

# The Nanostructured Origami<sup>TM</sup> 3D Fabrication and Assembly Process

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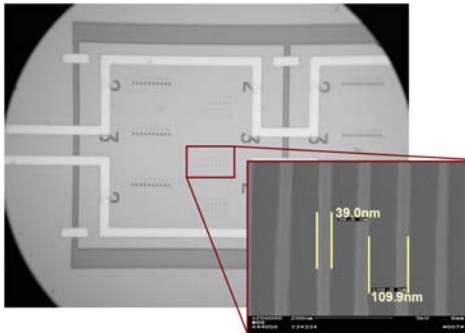
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**ABSTRACT** — Nanostructured Origami<sup>TM</sup> 3D Fabrication and Assembly Process is a method of manufacturing 3D nanosystems using exclusively 2D litho tools. The 3D structure is obtained by folding a nanopatterned 2D substrate. We report on the materials, actuation, and modeling aspects of the manufacturing process, and present experimental results from fabricated structures.

## I. INTRODUCTION



**Figure 1** Nanostructured Origami<sup>TM</sup> 3D Fabrication and Assembly Process

The increasingly frequent use of nanoscale features in system manufacturing provides new tools, and also new challenges for precision engineering. For example, methods such as scanning tunneling microscopy and atomic force microscopy enable patterning of features at atomic scales in two dimensions in serial fashion (one feature at a time). Parallel methods such as electron beam and x-ray lithography, nanoimprinting and dip-pen lithography reliably produce features in the range of 10-40nm. These methods are well suited to planar nanoelectronics and other applications where 2D feature layouts are sufficient. In this paper we report on nanomanufacturing in the 3<sup>rd</sup> dimension via the Nanostructured Origami<sup>TM</sup> 3D fabrication and assembly process [1].

The 3<sup>rd</sup> dimension often provides maximum flexibility in the design and manufacturing of nanosystems. 3D nanopatterning may enable new functions as is the case, for example, in photonic crystals [2] and other nanophotonic devices, as well as electro-chemical energy conversion or storage devices [3]. The 3<sup>rd</sup> dimension is even more critical in hybrid systems, where the energy storage and mechanical, electrical, optical and other components must be assembled. However, 3D nano-fabrication and assembly remain challenging because of the lack of parallel (in-line) manipulation tools that would allow the placing of components in their proper places. The 3<sup>rd</sup> dimension also helps overcome the related challenge of bridging the gap between the nanoscale features of a system and the macroscale.

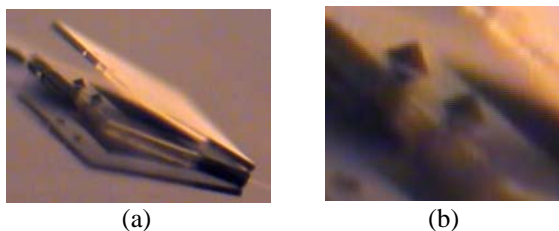
The Nanostructured Origami<sup>TM</sup> process assembles 3D systems with component features ranging from the nanoscale to the mm scale by using exclusively 2D litho tools. The process starts by patterning a large 2D membrane on a silicon substrate. This can be done via any of the commercial or research-grade methods. The 3<sup>rd</sup> dimension is achieved by folding the 2D membrane along well-defined creases. For rigid membranes such as silicon, the patterning step includes the definition of hinges. By proper design of the 2D feature layout and proper timing of the folding process, one can achieve almost arbitrary 3D layout.

Figure 1 shows an example of Nanostructured Origami, before the folding step. The surfaces of the three folding segments (only one is shown in the figure) were patterned with gratings of feature size 39nm using electron beam lithography. The lateral size of the segments was 0.5mm×0.5mm and their thickness was 5μm. Upon folding, the hinge curvature would lead to vertical spacing of approximately 10μm between the folded surfaces.

