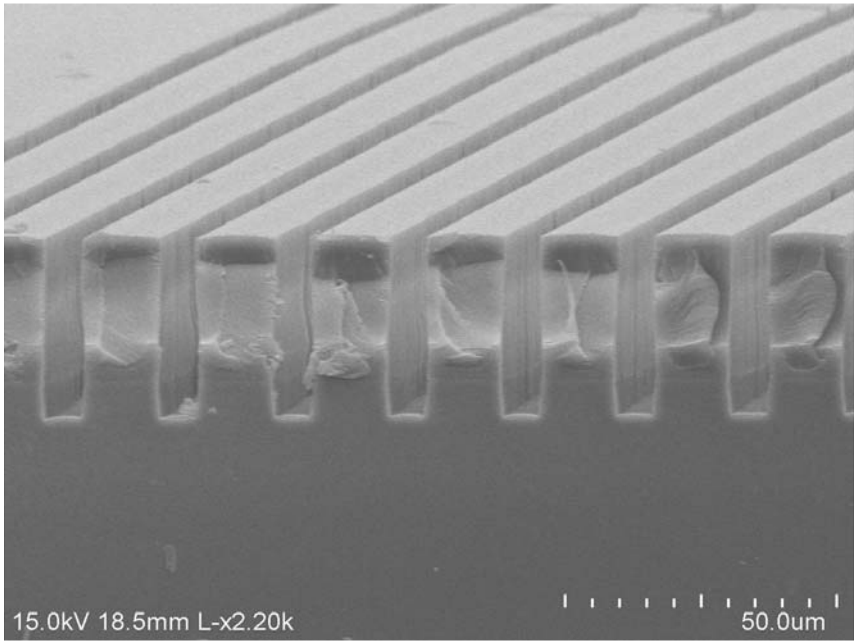
Noble Gas Dilution



Monte Carlo simulation based on plasma model in:
A. Vasenkov, et al. *J. Vac. Sci. Technol. A*. 22, 2004.

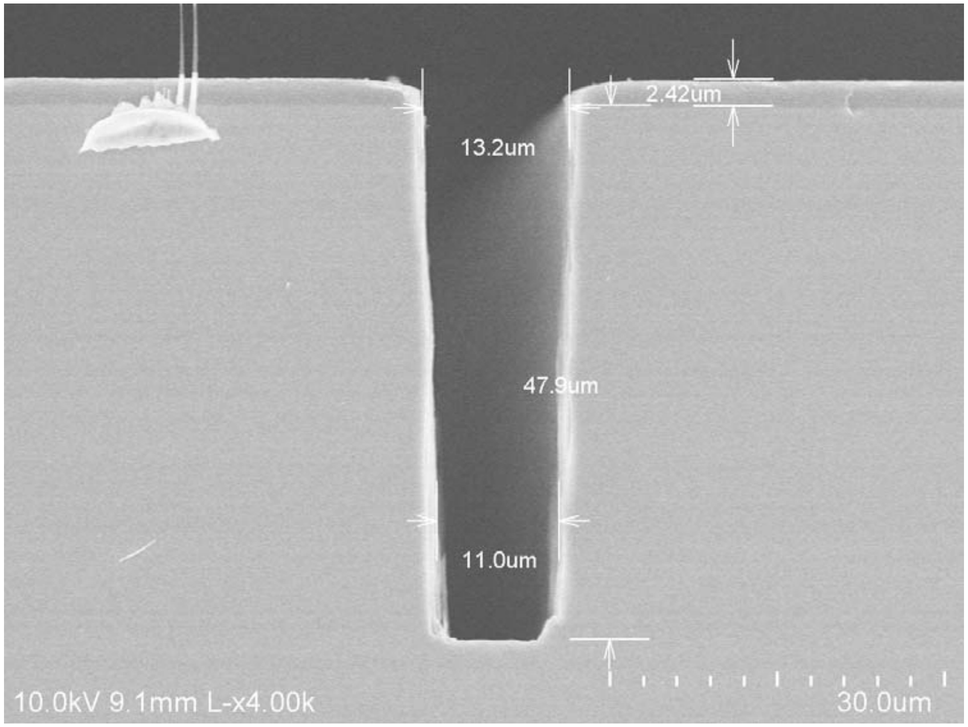
Final-ish process

- Power
  - 1400W coil
  - 600W platen
- Pressure 6mTorr
- Gas
  - 35sccm C_4F_8
  - 40sccm H_2
  - 200sccm He
- **0.48µm/min bulk etch rate**



