Fabricating Self-Rolling Microtubes for Tuning Semiconductor Bandgaps

2016 CNF REU Intern: Maya Martirossyan, Physics, Harvey Mudd College

CNF REU Principal Investigator: Prof. Grace Xing, Materials Science & Engineering and Electrical & Computer Engineering, Cornell University

CNF REU Mentor: Rusen Yan, Electrical & Computer Engineering, Cornell University

Primary Source of Research Funding: National Science Foundation under Grant No. ECCS-1542081

Contact: mmartirossyan@g.hmc.edu, grace.xing@cornell.edu, ry253@cornell.edu

Abstract:

The coupling between the mechanical and the optoelectronic properties of a semiconductor suggest the possibility of tuning a semiconductor's bandgap by applying mechanical strain. Transparent insulator materials can be used to roll two-dimensional (2D) semiconductors to apply mechanical strain and observe the resulting optical properties. Using silicon nitride (SiN_x) layers of differential strain, we fabricated self-rolling microtubes, the smallest of which have dimensions of 10 × 20 µm. The diameter of the microtubes can be controlled by tuning the stress and the thickness of our SiN_x bilayer.

Introduction:

A semiconductor's bandgap determines its optical and electrical properties. However, these properties are coupled with the mechanical properties of the semiconductor. It has been shown that an applied uniaxial strain can alter the bandgap of 2D molybdenum disulfide (MoS_2) semiconductors, which gives rise to powerful applications such as tunable photodetectors, LEDs, and electro-optical modulators, as well as nanoscale stress sensors [1].

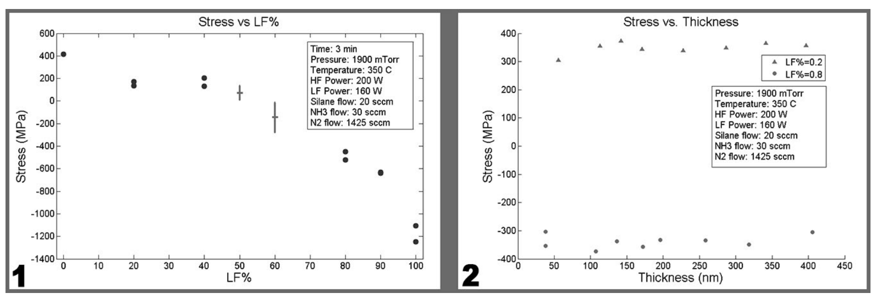


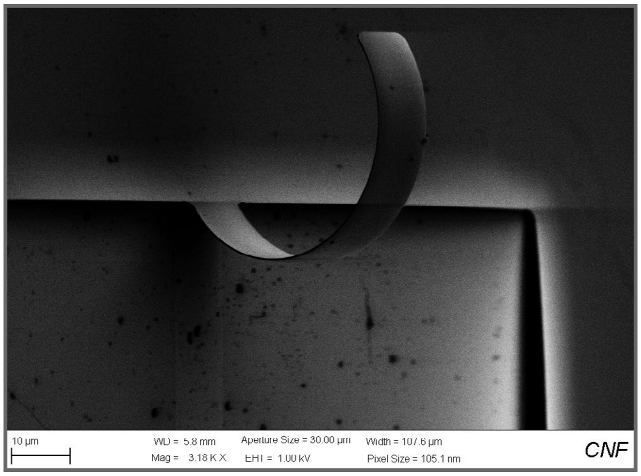
Figure 1, left: Stress vs. LF% for depositing SiN_x on the Oxford PECVD, which tells us how to control the stress of each SiN_x layer by changing the percentage of time that low frequency signal is used to ionize the plasma. Figure 2, right: Stress vs. Thickness for depositing SiN_x on the Oxford PECVD, which means we can tune the thickness of a film without affecting its stress.

Our goal is apply strain to a 2D semiconductor by making it curl. We will roll the 2D semiconductor by attaching it onto a self-rolling microtube of a transparent insulator material, in our case silicon nitride (SiN_x). Bilayer SiN_x will roll due to differential stresses between the layers [2,3]. The aim of my project was to create these self-rolling microtubes. Once rolled, we can test the optical properties of the semiconductor in order to determine the changes in its bandgap.

Summary of Research:

We used bilayer SiN_x with a bottom compressive film and a top tensile film in order to create self-rolling structures. The Oxford plasma-enhanced chemical vapor deposition (PECVD) tool was used to deposit our SiN_x layers. The diameter of our rolled-up microtubes is primarily influenced by both the thickness and the stress of the layers. Thinner SiN_x layers result in tubes of smaller diameters [2]. As seen in Figure 1, the stress of the layer can be tuned by changing the ratio between the amount of low frequency signal (LF) and high frequency signal (HF) used to excite the plasma during deposition (this parameter is called LF%). The thickness of a film can be tuned by changing the deposition time without affecting the stress of the film, as shown in Figure 2.

For our SiN_x bilayers, we chose to have the highest possible compressive and tensile stresses for each layer to best match the literature, which meant using LF% = 100 for compressive films, and LF% = 0 for tensile films [2].



