Thin Films from Atomic Layer Deposition for Membranes, Metamaterials, and Micromachines

CNF Project Number: 900-00

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Primary CNF Tools Used: Oxford FlexAL ALD, Arradiance ALD, Autostep AS200 i-line stepper, CVC e-beam evaporators, Oxford 81/82 etchers, PT770 and PT740 etchers, Anatech Asher, Zeiss SEMs, Veeco atomic force microscope, Tencor P7 profilometer, Filmetrics UV, Woollam ellipsometer, DISCO dicing saw, Heidelberg DWL2000

Abstract:

Ultra-thin films of inorganic materials are well-suited for fabrication of micron-scale actuators because they can sustain small radii of curvature, have large force outputs, are compatible with semiconductor processing, and are chemically robust. We leverage atomic layer deposition (ALD) on sacrificial substrates to produce micron-scale free-standing mechanical devices with sub-5 nm film thicknesses. We fabricate cantilever springs from ALD films and characterize the material's bending stiffness and elastic properties. We find values for the bending stiffness that are consistent with expectations from elasticity theory. The mechanical properties of ALD are further modified by lithographic patterning of the ALD. Lattices imposed into the film decrease its effective Young's modulus. We integrate these results and device concepts to produce magnetically actuated three-dimensional devices with applications in micromachinery. Our results establish thin ALD films as a scalable basis for micron-scale actuators and robotics.

Summary of Research:

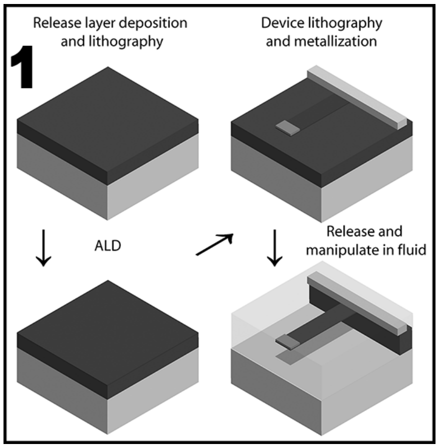
Self-folding is a strategy for producing both static and dynamic three-dimensional devices from two-dimensional sheets at all size scales [1,2]. This conceptual framework is particularly well suited to the fabrication of micron-scale machinery because the dominant mode of manufacturing microscopic features is two-dimensional lithography. Folding therefore enables production of three dimensional parts by lithography. Furthermore, process integration with electronics fabrication is retained in this approach.

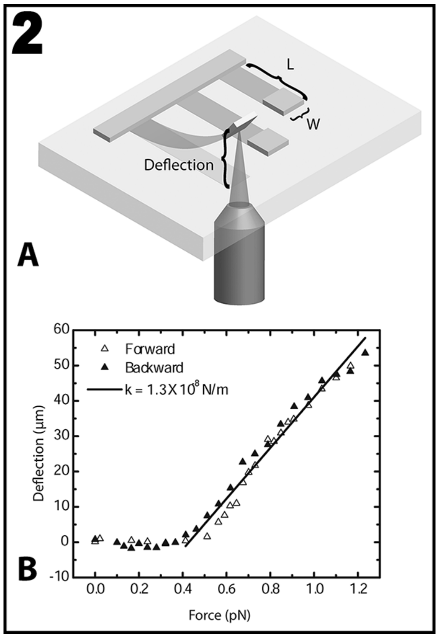
The relevant energy scale for design of micro-actuators is the actuator's bending stiffness. Micro-actuators that produce large deflections for small energy inputs must be made out of a material with low bending stiffness. Our approach is to scale hard materials to atomic-scale thicknesses [3-5]. In this work, we demonstrate that sub-10 nm thin films produced by atomic layer deposition (ALD) can serve as the backbone of small machinery.

We fabricate mechanical devices using ALD on films of aluminum, as is described in Figure 1. The aluminum serves as a sacrificial layer that can be undercut during wet-etching in dilute developer solution to release completed devices from the fabrication substrate. We manipulate devices in aqueous environments with surfactants to avoid stiction between the films and the substrate.

We use optical forces supplied by an infrared laser to actuate cantilever beams fabricated from 5 nm thick films of SiO_2 (Figure 2a). Although these forces are very weak, they can produce large deflections in the beam because of the low spring constants achievable. A force-distance curve from a representative device (Figure 2b) shows reversible elastic behavior with a spring constant on the order of 10^{-8} N/m, over nine orders of magnitude lower than typical AFM cantilevers.

The tailorable elastic response of springs fabricated from thin ALD films inspires design of stretchable metamaterials composed of panels and hinges. Figure 3a shows a sheet with a triangular lattice patterned with metallic panels. The cut pattern is shown in the inset.