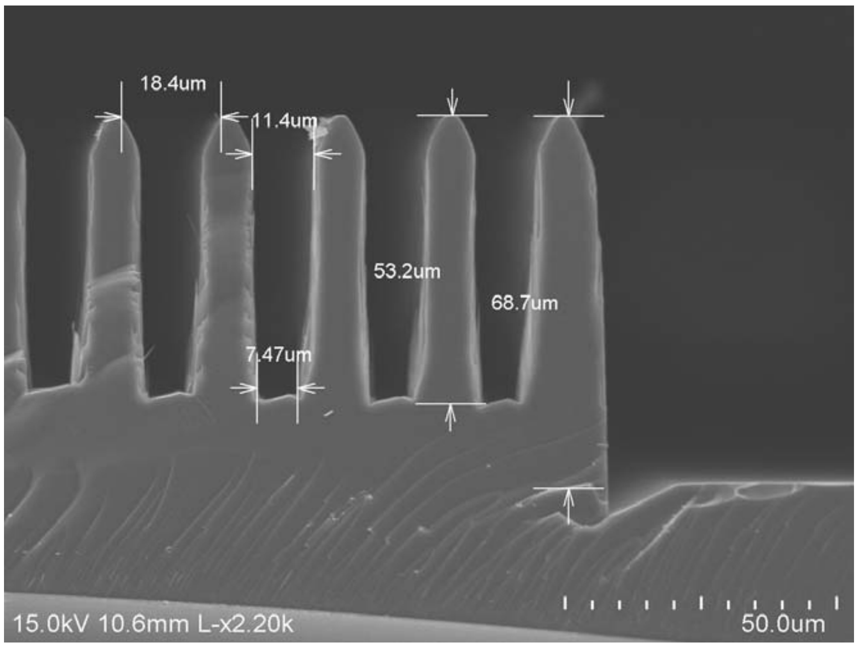
150 min etch

- Resolution not equivalent to metal mask yet, but getting closer
- 'Effective Selectivity' better than silicon mask

