Atomically Thin Actuator-Enabled Micro-Machines and Micro-Structures

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Primary CNF Tools Used: Oxford ALD FlexAL, Arradiance ALD Gemstar-6, Oxford 81/100 etchers, ABM contact aligner, SC 4500 odd-hour, AJA sputter, AJA ion mill, Oxford Cobra ICP etcher, Heidelberg DWL2000

Abstract:

The ability to actuate an object at the microscale is an important technological aspect of manufacturing micro-robots and micro-machines. Here we demonstrate that micro-actuators made by atomically thin layers of metals and dielectrics could bend in response to electrical or chemical signals. The electrical micro-actuators could work in both volatile and shape memory regimes depending on the applied voltages, enabling electrically programmable three-dimensional structures and artificial cilia. The chemo-responsive actuators allow for self-folding three-dimensional origami structures activated by the pH of the aqueous solution.

Summary of Research:

Our team has developed atomically thin actuators that can bend in response to electrical and chemical stimuli. This approach makes it possible to create complex structures, machines, and microrobots by using origami design principles at the microscale.

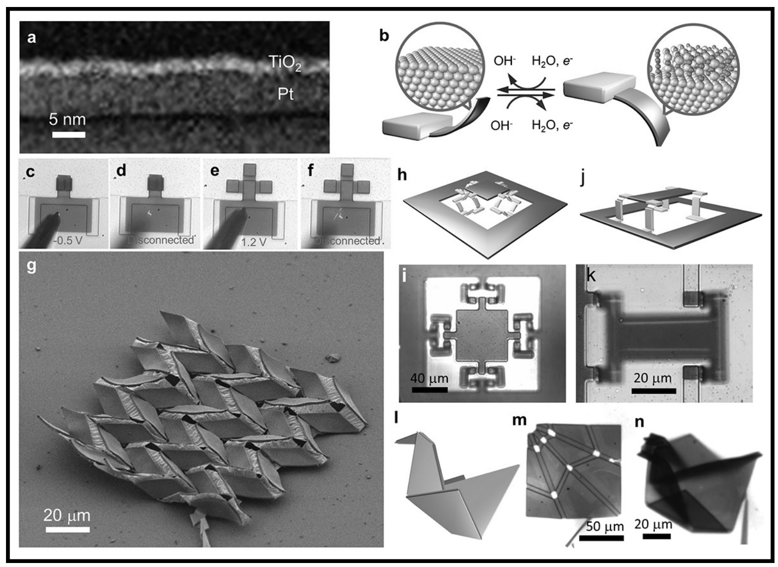

Figure 1: Electrically programmable shape memory actuator-enabled micro-devices. (See cover for Figure 1g in full color. Used with permission.)

Our team first discovered a microscale multistable electrochemical shape memory actuator that "memorizes" a continuous range of shapes, which is distinct from only one or two stable shapes of the conventional shape memory materials associated with the transformation of crystal structures [1]. The core of the device comprises of an electrochemically active platinum membrane capped on one side by an inert layer (Figure 1a). To achieve a continuous range of shapes, the team developed a technique based on applying voltage to shift the electrochemical balance between platinum and a surrounding electrolyte in order to drive oxygen ions through one surface of the platinum membrane (Figure 1b). This electrochemical redox reaction of platinum creates a differential in stress between the two sides of the actuator, causing the structure to cycle and maintain a submicron bending radius for a long time (Figure 1c-f).

This electrical programmability of nanometer-thin membranes can be harnessed to create three dimensional shapes that can be reversibly erased and rewritten by short electrical pulses. We then localized the bending position by patterning rigid polymeric panels (Figure 1g). Origami principle could be employed to design micro-machines owing to the capability of the bidirectional folding of actuators by reversing the deposition order of the platinum and inert layers. We demonstrate electrically reconfigurable micro-origami motifs and bistable microactuators (Figure 1h-n).

