Atomic-Scale Origami for the Fabrication of Micron Sized Machines

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Primary CNF Tools Used: Oxford ALD FlexAL, Arradiance ALD Gemstar-6, Oxford 81 etcher, ABM contact aligner, SC 4500 odd-hour, Glen 1000 resist strip, Heidelberg DWL2000

Abstract:

Origami allows the creation of complicated three-dimensional structures from simple two-dimensional patterns. We are inspired to use origami for the fabrication of three-dimensional microscopic machines. The first step in such technology is the ability to fold thin sheets on-demand. Our work has demonstrated multiple mechanisms to actuate the folds in microscopic origami patterns, using standard processing techniques of the semiconductor industry.

Summary of Research:

Origami has emerged recently as a promising design strategy for creating arbitrarily complex three-dimensional structures from two-dimensionally patterned thin sheets [1,2]. As long as the two-dimensional pattern contains the proper array of mountain and valley folds, with a suitable actuation mechanism, we can create complicated three-dimensional origami structures that assemble themselves. Our work has demonstrated actuation mechanisms that works for nanometer-thin sheets, patterned using standard semiconductor processing technologies. This promises the smallest possible scale of origami devices.

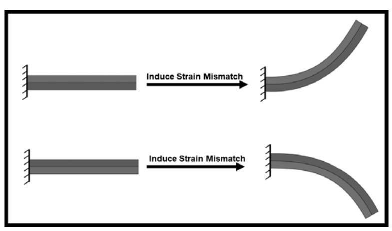

Figure 1: By introducing a strain mismatch between the bi-morph layers, we can cause a cantilever beam to bend.

Our devices rely on the bi-morph principle for actuation. One device, made from a stack with different materials in each of two layers, can be made to bend if the two layers strain by different amounts in response to an external stimulus, such as changing the temperature, or as in our previous work, the pH. Introducing a strain mismatch between the layers causes one layer to be in tension and the other to be in compression. By placing the bimorph stacks only in pre-specified regions, we can use the appropriate external stimulus to cause a thin sheet with an origami pattern to fold all at once.

Our prior work focused on bimorphs of silica (SiO_2) and graphene [3]. We first evaporate a sacrificial aluminum release layer onto a boro-silicate glass substrate, and then deposit a 2 nm layer of SiO_2 using the Oxford ALD FlexAL atomic layer deposition (ALD) tool. We then transfer graphene onto the SiO_2 layer, photolithographically pattern hinges and beams in any regions we would like to introduce a fold, and deposit pads of rigid SU-8 polymer over any regions we would like to remain flat. Finally, we remove the sacrificial aluminum layer with a wet etch to release our devices from the substrate into solution. Ion exchange causes the SiO_2 layer to swell.

Transferring graphene to the substrate is difficult and time-consuming as compared with deposition of an SiO_2 layer using the ALD tool, so it is beneficial to deposit both bimorph layers using ALD. We explored some of the materials available, and have settled on bimorph stacks of SiO_2 and silicon nitride (Si_3N_4), where each layer is 2 nm thick. The ion exchange mechanism is slightly different for the two layers, so lowering the pH still introduces a strain mismatch, causing cantilever beams to bend to roughly 10 μm radii of curvature, as in Figure

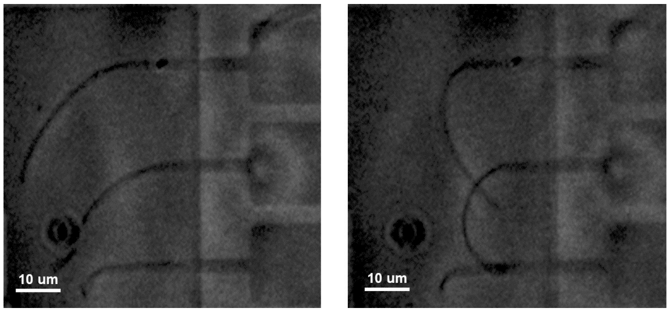

Figure 2: Bending of SiO_2 / Si_3N_4 bimorph cantilever beams by means of pH-induced ion exchange. Simply changing the solution from basic to acidic causes the beams to bend.

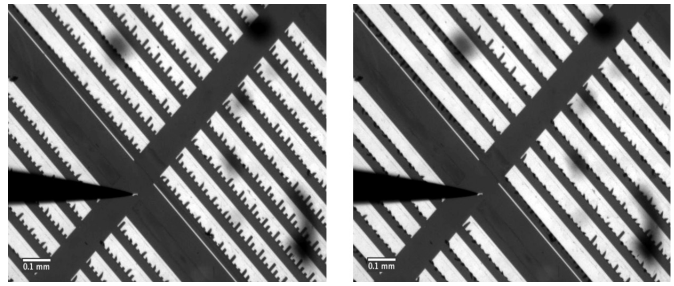

Figure 4: Applying a potential difference across an array of graphene / platinum bimorphs causes the entire array to fold at once.

2. Bimorphs with Si_3N_4 avoid some of the pre-stressing that occurs when using other materials.

Some work this year has focused on process development to allow us to use more sophisticated folding patterns. Devices fabricated with a single kind of bimorph stack are constrained to have all mountain or all valley folds, whereas most origami patterns require a single sheet to have both mountain and valley folds in different locations. We need devices capable of bi-directional folding. We have developed and refined a process that allows the fabrication of one bimorph stack together with the inverted bimorph stack as part of a single device, allowing beams with the two bi-morph stacks to fold into an S-shape, as in Figure 3. This has unlocked a whole realm of complex origami patterns. Professional origami artists have developed software that automatically generates design files we can include in mask designs.

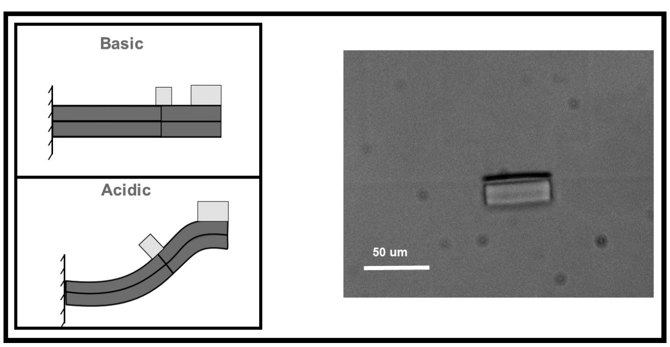

Figure 3: Schematic and experimental demonstration of bi-directional folding in SiO_2 / Si_3N_4 bimorph cantilever beams. The flat rectangle is a rigid SU-8 pad, parallel to the substrate, while the dark line above it is an SU-8 pad of the same size perpendicular to the substrate.

Our pH-based ion exchange mechanism allows us to change devices from the flat to the folded state at will, but it does not allow precise control over the radius of curvature in our devices when bent. As a promising new direction, part of our team has developed devices offering such precise control. Here, we use graphene with a 5 nm layer of platinum as our bimorphs. To actuate folds, we apply a voltage across our devices, and this potential difference allows ions from the solution to be absorbed into the platinum, swelling that layer as compared with the graphene, bending the device as before. By varying the applied potential difference, we can control the amount of bending, as shown in Figure 4. This technique allows an unprecedented control over the final three-dimensional configuration of our bending-actuated devices.

Our actuation mechanisms are well-suited for origami patterns in which all folds may be actuated at once. However, this is only a subset of all origami patterns. More complicated patterns require folds to be actuated in a specified sequence. Therefore, a major future direction of our work is to uncover techniques for actuating various folds sequentially.

References:

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