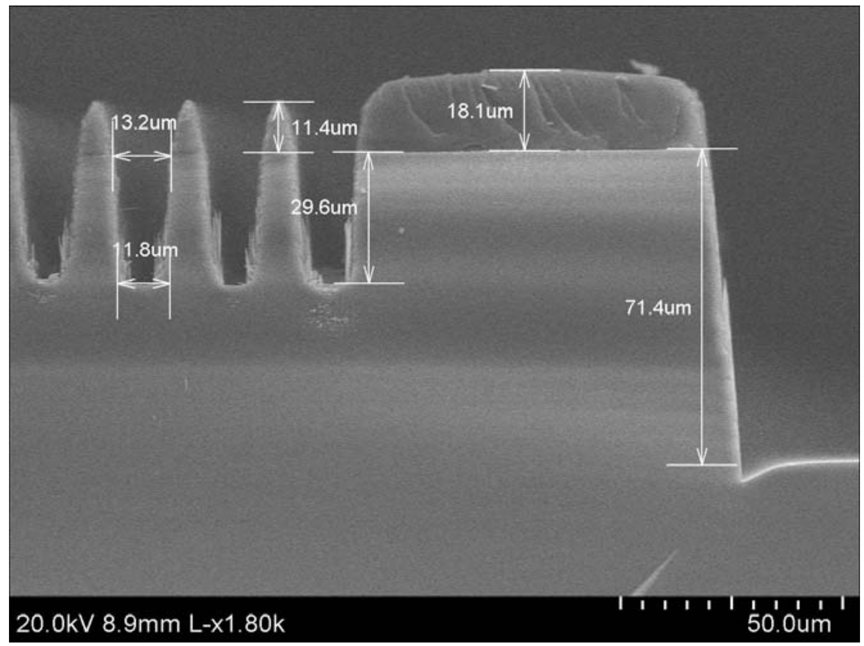


Process Variation

One time…



Another time…



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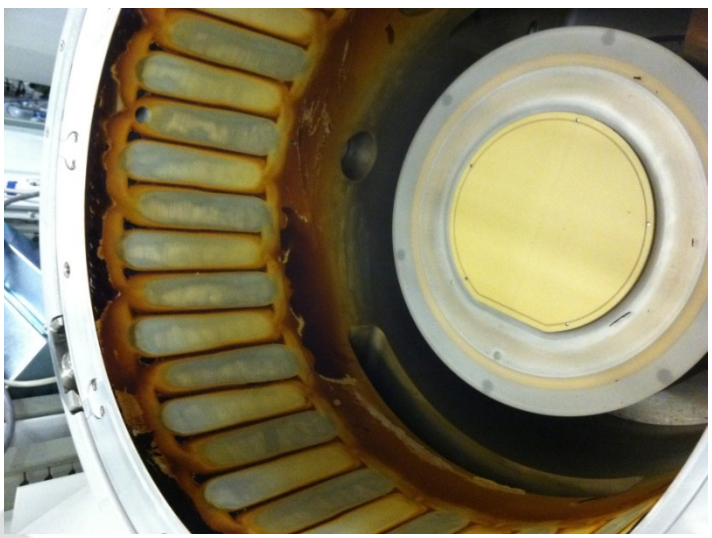
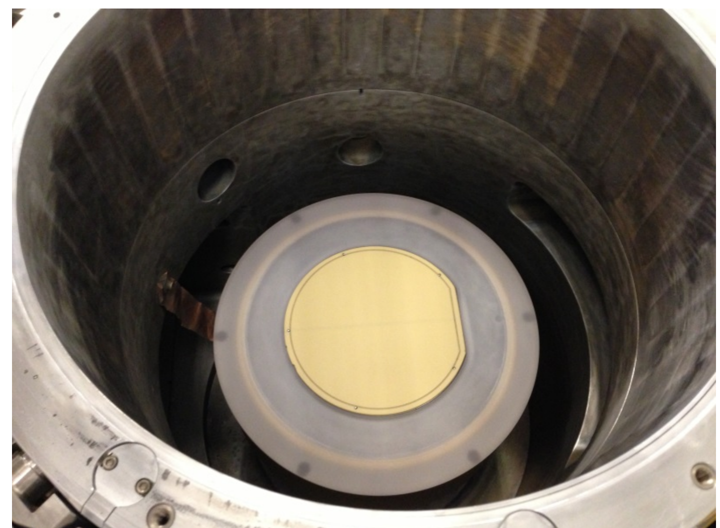
Effect of Chamber Condition

- Etch results can vary significantly with chamber condition
  - Likely results from a change in sheath potential between sample and plasma
  - Most obvious later in the process
- We added a ground strap to the platen – improved things significantly