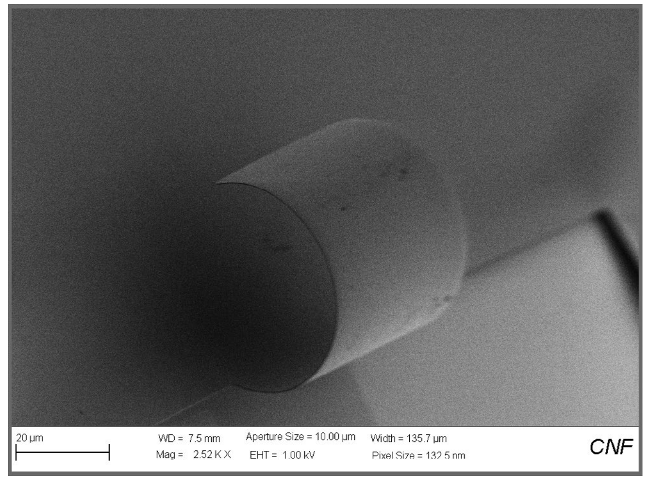


***Figure 3, left:** Curled cantilever with dimensions 10 x 70 microns. Image taken using SEM tool at a 45 degree angle.* ***Figure 4, right:** Curled cantilever with dimensions 40 × 200 microns. Image taken using SEM tool at a 45 degree angle.*

We chose to try two designs in our fabrication process. Both designs included a rectangular pattern that would curl upward off the surface of the substrate and form microtubes. The rectangular patterns ranged from aspect ratios of 1:2 to 1:7, and from widths of 10-160 μm.

Design I required making a 20 nm thick Ge rectangular mesa using e-beam evaporation, and depositing and patterning bilayer SiN_x on top using optical lithography and RIE etching [2]. Then, the Ge mesa was isotropically wet etched with 30% wt. H_2O_2 at 70°C from one side of our rectangular features, releasing the rectangular structures. We were not able to successfully release our structures with this design, but it is the most similar to the procedure used in the literature, and is still a viable design.

Design II required making a 20 nm thick Ge layer using e-beam evaporation, depositing bilayer SiN_x on top and patterning a cantilever structure using optical lithography and RIE etching. Then, three sides of the cantilever were undercut and released by isotropically wet etching the Ge with 30% wt. H_2O_2 at 70°C and drying with IPA. We were successful in getting microtubes to roll along their longitudinal axis, as desired.

Results and Conclusions:

Using SEM imaging, we were able to obtain pictures of our self-rolling microtubes that were made using Design II. Both images in Figure 3 and Figure 4 were from a wafer where the stress of SiN_x compressive layer was -1150 MPa, the thickness of compressive layer was 109 nm, the stress of SiN_x tensile layer was 415 MPa, and the thickness of tensile layer was 134 nm. The feature in Figure 4 was released after a longer wet etch time than the feature in Figure 3, since the feature is Figure 4 is significantly larger and thus needs more time for the wet etch to undercut the entire feature.

Future Work:

With our fabrication procedure working, we can next make tubes of different diameters by changing the thickness of the SiN_x bilayer. Additionally, it will be important to characterize the diameter of the tubes as a function of SiN_x film thickness. These tubes can then be used to strain 2D MoS_2 semiconductors and measure their optical properties. Characterization of the Oxford PECVD, Oxford 80 Etcher, and ABM contact aligner can be refined as well. Lastly, other alternatives may be explored to create microtubes, such as polyimide, a stressed polymer, or LPCVD silicon nitride, but the strain control in these films needs to be understood first.

CNF Tools Used:

Oxford PECVD, SC4500 odd-hour evaporator, Oxford 82 etcher, ABM contact aligner, Flexus film stress measurement, P10 profilometer, Heidelberg Mask Writer-DWL2000, Zeiss Ultra/Supra SEM.

Acknowledgements:

I would like to thank my PI, Prof. Grace Xing, and my mentor, Rusen Yan, for instructing and helping me throughout my project. I would also like to thank the CNF REU Program Coordinators and the CNF Staff. This research was supported by the National Science Foundation under Grant. No. ECCS-1542081.

References:

[1] H.J. Conley, B. Wang, J.I. Ziegler, R.F. Haglund, Jr., S.T. Pantelides, and K.I. Bolotin. "Bandgap Engineering of Strained Monolayer and Bilayer MoS2." Nano Letters 2013 13 (8), 3626-3630.

[2] W. Huang, S. Koric, X. Yu, K. J. Hsia, and X. Li. "Precision Structural Engineering of Self-Rolled-up 3D Nanomembranes Guided by Transient Quasi-Static FEM Modeling." Nano Letters 2014 14 (11), 6293-6297.

[3] P. Froeter, X. Yu, W. Huang, F. Du, M. Li, I. Chun, S.H. Kim, K. Hsia, J. Rogers, and X. Li. "3D hierarchical architectures based on self-rolled-up silicon nitride membranes." Nanotechnology 24, 475301 (2013).