ALD for Membranes, Metamaterials, and Mechanisms

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 AFM, Tencor P7 profilometer, Filmetrics UV, Woollam ellipsometer, DISCO dicing saw, Heidelberg DWL2000, AJA sputterer

Abstract:

Bending and folding techniques such as origami and kirigami enable the scale-invariant design of three-dimensional structures, metamaterials, and robots from two-dimensional starting materials. Such techniques have been used in everything from deployable spacecraft solar panel arrays [1], soft robots [2], and microelectromechanical systems (MEMS) [3]. These design principles are especially valuable for small systems because most micro- and nanofabrication involves lithographic patterning of planar materials. Ultra-thin films of inorganic materials serve as an ideal substrate for the fabrication of flexible microsystems because they possess high intrinsic strength, are not susceptible to plasticity, and are easily integrated into microfabrication processes [4]. In recent work, we employed atomic layer deposition (ALD) to synthesize films down to 2 nm thicknesses to create membranes, metamaterials, and machines with micron scale dimensions [5]. In this thickness limit, ALD films behave elastically and can be fabricated with femtojoule-scale bending stiffnesses. Further, ALD membranes are utilized to design micron-scale mechanical metamaterials and magnetically actuated three-dimensional devices. These results establish thin ALD films as a scalable basis for micron-scale actuators and robotics.

Summary of Research:

ALD is an ideal technique for scaling mechanical systems to micron-scale dimensions. We have developed an entire fabrication strategy around ALD, including lithography, etching, release, and integration. ALD films are grown conformally on a sacrificial layer of aluminum, as shown schematically in Figure 1. The devices consist of lithographically patterned regions of ALD membranes and thicker panels of other materials that provide rigid structure and additional functions such as mirrors or magnets. The devices are fabricated at wafer scales at yields exceeding 90%. The wafer is diced and devices are released by immersing in dilute base, followed by rinsing in water. Upon release, all experiments are carried out in aqueous environments, often with added surfactant, to avoid stiction of the free membranes.

We investigated the mechanical properties of these films by measuring the bending stiffness of over 60 magnetically actuated glass hinges. Ferromagnets with a saturated in-plane moments are patterned on panels at the ends of the hinges. The panels are deflected when we apply an out-of-plane magnetic field B (Figure 2a). Figure 2b shows the measured hinge deflection angles for ALD films of two different thicknesses, 5 and 8 nm, as a function of the magnetic field B. The hinges are deflected reversibly with no observable hysteresis. By equating the magnetic torque to the opposing mechanical torque due to the bending stiffness of the film, we deduce a linear relationship between the deflection angle and the applied field. The bending stiffness of each individual hinge can be extracted from the slope of this relationship.

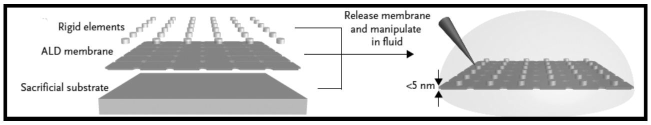

Figure 1: Schematic of the fabrication and release processes.

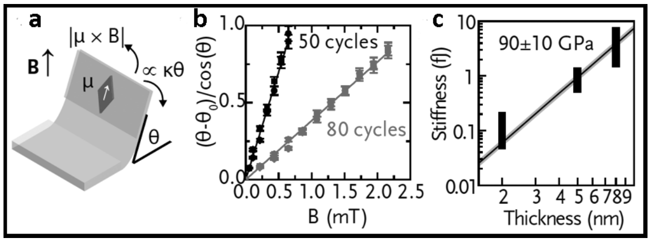

Figure 2: Mechanical characterization of ALD glass hinges.

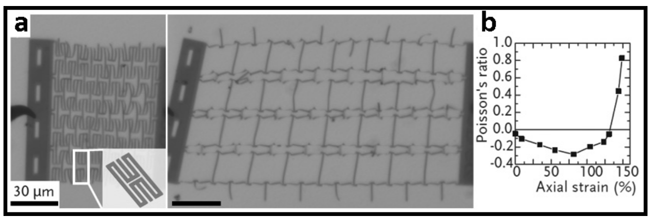

Figure 3: Auxetic mechanical metamaterial made of ALD Pt.

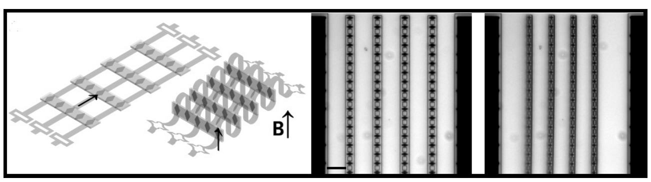

Figure 4: Magnetically actuated muscle-like device.

Scaling the thickness from 2 nm to 8 nm, we find bending stiffnesses spanning nearly two orders of magnitude in the femtojoule range (Figure 2c). We extract the Young's modulus of ALD glass from the fit in Figure 2c, finding Y = 90 ± 10 GPa. This value is comparable to values for bulk material (70-80 GPa), indicating that even at 2 nm thickness, the films behave mechanically similar to macroscopic counterparts.

We additionally use ALD membranes to fabricate mechanical metamaterials through in-plane and out-of-plane patterning. The sheet can become stretchable by cutting patterns that allow parts of the sheet to bend/buckle out of its fabrication plane. A metamaterial with a negative Poisson's ratio, also known as an auxetic, is shown in Figure 3a. This material is patterned from 5 nm-thick sheet of ALD platinum. Under application of an axial strain, the sheet expands in the transverse direction, yielding a negative Poisson's ratio (Figure 3b).

These ultra-thin materials can also be used for micron-scale actuators and machines that function with exquisitely small forces and torques. The device shown in Figure 4 is a magnetically actuated mechanism that contracts to bear a load. The magnetic panels are attached to linear springs. Upon application of an external field, the panels rotate out of the plane and move laterally closer to each other while applying a load on the springs in a fashion analogous to a muscle.

The mechanical properties and fabrication protocols for ALD membranes and metamaterials facilitates their potential application in very sophisticated micromechanical systems. For example, the low processing temperatures and fabrication compatibility enable ALD actuators to be added to silicon-based integrated circuits for smart microsystems and machinery. In addition, the diverse materials palate offered by ALD enables bimorph actuators of dissimilar materials while still maintaining a low bending stiffness for the film stack. These actuators can be leveraged to create self-assembled and environmentally responsive three-dimensional structures and actuators. An additional benefit of ultra-thin versions of bulk materials is that the surface chemistry of many ALD films is well-studied. This enables chemical functionalization and patterning, enabling the coupling between chemical sensitivity and mechanical responsivity. Combination of these capabilities may be used for sensors, self-assembled devices, optical devices, and microscale robotic systems.

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