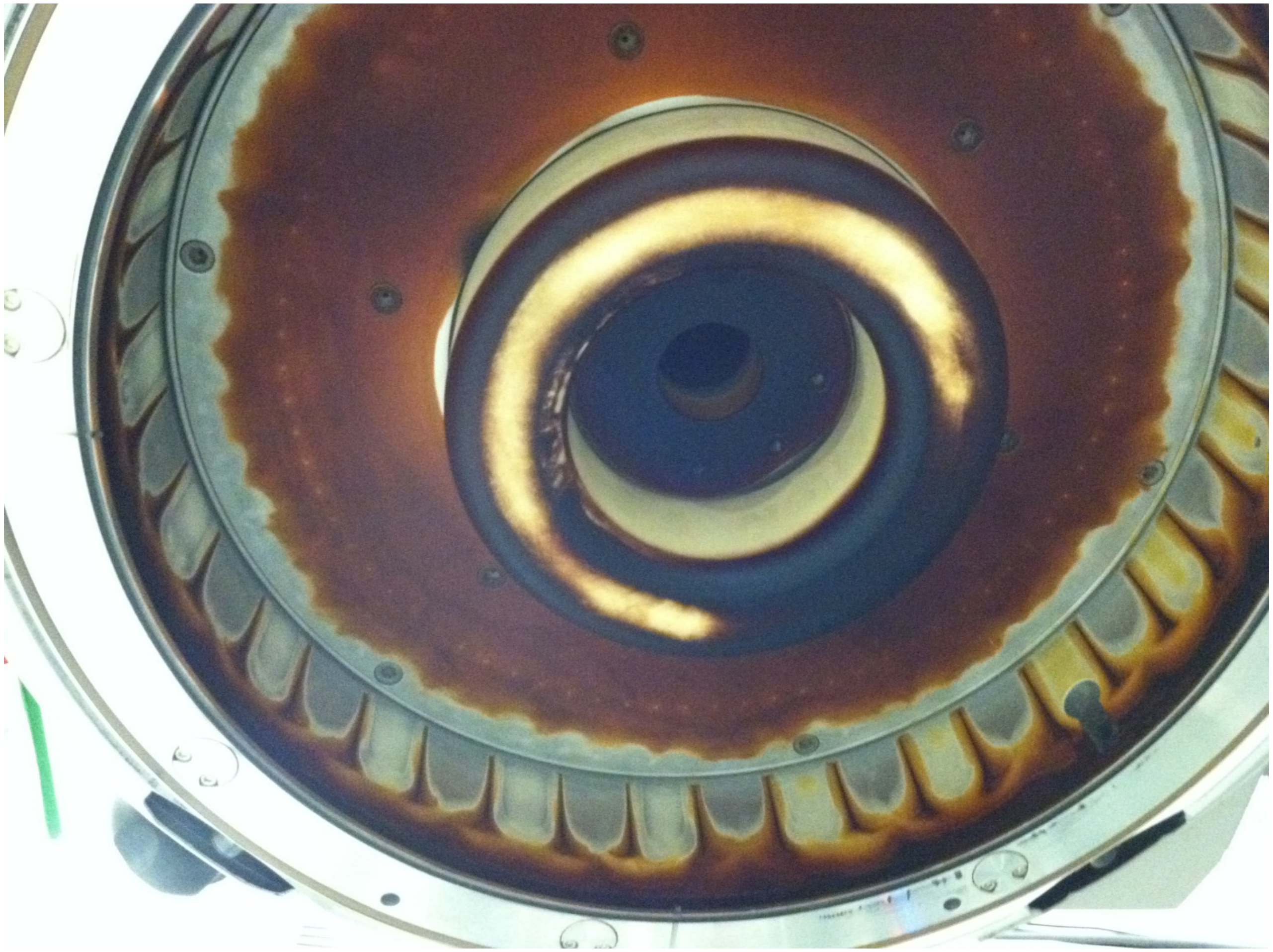
Chamber Cleans

- Add chamber cleans every 30min
  - Combination of SF_6 and O_2/CF_4 plasmas
  - 60min is too long without a clean
- Improved repeatability between etches
- Makes wet cleans much easier





