Atomically Thin Metamaterial Robots, Origami, and Artificial Flagella

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Primary CNF Tools Used: Oxford ALD FlexAL, Arradiance ALD Gemstar-6, Oxford 81 etcher, Oxford 100 etcher, 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. These actuators could be designed into bidirectional bending modes, enabling chemically responsive micro-scale complex origami structures. By harnessing the electrical controllability and bidirectional folding structures, a mechanical metamaterial microrobot has been fabricated, allowing remotely controllable robotic sheets with large degree of freedom of motion.

Summary of Research:

Using commercial semiconductor processing techniques, our team has developed methods to deposit and pattern atomically thin films that can bend in response to chemical and electrical stimuli. This approach makes it possible to create complex structures, machines, and microrobots by using origami design principles at the microscale.

Our team first demonstrated an electrically responsive micro cantilever with an ultra small bending radii of 1-2 µm. The microcantilever has a bimorph structure comprising of 5 nm platinum (Pt) and 2 nm silica (SiO_2), both of which are deposited by atomic layer deposition (ALD). The exposed platinum surface expands at a low voltage of -0.2V in a buffer solution due to the hydronium (H_3O^+) adsorption on the platinum surface, bending the bimorph structure toward the silica layer. Based on this actuation mode of platinum/SiO_2 bimorph, we fabricated artificial flagella that could swing and drive the small particles to move in a buffer solution, as shown in Fig. 1.

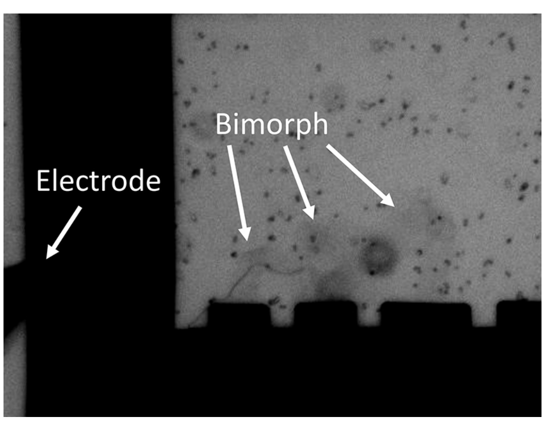


Figure 1: Electrically driven artificial flagella made by atomically thin Pt/SiO_2 bimorph structure swing in the buffer solution.

Our team has also demonstrated a technique to create micron scale folds using ultra-thin bending actuators composed of 2 nm of ALD grown SiO_2 and a sheet of monolayer graphene. These actuators are driven by ion exchange reactions, where larger H_3O^+ ions take the place of smaller Na^+ ions in the SiO_2 layer, causing swelling and creating a strain mismatch that produces unidirectional bending action.

Photolithographically defining fold patterns and localizing the bending using 1 µm thick panels of rigid SU-8 polymer enables the fabrication of elementary folded structures like cubes and tetrahedra [1].

Since origami design principles can be used to map any arbitrary shape to a crease pattern with fold angles ranging from -180° to +180°, bidirectional bending action is needed to create a complete platform for origami-based self-assembly at the microscale. The basic idea is that if one type of bimorph stack bends upwards, the order of the stack can be inverted to produce downward bending. To achieve this, our group has developed a method for growing and stitching together all ALD grown Si_3N_4-SiO_2 bimorph stacks. Replacing graphene with ALD Si_3N_4 not only makes the fabrication more easily scalable, but also eliminates the need for any additional functionalization step that would be required to perform ALD on graphene. This strategy makes it possible to design and fabricate origami devices of variable complexity that can sense changes in pH and change configurations from flat to folded according to prescribed mountain-valley folds.

