Microassembly based on hands free origami with bidirectional curvature

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Microassembly based on origami, the Japanese art of paper folding, presents an attractive methodology for constructing complex three-dimensional (3D) devices and advanced materials. A variety of functional structures have been created using patterned metallic, semiconducting, and polymeric thin films, but have been limited to those that curve in a single direction. We report a design framework that can be used to achieve spontaneous bidirectional folds with any desired angle, and we demonstrate theoretical and experimental realizations of complex 3D structures with $+90^\circ$, -90° , $+180^\circ$, and -180° folds. The strategy is parallel, versatile, and compatible with conventional microfabrication. © 2009 American Institute of Physics. [DOI: 10.1063/1.3212896]

It is extremely challenging to construct complex, lithographically patterned three-dimensional (3D) microdevices and metamaterials due to the inherent two dimensionality of conventional microfabrication. While it is straightforward to construct macroscale, light weight materials for packaging, deployable solar panels,¹ and stents by manual folding or sheet metal forming,² it is challenging to construct these structures on the microscale. Such bidirectionally folded microstructures have been realized in a serial manner by manual or machine folding with tweezers or probes,^{3–5} which is limited in precision and throughput. Microassembly based on origami pop-up structures allows one to harness the strengths of conventional parallel microfabrication while enabling complex 3D fabrication. For example, it has been suggested that the precise structuring of folded components will allow for the construction of microscale supercapacitors³ and 3D electronics. Self-folding has been used previously to fabricate containers, mirrors, nanotubes, rotors, and coils from flat substrates in a parallel manner.^{6–10} These structures have been limited by folding in only one direction, thereby greatly limiting the complexity of structures that can be fabricated. Therefore, there is a need to construct microstructures that self-assemble with any arbitrary folding angle in both positive and negative directions.¹¹

In this letter, we propose and demonstrate a method to design and fabricate complex, bidirectionally folded microstructures similar to those seen in tessellated origami, pop-up books, and macroscale sheet metal forming.¹² We liken our approach to a combination of rigid origami,^{13,14} a subtype of origami using flat paper and linear fold lines, and kirigami,¹⁵ the art of paper cutting. In this approach, specific regions of a flat sheet are cut out, bent up to form a mountain fold, bent down to form a valley fold, or left flat. Our strategy uses thin film sheets with two kinds of hinges:^{16,17} (1) A bilayer hinge consisting of a chromium (Cr)/copper (Cu) bilayer, which curves into the substrate (we denote this curvature as a positive fold angle); and (2) a trilayer hinge consisting of a chromium (Cr)/copper (Cu)/chromium (Cr) that curves away

(negative fold angle) from the substrate. In both cases, folding occurs spontaneously as a result of the large (~ 1 GPa) residual tensile stress within the Cr film, while the Cu provides structural support.^{18,19}

Flat sheets were fabricated using conventional microfabrication on a commercial polymeric sacrificial layer spun onto a flat wafer. We explored the use of three sacrificial layers: Poly(methyl methacrylate), AZ5214E (Clariant), and preferably, PC3-6000 (Futurrex). The Cr and Cu films were deposited using thermal evaporation at 10^{-5} Torr. Three layers of conventional photolithography were used to pattern the sheets (Fig. 1). The hinges were connected by rigid panels constructed of $3\text{ }\mu\text{m}$ thick nickel (Ni) films. When placed in organic solvents such as acetone or t-butanol, the sacrificial layer dissolved and all hinges folded spontaneously to form the final assembled structure. Although individual hinges within simple structures such as linear strips often tore apart due to liquid shearing forces during assembly, interconnected structures with large numbers of hinges were remarkably robust.