Another fun pic…



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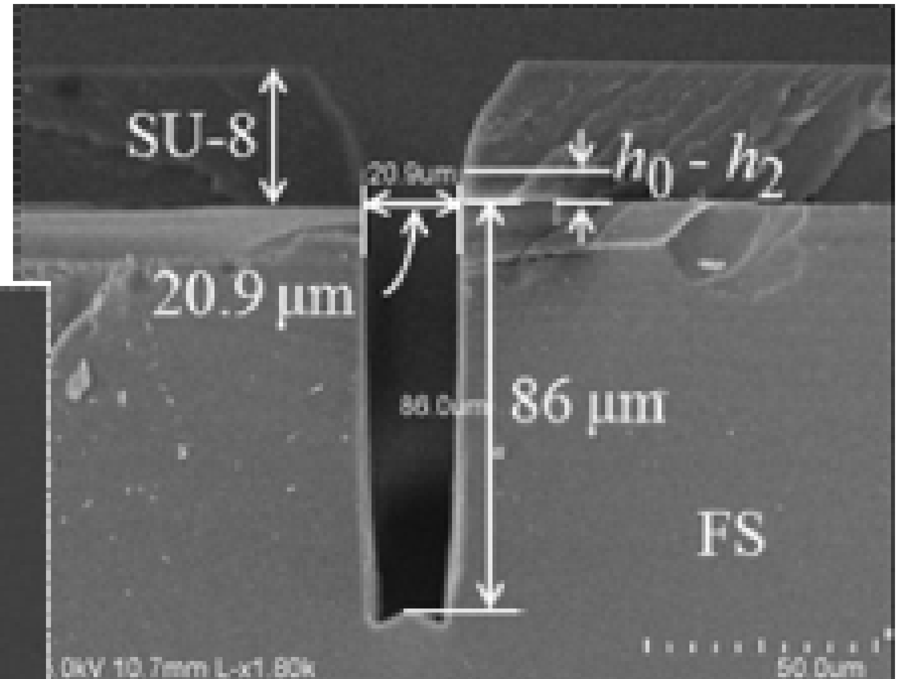
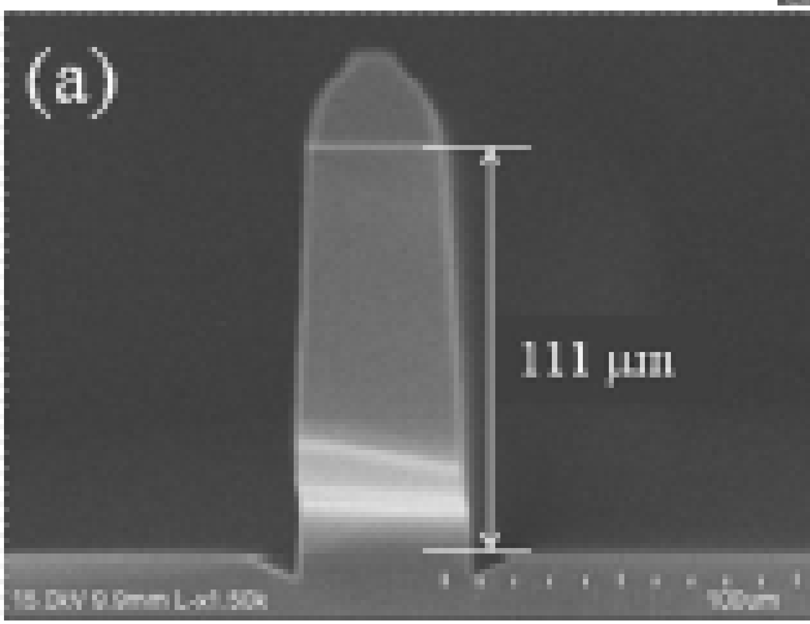
Final Results