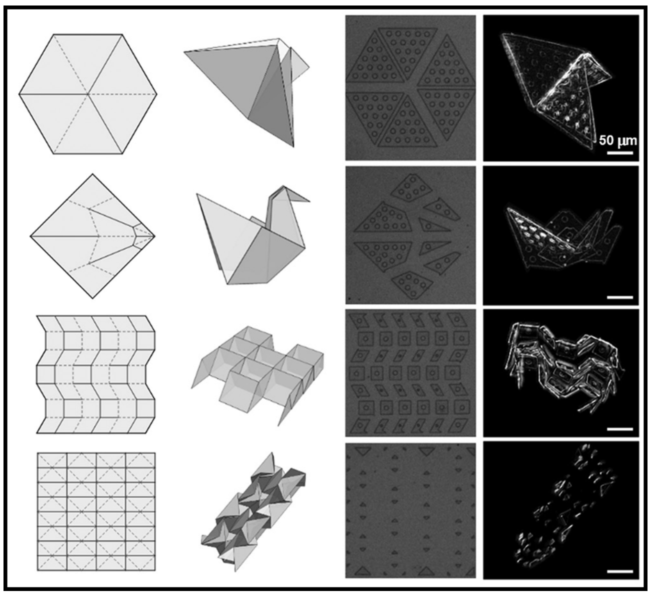
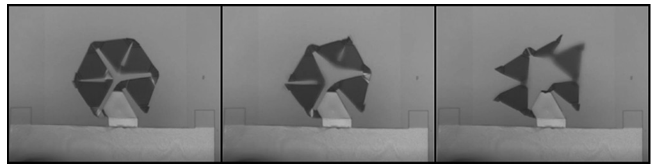


Figure 2: Origami designs of variable complexity constructed at the microscale using all-ALD bimorphs. Columns from left to right: Origami crease patterns, computer models of folded shapes, micro-origami devices (unfolded), micro-origami devices (folded). Scale bars are 50 µm.

Figure 2 shows a variety of origami designs fabricated using this method, ranging from relatively simple ones with six folds to more complex structures with more than 100 folds. The origami bird made using our approach is less than half the size of the current state of the art [2]. Having established a complete platform for micro-origami with ion exchange actuated bimorphs, our group is preparing to develop bimorphs consisting of atomic layer deposition Pt and SiO_2, which will make it possible for us to achieve bidirectional bending action through electrical actuation.

By harnessing the electrical controllability and bidirectional folding structure, our team designed and fabricated



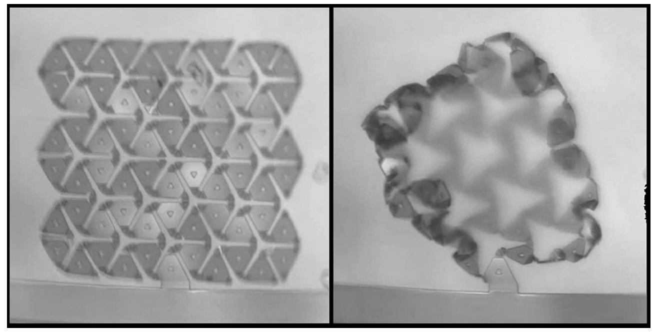


Figure 3, top: Three images from a movie showing voltage-based actuation of nm thin hinges of a six-panel metamaterial sheet.

Figure 4, bottom: A flat mechanical metamaterial microrobotic sheet (left) shows expansion and wrapping modes (right).

metamaterial robots that could locally expand and change its Gaussian curvature. Once integrated with electronics, such robots will be able locomote, wrap, and encapsulate synthetic and biological materials. To generate local expansion of the metamaterial robot it is necessary to create hinges that allow panels to splay. The three folding actuators with opposite bending directions are connected to two panels. The middle hinge can bend at an angle of 180°, while the two side hinges can bend at an angle of 90° in the opposite direction.

Having determined that this design was mechanically feasible, we fabricated, using alternating layers of ALD grown Pt and sputtered Ti that are 7 nm thin, the first bidirectional surface electrochemical actuators. We used these voltage-driven actuators to implement a proof or principle scaffold for the metamaterial robot (Figure 3). Integrating these building blocks into a sheet structure, we fabricated mechanical metamaterial-based microrobots with large degree of freedom (Figure 4). This sheet-like microrobot could expand into three-dimensional structure, wrap the target object and shrink its size, opening the door to diverse applications in medical treatment and drug delivery.

References:

[1] 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).

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