Electro-Mechanical Characterization of Gold Nanowire Meshes

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M A T S

Abstract:

The fabrication of stretchable interconnects is imperative for producing stretchable and flexible microelectronic devices, but current patterning approaches are limited to micron-scale features. Successful fabrication of smaller stretchable devices requires the use of new patterning methods, and block copolymer lithography is an emerging technique capable of patterning feature sizes below 10 nm. Upon self-assembly, lamellar-forming block copolymers generate a pattern colloquially known as the "fingerprint" morphology, due to the loops, whorls, and curved interfaces. The lamellar pattern shares many structural features with stretchable interconnects for macroelectronics, and successful translation of the pattern into functional materials may enable the production of stretchable electronic devices at sizes magnitudes smaller than state-of-the-art.

In this work, lamellar-forming polystyrene-block-poly(methyl methacrylate) (PS-*b*-PMMA) was used as a template to fabricate continuous gold nanowire networks (nanomeshes). The sheet resistance of these nanomeshes was below 1000 Ω/☐ and the nanomeshes were nearly transparent, with transmittances greater than 85% across the visible spectrum. Successful transfer of the nanomeshes to stretchable substrates showed that nanomesh continuity was maintained during strain — because the path length between network nodes was much greater than the distance between nodes, allowing individual nanowires to elongate and straighten in the direction of strain while maintaining continuous pathways for charge transport.

Introduction:

The motivation of our research is the miniaturization of stretchable and flexible electronic devices. The fabrication of stretchable and flexible microelectronics depends on the fabrication of stretchable and flexible interconnects that present nanoscale features, but current interconnects, known as microribbons, are several microns wide. The nanoscale morphological analogues of microribbons are nanowire networks that assume patterns created by the random self-assembly of lamellar block copolymer structures.

The block copolymer template we use is polystyrene-block-poly(methyl methacrylate) (PS-*b*-PMMA). Since we want continuous nanowire networks, it is important to adjust the composition of PS-*b*-PMMA so that there is a continuous PMMA domain over the wafer. The curvy domains of the block copolymer ensure that the nanowire network will be stretchable once fabricated because the path length between two points is significantly larger than the distance between them. When submitted to a strain, wires will straighten and align themselves in the direction of the force, ensuring that network continuity is maintained.

Fabrication Process:

Block copolymer self-assembly was the first step in the fabrication process of the nanowire networks. A polymer brush was applied to a silicon oxide wafer. This allowed the lamellar structures of PS-*b*-PMMA to orient themselves perpendicularly to the wafer, assuming a two dimensional structure. To achieve lamellar PS-*b*-PMMA structures with a PMMA domain that was continuous throughout the wafer area, the block copolymer's volume fraction had to be adjusted so that there was slightly more PMMA than PS. The end result of this process was a block copolymer that presents a "fingerprint" morphology.

The next step in the process was to remove the continuous PMMA domain from the wafer by exposing the sample to UV light and submerging it in acetic acid. This was followed by a descum step with an oxygen plasma reactive ion etch (RIE), completing a template for continuous nanowire networks. A 2 nm chrome adhesion layer was evaporated, followed by evaporating the desired thickness of gold. PS was then removed by sonicating the sample in toluene, and the nanowire network was all that remained on the silicon oxide, as seen in Figure 1.

Finally, the nanowires were undercut by an SF_6 plasma RIE and transferred to a stretchable or flexible substrate.

Results and Conclusions:

The nanomesh sheet resistance was measured using a two-point probe. We used manually-placed silver epoxy dots as electrodes, verifying under an optical microscope that the electrodes were not short-circuiting the probe measurement, and found areas that were conductive over distances of a few hundred microns.

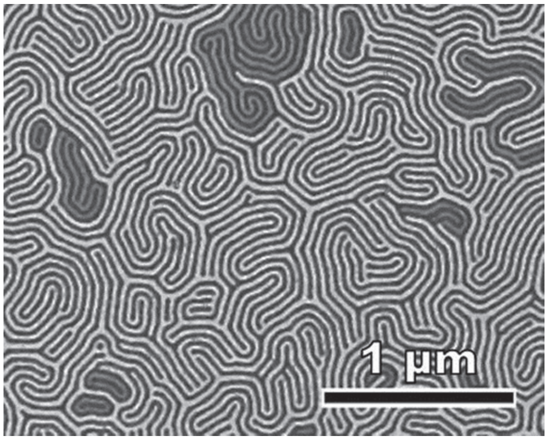

Figure 1: Gold nanomesh. The brighter nanowires are part of a continuous network.