Selecting the appropriate thickness of Cr and Cu is critical to achieve a specific set of positive and negative fold angles with bilayer and trilayer hinges. The necessary thicknesses can be estimated based on a multilayered curvature model with input parameters of thin film stresses, elastic moduli, and Poisson ratios for each layer.²⁰ In order to demonstrate a rational methodology, we designed hinges to fold with a positive and negative 90° fold angle. In order to design hinges with opposite fold angles, one might guess that merely doubling the Cr thickness atop the Cr/Cu/Cr trilayer hinge would cause it to bend with an opposite fold angle to a Cr/Cu bilayer hinge. However, this simple approximation neglects the underlying thin film mechanics. Although these hinges folded in opposite directions, their magnitude was different. For example, we fabricated $70\text{ }\mu\text{m}$ long bilayer hinges with 50/300 nm of Cr/Cu and $70\text{ }\mu\text{m}$ long trilayer hinges with 50/300/100 nm of Cr/Cu/Cr. The experimental results were in agreement with the model and while the bilayer hinge folded with an angle of 80° , the trilayer hinge folded with an angle of -8° . The model was then used to predict the right thicknesses of Cr and Cu for $+90^\circ$ and -90° fold angles. Practically realizable values for t_1 (Cr), t_2 (Cu),

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FIG. 1. (Color online) Schematic for generating origami with mountain and valley folds via lithographic patterning. (a) A sacrificial layer is spincoated onto a rigid flat substrate. (b) A Cr thin film, with a tensile residual stress, is deposited onto the sacrificial layer by thermal evaporation. (c) A Cu film is then deposited with minimal residual stress, onto the Cr film by thermal evaporation. (d) Additional Cr is deposited in selected regions via lift-off metallization. These areas will become valley folds. (e) Thick, rigid Ni (with a thin capping Au layer, not shown) is patterned onto the Cu layer using photolithography and electrodeposition. (f) Exposed Cu and Cr are removed to create hollow regions in the sheet, all hinges are protected with photoresist (not shown). (g) The sacrificial layer is dissolved causing the sheet to assemble while lifting off of the substrate. (h) An assembled structure with $r=1$ rigid panel: flexible hinge ratio, with positive and negative fold angles of $\pm 180^\circ$. (i) Optical micrograph of an assembled structure with $r=5$ ratio and $\pm 180^\circ$ fold angles. (j) Optical micrograph of an assembled structure with $r=3$ ratio and $\pm 180^\circ$ fold angles. Here, alternating rigid panels have been patterned with pores consisting of triangles and squares.

and t_3 (Cr) were obtained by carrying out an optimization with three constraints: (1) Fold angles of $+90^\circ$ for the bilayer and -90° for the trilayer hinge were specified; (2) the bottom layer t_1 (Cr) was limited to a minimum of 5 nm; and (3) the top layer t_3 (Cr) was limited to a minimum of 10 nm. Figure 2 shows a plot of predicted thickness of Cr and Cu that need to be incorporated into bilayer and trilayer hinges to achieve a $+90^\circ$ and -90° fold angle for different hinge lengths. In our experimental demonstrations, we utilized a hinge length of $45 \mu\text{m}$, which required Cr/Cu/Cr thicknesses of 10.2/136.3/50.2 nm, respectively. It should be noted that this paradigm can be extended to design hinges with any desired bidirectional fold angles. For example, 180° folds [shown in Figs. 1(i) and 1(j)] can be constructed by doubling the hinge length from a 90° design, as the radius of curvature is constant for a given hinge design.

The above strategy was used to design and assemble a complex microstructure with bidirectional curvature and thousands of interconnected hinges. We chose to self-fold the familiar cubic core structure.^{2,12} One key difference between paper folding and our self-folding methodology is that the hinges in paper-folded structures have negligible lengths [Fig. 3(a)] while our patterning strategy requires the use of

FIG. 2. (Color online) Design criteria for mountain and valley folds fabricated from Cu and strained Cr thin films. For each designated hinge length (x -axis), an equilibrium model was used to optimize a combination of thicknesses of the three hinge layers (t_1 =Cr, t_2 =Cu, t_3 =Cr) that resulted in specified hinge angles of $\pm 90^\circ$. Both mountain and valley folds utilize the same bottom (t_1) and middle layers (t_2), whereas the top Cr layer (t_3) is used only to enable valley folds. The total hinge thickness needed to achieve $\pm 90^\circ$ decreases with decreasing hinge length leading to increased tearing of structures during assembly. The gray shaded area shows experimentally realizable size scales for our approach.

hinges of finite lengths [Fig. 3(b)] in order to be resolved using optical lithography. We define a parameter r [Figs. 3(c) and 3(d)] as the ratio of the length of the square rigid panel to that of the hinge. We then fabricated flat sheets such as the one shown in Fig. 3(b), where the length of the rigid panel was varied to construct structures with r varying between 1 and 10. In contrast, paper folded structures have large r values, typically greater than 50.

