Flexible Exoskeletons for Magnetically Actuated Microscopic Robots using Atomic Layer Deposition

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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/PT740 etchers, Anatech Asher, Zeiss SEMs, Veeco AFM, Tencor P7 profilometer, FilMetrics UV, Woollam ellipsometer, DISCO dicing saw, Heidelberg DWL2000, AJA sputterer

Abstract:

One of the grand challenges in robotics is to create truly microscopic robots, i.e. those too small to be resolved by the naked eye. We attack this problem by combining programmable magnetic panels with nanometer-thick flexible materials to make micron-scale, magnetically controlled robots and smart assemblies. The ideal material for this flexible exoskeleton must be elastic, possess high intrinsic strength, and integrate easily into standard microfabrication processes. We employ atomic layer deposition (ALD) to synthesize films down to 2 nm thickness to create membranes, metamaterials, and machines [1]. We demonstrate that these ALD films behave elastically under repeated deformation and have fJ-scale bending stiffness. We further incorporate magnetic panels to controllably actuate simple mechanisms and machines. These results establish ultrathin ALD films as flexible materials for microscopic actuating systems. Our current pursuit focuses on improving functionality of these systems by encoding them with magnetic information. This idea can be implemented to program dipole orientations in individual magnetic panels, enabling more complex modes of actuation for executing specific tasks [2]. Moreover, patterned magnetic multipoles can be utilized for smart self-assembly via specific binding [3]. Ultimately, the use of magnetic programing techniques to design actuating systems based on ALD films will provide a unique platform for constructing and manipulating microscopic robotic systems.

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

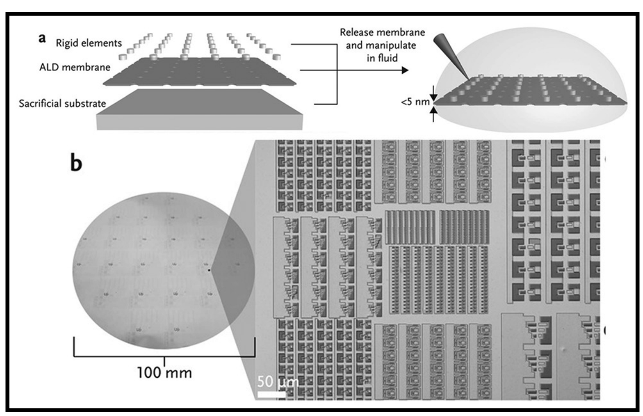

Figure 1: (a) Schematic of the fabrication and release processes. (b) Photograph of a 100 mm wafer with myriad ALD devices.

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 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, and the bending stiffness is determined by measuring the corresponding deflections of the hinges. Scaling the thickness from 2 nm to 8 nm, we find bending stiffnesses spanning nearly two orders of magnitude, with the lowest being in the femtojoule range. We additionally find the Young's modulus of ALD glass to be 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.

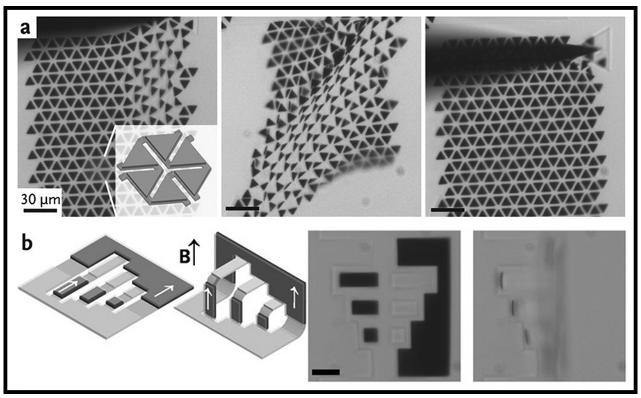

Figure 2: (a) Biaxially stretchable mechanical metamaterial. (b) Magnetically actuated pop-up staircase.

We additionally use ALD membranes to fabricate a range of microscopic actuatable systems (Figure 2). Glass and platinum sheets can be patterned into geometries that allow parts of the sheet to bend/buckle out of its fabrication plane, producing highly stretchable and auxetic metamaterials. Moreover, ferromagnetic panels can be introduced to create magnetically actuated machines that function with exquisitely small forces and torques. These span from pop-up book style devices that can be snapped shut, to muscle mimetic load bearing mechanisms.

Our recent efforts focus on improving functionality of these actuatable systems by encoding them with magnetic information. This idea can be implemented

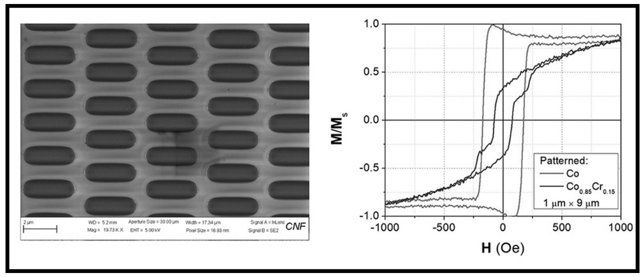

Figure 3: (a) SEM image of lithographically patterned Co. (b) Magnetic hysteresis loops of similarly patterned Co and CoCr.

to program dipole orientations in individual magnetic panels, enabling more complex modes of actuation for executing specific tasks. In order to achieve magnetic writing capabilities, we must define the appropriate combination of magnetic materials and writing technique. Using the AJA magnetron sputterer in CNF, we have investigated materials such as Co, CoCr alloys, and Co/Pt multilayers and measured their magnetic properties via vibrating sample magnetometry (VSM) and magnetic force microscopy (MFM). Additionally, we have patterned these films to understand the effects of shape anisotropy on their magnetic properties (Fig.3).

We are currently using these results to determine viable approaches for magnetic recording. One promising method would rely on the disparity of the in-plane coercivity between Co and CoCr. One could use a large field to orient Co, a high coercive field material, in one direction, and subsequently use a smaller field to write CoCr, a softer material, in the opposite direction without affecting the Co. Leveraging shape anisotropy, one could repeat this process along an orthogonal axis to achieve four unique magnetic orientations. This simple magnetic writing scheme for magnetic panels combined with a flexible and robust exoskeleton deposited using ALD would facilitate the design of microscopic actuating systems for smart self-assembly and robotics.

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