- 4hr etch
- 48µm SU-8 mask

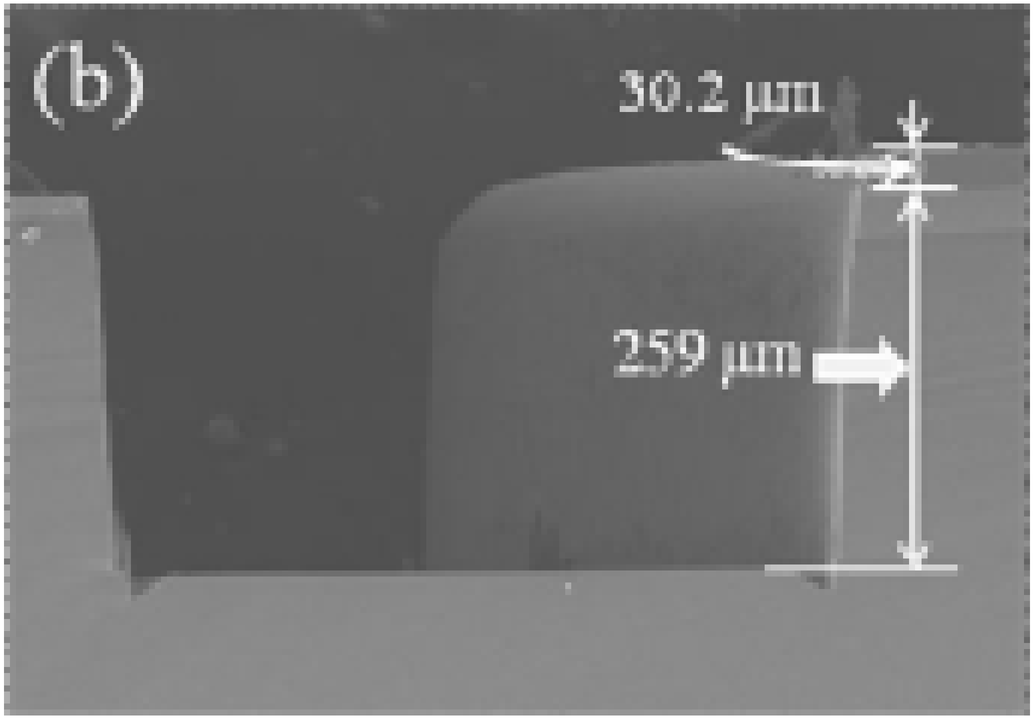




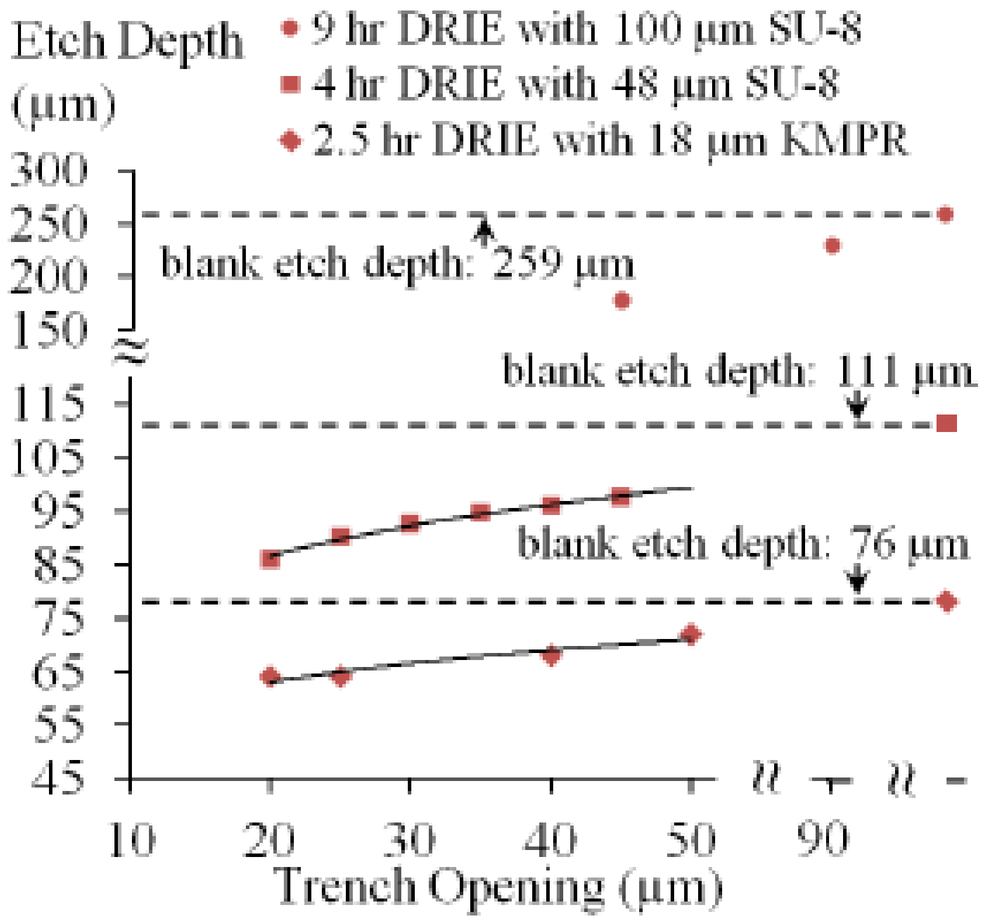
Results published in:
Z. Cao, et al. *MEMS 2013.*

Final Results

- 9hr etch
- 100µm SU-8 mask
  - Did not have great patterning
- Two wet cleans in between etching



Final Results



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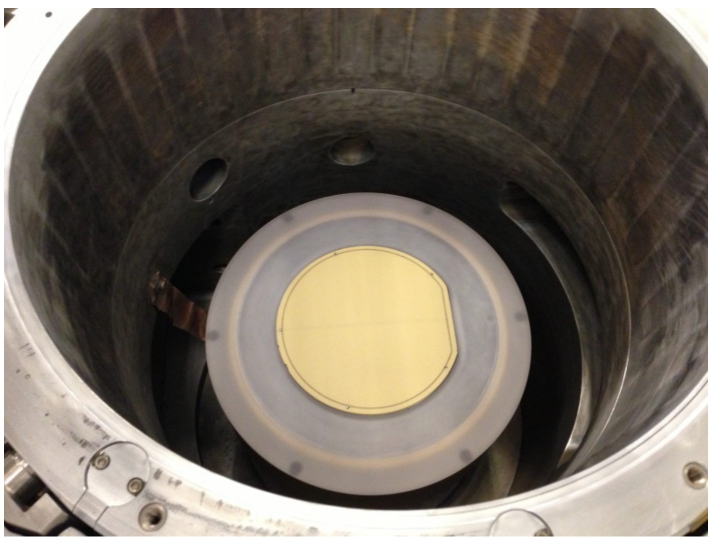
Issues moving forward