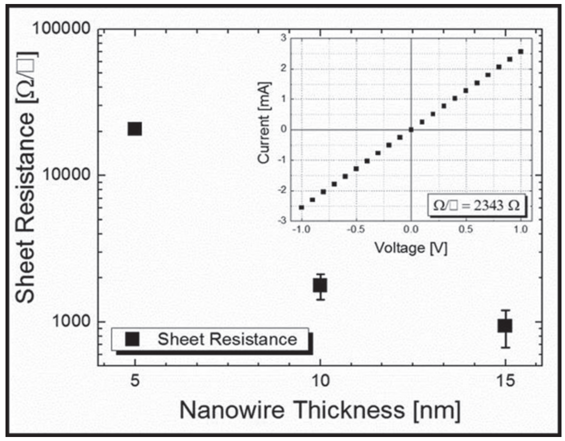

Figure 3: Sheet resistance of nanomeshes of various thicknesses.

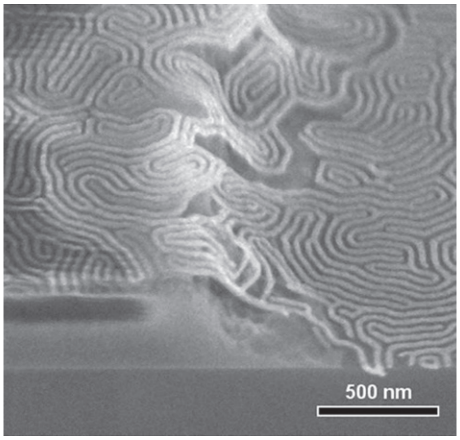

Figure 2: Nanowires stretching to accommodate different step heights.

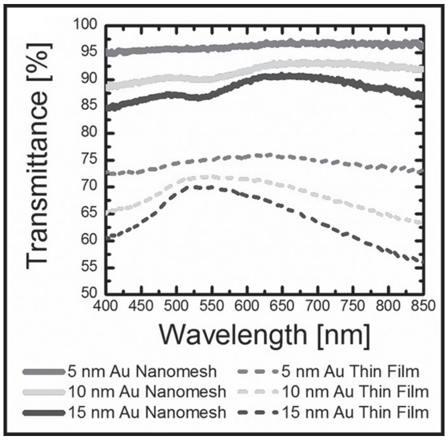

Figure 4: Optical transmittance of nanomeshes throughout the visible spectrum.

Prior to transferring the nanowires to a flexible or stretchable substrate, sheet resistances for nanomeshes of different thicknesses were measured. Nanomeshes that were 15 nm thick had sheet resistances of under 1000 Ω/□. As the nanomesh thickness decreased to 10 nm, the sheet resistances increased to 2000 Ω/□. Transmittances of over 85% were achieved throughout the visible spectrum for 15 nm thick nanowires, a very significant improvement over gold films of the same thickness.

After transferring a different 15 nm nanomesh to a flexible substrate, we achieved a sheet resistance of 3200 Ω/□, showing that the continuity of the network was preserved during the process of transferring the nanowires to a stretchable or flexible substrate.

Our fabrication process was not exclusive to gold nanomeshes. We have also fabricated chrome, zinc oxide, aluminum, silver, copper, and amorphous silicon networks. As a side project, we used nanowire networks composed of these different materials as etch masks for high aspect-ratio anisotropic etching, achieving etches that were several hundred nanometers deep with mask structures that were 25 nm wide. This significantly increased the light absorption of silicon, and could potentially be used to increase the efficiency of solar cells.

Future Work:

The focus of the project was to characterize the electrical and optical properties of gold nanowire networks, as we strived to achieve low sheet resistance and high optical transmittance over the visible light spectrum. We reached these goals and determined that the next step that should be taken in future research is to fabricate devices that are connected by stretchable nanomeshes, as the end goal is to enable the fabrication of stretchable or flexible microelectronics.

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