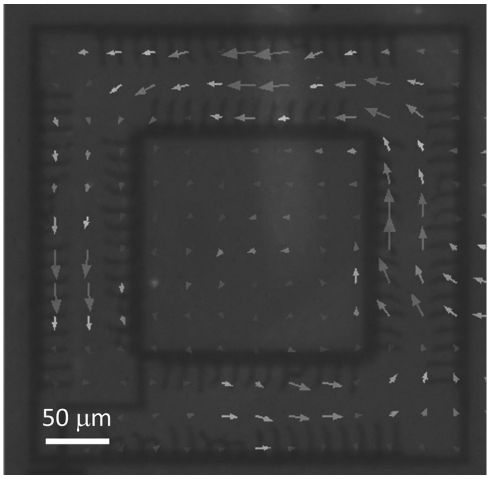

Figure 2: Electrical artificial cilia-pumped flow pattern with its direction indicated by arrows. (See pages vi-vii for full color version.)

Figure 3: A spacer Miura-ori fold made using ultra-thin, self-folding atomic layer deposited sheets.

The manufacturing process is fully compatible with the microelectronic fabrication technology, making it easy to integrate with control circuit. These results could lead to new micro- or nano- electromechanical systems for robotic applications.

Besides the shape memory effect, the atomically thin platinum/titanium membrane could work as a volatile actuator. The actuators bend due to the difference in stress between the platinum and titanium layers that stems from the electrochemical adsorption of oxygen species on the surface of platinum. By harnessing this new type of electrical micro-actuator, our team developed electrically controllable artificial cilia that efficiently pump fluid in a steady unidirectional flow (Figure 2).

Individually addressable micro-scale robotic cilia have the potential to enable unprecedented control over microfluidic environments. They could be used to sort microscale particles, control chemical reactions, and transport viscoelastic materials. Such systems could also be used to better understand biological processes such as neurotransmitter transport in the brain, as well as clearing in the liver and lungs. The electrical nature of these artificial cilia makes it possible to integrate control circuits and power sources, allowing for sequential and addressable generation of arbitrary flow patterns. We envision that this technology will find broad applications. For example, in addition to ushering unparalleled control of fluids moving over surfaces, such electrically programmable artificial cilia could serve as actuators for aquatic microscale robots.

Our team also developed chemo-responsive micro-actuators that enable self-folding three-dimensional micro-architectures using origami principle. The mapping of an arbitrary three-dimensional shape to an origami fold pattern requires the assignment of fold angles ranging from -180° to +180°. Therefore, bidirectional folding action is essential in creating a complete platform for origami-based self-assembly.

Our previous work achieved unidirectional folding with atomically thin sheets of hard materials [2], but could not be used to fabricate complex geometries that required bidirectional folding. To address this problem, our team has developed a scalable microfabrication process to create microscale bidirectional folds using 4 nm thick atomic layer deposition SiN_x - SiO_2 bilayer films [3]. Strain differentials within these bilayers result in bending, producing microscopic radii of curvature. To take advantage of this intrinsic curvature, we photolithographically pattern these bilayers and localize the bending using 1 µm thick panels of rigid SU-8 polymer. This allows us to fabricate a variety of complex micro-origami devices, ranging from relatively simple geometries with six folds to more complex ones with nearly 100 folds, such as the spacer Miura-ori fold seen in Figure 3.

Upon release, these devices self-fold according to prescribed patterns. Our approach combines automated lithography mask design with easily scalable planar microfabrication methods, making it easy to fabricate and deploy micro-origami devices en masse. This work has been compiled into a manuscript and submitted for publication.

References:

[1] Liu, Q., Wang, W., Reynolds, M., Miskin, M., Cao, M. C., Muller, D. A., McEuen, P. L. Cohen, I., Electrically Programmable Micro-Scale Shape Memory Devices, APS March Meeting, 2020.

[2] Miskin, M., Dorsey, K., Bircan, B., Han, Y., Muller, D., McEuen, P., and Cohen, I. Graphene-based bimorphs for micron-sized autonomous origami machines. Proceedings of the National Academy of Sciences, 115: 466-470 (2018).

[3] Bircan, B., Miskin, M., Dorsey, K., McEuen, P. and Cohen, I., Bidirectional Folding with Nanoscale Sheets for Autonomous Micro-Origami, 2018.