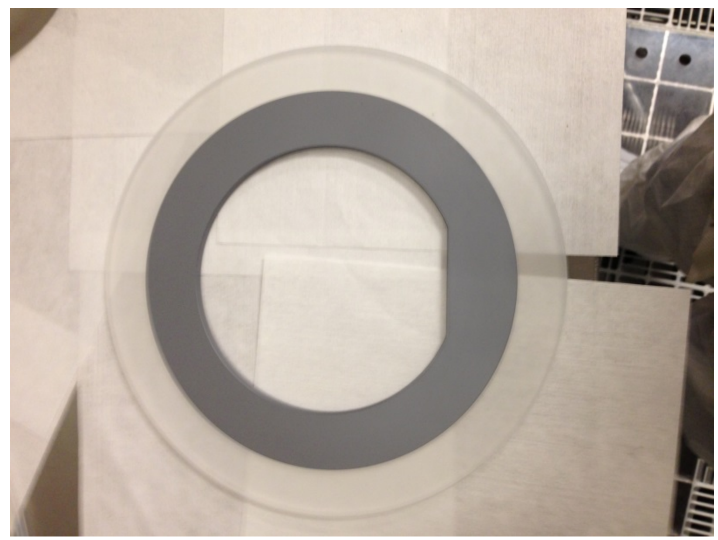
- We need better patterning of thick masks
  - i-line filtering of contact aligners
  - Reflective coating underneath (e.g. poly-Si)
    - Also could improve sidewall roughness
- How do we determine if chamber condition is good enough?
  - Working on a short nanoscale etch that can tell us
- Tool redesign

Tool redesign

Process Kits

- Comes with quartz ring
  - Gets etched during process
  - Plasma has no way to “talk” to the platen
- Have designed new process kit, not tested





