Programming Matter Through Strain

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Mesoscale self-assembly (MESA, see ref [1-5] for review articles) offers the potential to extend molecular self-assembly to the micrometer- to millimeter-size regime. The motivation behind MESA is that the individual components are typically easy to fabricate and offer a broad range of forces and selectivity for the building process, which are also more defect tolerant than molecular self-assembly components. MESA is not limited to the building of larger features from discrete building blocks. Within MESA, there is recent interest in the formation of three-dimensional (3D) objects that are self-assembled through the folding of a two-dimensional (2D) precursor.[6-11] These folding techniques typically rely on well-developed planar micro fabrication techniques and are capable of imparting electronic functionality into the material. Forces that have been used to drive the 3D folding assembly process include magnetic[7], capillary interactions[11], surface tension[6, 12, 13] and swelling strain[10]. These folding systems generally have only one final folded configuration and lack a programming tool to direct the folding to a desired form.

In this presentation a novel polymer based folding system that uses light as the "programming" tool is discussed. Using light as the programming tool allows for rapid photo patterning of a flat 2D polymer surface. The light is used to generate a cross-linking gradient, which imparts controlled areas of strain that allows the material to fold into 3D shapes when immersed in organic solvents to generate swelling strain. This system allows for greater control, as the folding is not limited solely to solvent selection but can also be controlled through the exposure pattern, allowing for more complex folding geometries to be obtained. The overall objective of this work was to demonstrate that common, well-characterized materials can be programmed on demand to generate structures with variable configurations controlled by the light-programming step.

To accomplish this task, materials that are both well characterized and low-cost were used. Two starting materials that match these criteria are polydimethylsiloxane (PDMS) and SU8 photoresist. PDMS, a flexible rubbery material, is the most commonly used material in soft lithography, and is known to swell in the presence of nonpolar solvents (e.g. toluene, hydrocarbons, chlorinated solvents).[14, 15] This high degree of swelling allows for great volume changes, which results in large strains, and thus drives the folding process. In contrast, SU8 50 was selected as the light accepting programming agent because of its insolubility in organic solvents and its ability to from a stiff material once cross-linked. When taken together as a composite mixture, these two materials can be used to manipulate and control the folding of the composite material into three-dimensional geometries.

The SU8 component within a composite mixture of the two materials is "programmed" by exposure to a mask aligner. By covering the sample with different photomasks the SU8 contained within the sample can be selectively cross-linked, much like a traditional photoresist, but with a depth gradient. The unexposed regions will behave similarly to bulk PDMS and the exposed regions will have mechanical characteristics closer to that of cross-linked SU8. Immersion into solvents will cause the PDMS to swell in the regions where the SU8 is lightly or uncross-linked. The light exposed regions will resist swelling due to the presence of the cured highly cross-linked SU8. The cross-linking gradient of the SU8 generates a swelling difference between the top exposed face and the back surface. This difference in material behavior will

create a strain in the system and, after reaching a critical point, will result in deformation of the material. This folding process is depicted in Figure 1(A). Judicious use of this method to create internal strain allows for the directed folding of the material into discrete 3D shapes determined by the pattern of the photomask and the solvent. Figure 1(B) is a photograph of several samples that were programmed with a line pattern. With this programming geometry the samples folded into cylinders when immersed in toluene. This folding is control in that the samples always fold along the length of the line and the exposed face is on the interior of the folded structure.

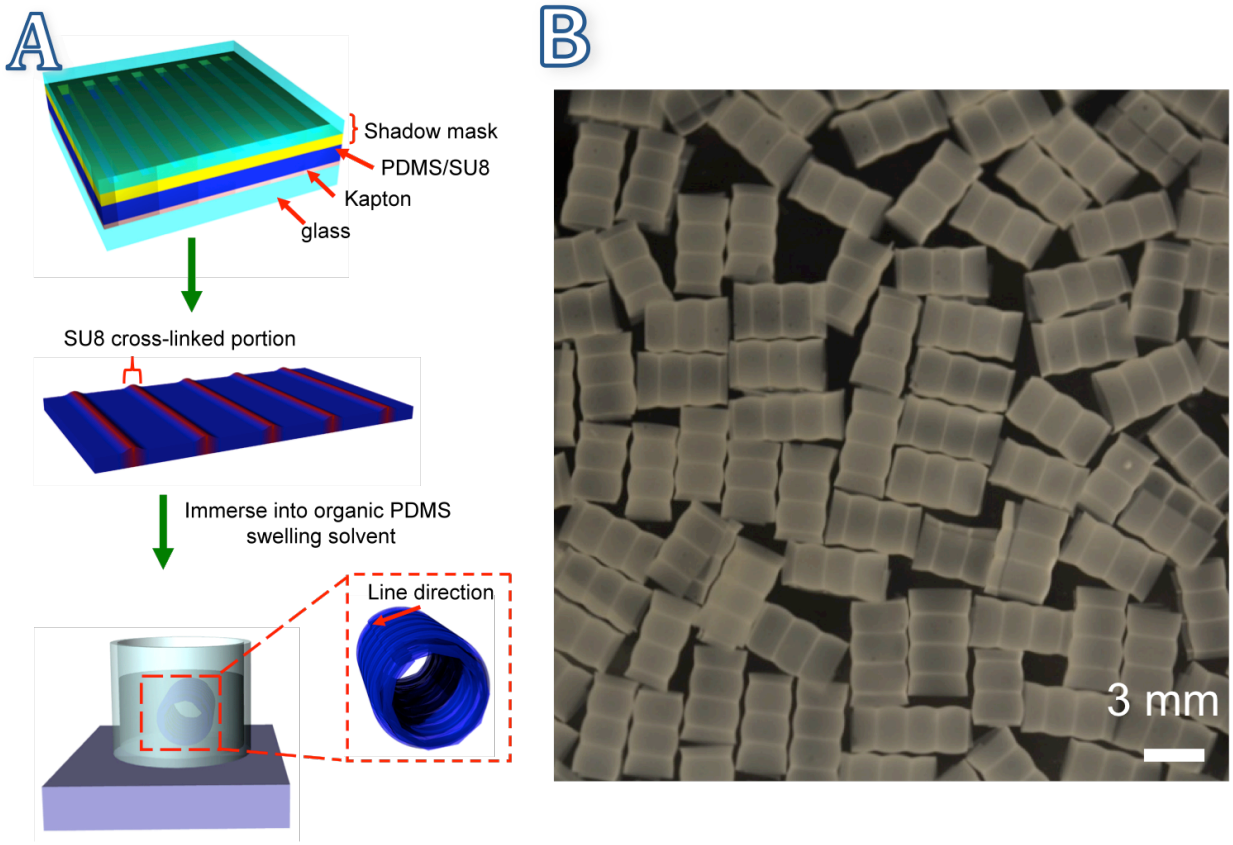

Figure 1. (A) Schematic depiction of the light programming and folding process.
(B) Photograph of multiple samples that were identically programmed to fold into a cylinder.

Detailed experiments controlling the variables (e.g. mix ratios, thickness, exposure mask design) will be discussed within the presentation. These experiments were performed within the context of achieving precise control over the folding as well as understanding the mechanics and limitations of this unique folding system. Additionally, the discussion will address experiments that were performed to examine the nature of the cross-linking gradient within the composite material. A fundamental understanding of the system variables will be demonstrated through the generation of unique 3-D patterns. The talk will conclude with discussions of possible future directions of using these small units as building blocks for larger self-assembled structures. Ultimately, we envision applying the principals of programming strain gradients learnt within this demonstration to other systems that are better suited for incorporating additional functionality, particularly within the realm of electronic devices.

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