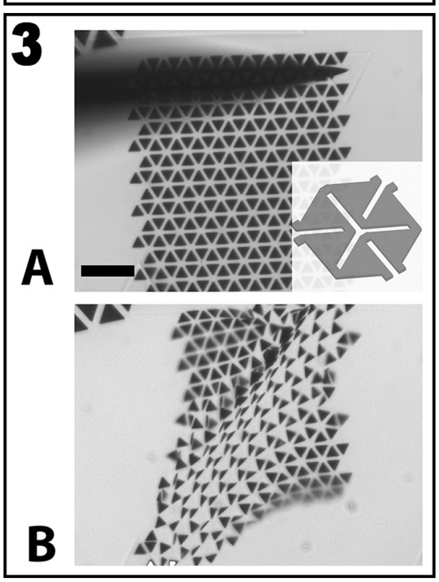


__Figure 1, top:__ Fabrication of free-standing films from atomic layer deposition. ***Figure 2, middle:*** *Mechanical characterization of 5 nm thick films of SiO_2.* ***Figure 3, bottom:*** *Stretchable meta-materials fabricated from SiO_2 hinges (scale bar 30 µm).*

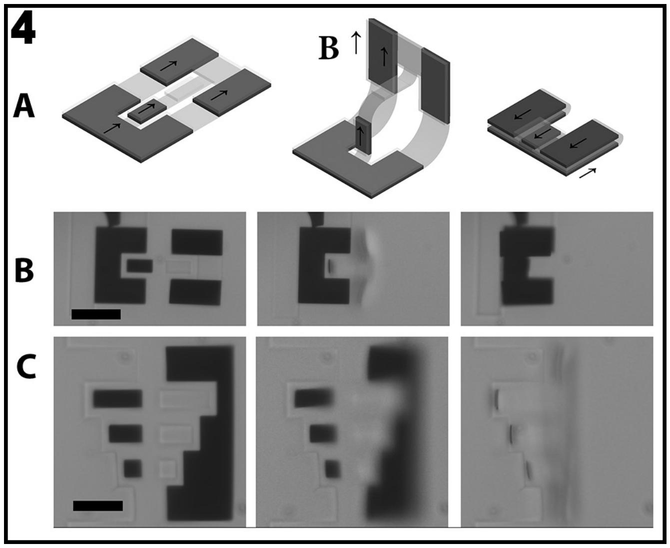


Figure 4: 3D magnetically actuated pop-up structures (scale 10µm).

Upon application of strain with a micromanipulator, the sheet can be stretched in both directions to ~ 100% beyond its original length without failure (Figure 3b).

We further manipulate these devices by patterning thin cobalt films to act as magnetic handles. A device concept is illustrated in Figure 4a. Application of external fields allow rotation of free hinges as shown in Figure 4a. Further rotation of the external field can close a latch structure formed with a second magnet. This concept is realized in Figure 4b, which shows a three-dimensional "pop-up" structure being rotated from the fabrication substrate into its 3D target geometry. It is then closed and remains shut. This simple design paradigm can be extended to more complicated 3D structures such as the micron-scale staircase shown in Figure 4c. We envision the materials and design concepts described herein to be used as the building blocks of more sophisticated 3D machinery at the micron scale.

References:

[1] Leong, Timothy G., Aasiyeh M. Zarafshar, and David H. Gracias. "Three-Dimensional Fabrication at Small Size Scales." Small 6, no. 7 (April 9, 2010): 792-806.

[2] Miskin, Marc Z., Kyle J. Dorsey, Baris Bircan, Yimo Han, David A. Muller, Paul L. McEuen, and Itai Cohen. "Graphene-Based Bimorphs for Micron-Sized, Autonomous Origami Machines." Proceedings of the National Academy of Sciences, January 1, 2018, 201712889.

[3] Davami, Keivan, Lin Zhao, Eric Lu, John Cortes, Chen Lin, Drew E. Lilley, Prashant K. Purohit, and Igor Bargatin. "Ultralight Shape-Recovering Plate Mechanical Metamaterials." Nature Communications 6 (December 3, 2015): 10019.

[4] Eigenfeld, Nathan T., Jason M. Gray, Joseph J. Brown, George D. Skidmore, Steven M. George, and Victor M. Bright. "Ultra-Thin 3D Nano-Devices from Atomic Layer Deposition on Polyimide." Advanced Materials 26, no. 23 (June 1, 2014): 3962-67.

[5] Wang, Luda, Jonathan J. Travis, Andrew S. Cavanagh, Xinghui Liu, Steven P. Koenig, Pinshane Y. Huang, Steven M. George, and J. Scott Bunch. "Ultrathin Oxide Films by Atomic Layer Deposition on Graphene." Nano Letters 12, no. 7 (July 11, 2012): 3706-10.