As the sacrificial layer was removed, these structures spontaneously assembled into cubic core structures with desired hinge angles of $+90^\circ$ and -90° . Cores with a ratio of 1 did not resemble paper models because the hinges constituted a large proportion of the assembled structure [Fig. 4(a)]. Cores with ratios of 3 and 5 were progressively more

FIG. 3. (Color online) Schematic origami fold diagram for a cubic core that can be realized in paper and by self-folding. Hatched lines represent $+90^\circ$ mountain folds, solid red lines represent -90° valley folds, solid gray squares represent rigid panels, and white squares represent hollow areas where all material has been removed. (a) Paper fold diagram (b) Lithographic mask used to fabricate a cubic core with $r=3$, as defined by the schematic diagrams in (c) and (d).

FIG. 4. (Color online) Experimental results of bidirectional origami used to spontaneously assemble complex microscale cubic cores with varying r ratios. (a) Optical image of a core with $r=1$ (b) SEM micrograph of a core with $r=3$. (c) SEM micrograph of a lithographically patterned core with $r=3$ featuring square pores on horizontal faces and triangular pores on vertical faces. (d) Optical image of the entire structure shown in C with 224 hinges, inset: magnified view. (e) Optical image of a core with $r=5$ featuring triangular pores on horizontal faces and square pores on vertical faces, inset: magnified view. (f) SEM micrograph of a torn portion of a core with $r=10$.

akin to the paper and sheet metal structures; however they could be assembled spontaneously in a parallel manner [Figs. 4(b)–4(e)]. As this ratio increased to 10 [Fig. 4(f)], the self-assembly failure rate increased due to tearing at the hinges.

Any discrepancies in observed curvatures can be attributed primarily to interfacial effects (which are not captured in the model), specifically between the polymeric sacrificial layer and bottom Cr film, and second to variability of film thicknesses across the wafer. We observed that any asymmetry in folded angle between bi- and trilayer hinges led to bowing of the entire structure. Other defects such as warping were observed at the edges of the structures where rigid panels were connected to fewer hinges.

As the cores begin as two-dimensional lithographic masks, it is straightforward to integrate patterns onto rigid panels with precise planar selectivity. For example, it was possible to place square pores on all faces parallel to the core and triangular pores on faces perpendicular to the core [Figs. 4(c) and 4(d)]. Structures patterned with dissimilar dielectric and metallic patterns are especially relevant for optical applications. Additionally, the core templates spanned a volume while filling only a small portion of this space with material, such as a space filling truss used for structural applications.²¹ A core with a ratio of 3 was tested for static compression in the z direction; it held 0.883 g, or 7700 times its own weight without rupture. We also explored the use of these cubic cores as a structural component by constructing a metal/polymeric composite. A cubic core with a ratio of 10 was placed on a fluorinated sheet and wetted with a drop of cyanoacrylate glue, which wicked to cover all metallic surfaces. This structure weighed 7.8 mg, but was able to support upwards of 100 g, or 128 000 times its weight, without any obvious damage.

Unlike other methods of microscale 3D fabrication, our method permits easy adaptation of macroscale templates, in-

creased predictability of folded structures, and lithographic versatility to integrate devices and differing materials. The multilayer stack approach allows for design of hinges with a variety of stresses, thicknesses, and moduli resulting in different radii of curvature. Therefore, any combination of patternable materials that exhibit stress, such as semiconductors and ceramics, can be used to design thin film mountain and valley folds.

We foresee applications of these structures in the fields of tissue culture, deployable medical devices, robotics, sensors, auxetic materials, and 3D circuitry. The addition of programmable hinge stops¹⁸ will allow for reconfiguration of specific hinges in order and enable the folding and unfolding of more complex origami models. We also believe that the incorporation of nanoscale patterning and larger driving forces generated by epitaxial stresses^{10,22} can be used to create hinges with tighter nanoscale radii of curvature.

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