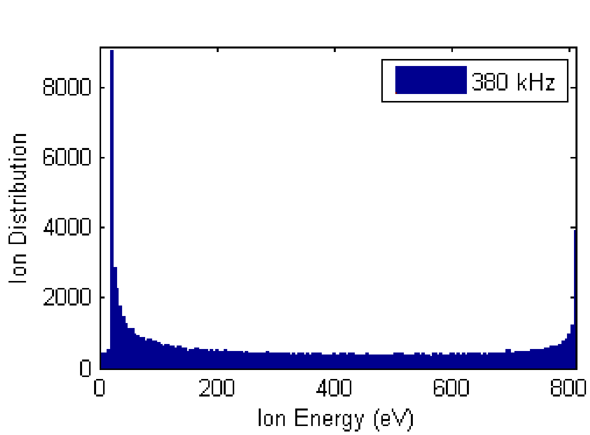
Tool redesign

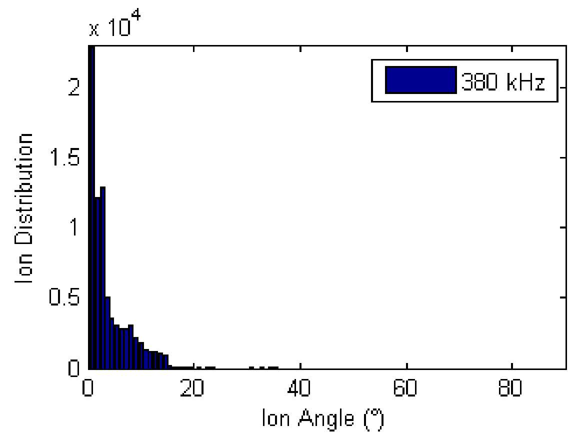
Bias Power Supply

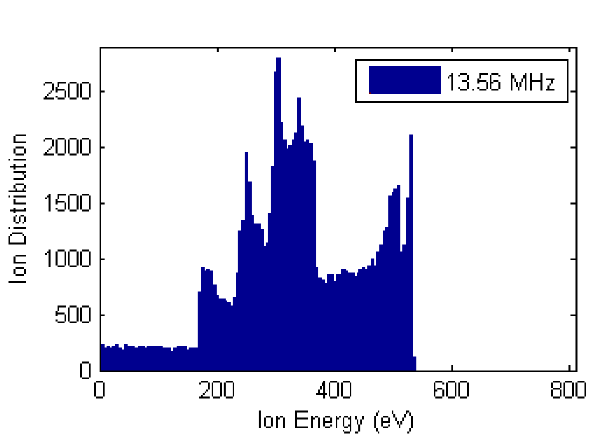
- Many effects and variability seem to come from charging
  - Pegasus tools come with low frequency, pulsed power supply
  - STS does not have a high power pulsed power supply option
  - We have investigated possible power supplies to integrate
- Low frequency power supply may actually improve ion energy

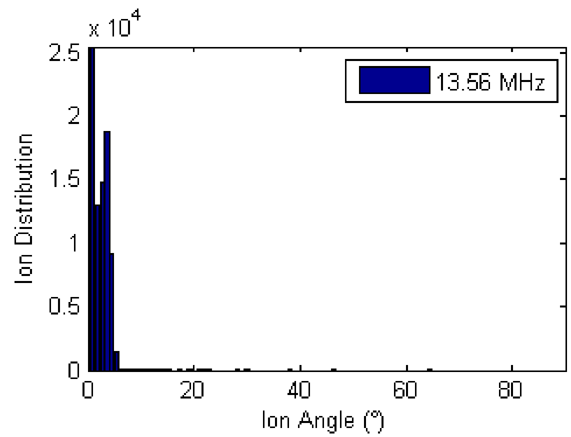
Tool redesign

Bias Power Supply









Conclusions

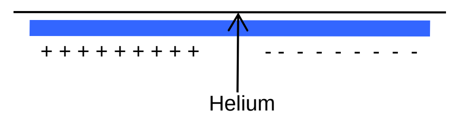
- Deep glass etching is HARD
  - Many of the tools out today are not the best
- We have shown significant improvement
  - For fused silica etching, mainly: almost 300µm deep
- Chamber condition and charging seem to be the most significant challenges
- Nanoscale deep etching is a goal for us currently
- Processing is more fun than fixing tools

Notes on Heat

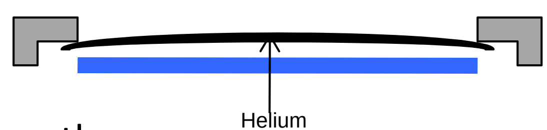
- The high power requirements of many deep etches create a great deal of heat
    - The plasma is hot
    - The chamber is hot to prevent redeposition
    - The reactions are often highly exothermic
- Good Cooling is critical – poor cooling may be catastrophic
- Good design should consider the transport path of heat from the surface of the sample and the etch interface to the cooled chuck
- Special circumstances that merit extra consideration
    - Bonded wafers with cavities – particularly if the bottom wafer is glass
    - Mounting to a handle to add structural support
    - Two sided etching where the etches meet

Electrostatic or Mechanical Chucking

- Electrostatic Chucks
    - Better cooling due to closer proximity of wafer
    - No bowing due to evenly distributed force
        - Better uniformity
        - Etch more perpendicular across wafer
    - Need handle wafer less often – generally only for through wafer etch
    - Intolerant to particulates – high rate of clamping failure in a research environment
    - Intolerant to topography on the bottom particularly near the perimeter
    - Most cannot clamp insulators



- Mechanical Clamping
    - Devices lost near the perimeter – exclusion area larger
    - Wafer bowing
    - Stress on wafer necessitates a handle much more frequently
    - Much more tolerant to variances on the wafer back side
    - Will clamp any material



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Conclusions

- Deep, high aspect ratio etching is difficult, particularly if the material is not silicon
- Maximize your chances of success
  - Minimize, depth and aspect ratio requirements as much as possible during the design phase
    - Consider thinner substrates or etching from both sides
  - Stick with well established processes
  - Remain within repeatedly published parameters when your existing processes aren't adequate
    - Remember, published data is often best case scenario on optimized test patterns
    - Process parameters do not translate exactly from one tool to another
- Remember
  - Avoid metal mask if at all possible – minimize exposed metal if you must use it
  - Quoted mask selectivity usually references bulk material, high aspect ratio structures will experience much lower selectivity
  - Quoted aspect ratios apply to trenches – hole capability is around 1/3