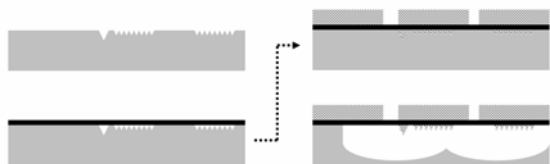
In this paper, we report on our progress in various aspects of realizing practical nanomanufacturing systems based on Nanostructured Origami. In Section II, we describe a new fabrication process in which the segments are made out of SU-8, a robust, epoxy-type photoresist. Because SU-8 is a dielectric, it is ideal for use in optical applications or in other instances where electrical isolation between the segments is desired. This is the case, for example, in energy storage devices [2]. In Section III, we report on a new method of origami folding using residual stress-induced strain mismatch to rotate segments around the hinges. In Section IV, we describe a new algorithm for modeling the kinematics of certain origami folding schemes. We conclude in Section V and briefly reference some applications of Nanostructured Origami that we are pursuing.

## II. SU-8 FABRICATION PROCESS

The Nanostructured Origami prototypes of Figure 1 were fabricated on a silicon-on-insulator (SOI) wafer. The origami segments were made out of silicon released from the 5 $\mu$ m thick device layer. The segments were connected via gold hinges, which also served as conductors for the current used to actuate the device via Lorentz force.



**Figure 2** (a) Origami using the SU-8 process. (b) Close-up view of the alignment pyramids.



**Figure 3** SU-8 process flow (gray=silicon; black=gold; striped=SU-8).

patterns defined in the previous KOH etch step acted as a mold for patterning the bottom side of the SU-8. In the final release step, XeF<sub>2</sub> gas was used to etch away the underlying silicon thereby releasing the entire structure.

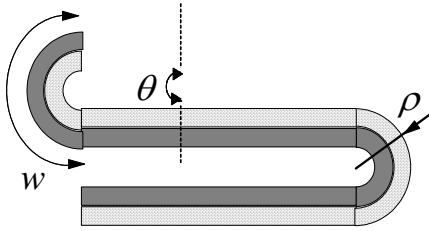
While the design of the hinges alone was sufficient to align the folded segments to <10 $\mu$ m [1], we exploited the possibility of double sided patterning mentioned earlier to provide an additional alignment mechanism in this design. The mechanism consists of pyramidal spacers and corresponding square openings that fit the spacers tightly. A close-up view of the pyramids is shown in Figure 2(b). With this scheme, alignment is limited exclusively by the available lithographic accuracy. In our case, this was estimated to be better than 3 $\mu$ m.

## III. STRAIN INDUCED FOLDING

The Lorentz actuation method is effective for a number of applications but requires the definition of surface-consuming actuation wires on the folded substrate. Moreover, the folding process can be time-consuming for multi-segment origami structures. A promising alternative is to deliberately introduce residual stress in selected areas of an original flexible substrate. The resulting stress can then fold the segment upon release.

Figure 2 shows a new device fabricated using a similar process except the origami segments were made out of octafunctional epoxidized novolac (SU-8). This is a robust, epoxy-type photoresist commonly used as structural material for micro-electromechanical systems. For Nanostructured Origami, the advantages of the SU-8 process are optical transparency, reduction in process complexity, high aspect ratio, wide range of achievable thicknesses (from 1 $\mu$ m to several millimeters), and the ability to be patterned on both sides.

The basic process flow is shown in Figure 3. Starting with a (100) silicon wafer, a KOH etch step defined patterns into the substrate. A layer of gold was then deposited and patterned to define the hinges. Subsequently, SU-8 was coated and patterned to serve as the structural layer for the origami segments. The



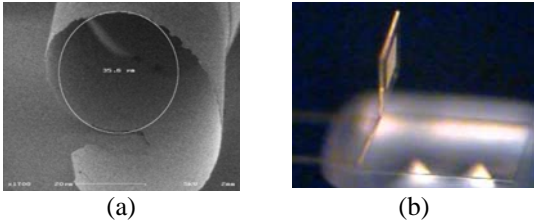
**Figure 4** Geometry of folding bilayer for the stress-induced actuation method.

The stress actuation method is implemented by forming a thin film bilayer strip of width  $w$  in the region where folding is to take place. If one material is under compressive stress (e.g. silicon nitride) and the other under tensile stress (e.g. chromium) then the bilayer curls in order to relieve the strain mismatch as shown in Figure 4. The curling must result in radius of curvature  $\rho$  sufficiently small to produce the desired folding angle  $\theta$ . In the case of complete folding ( $\theta=180^\circ$ )  $\rho$  also specifies the spacing between the folded segments. The design parameters are the ratio  $n$

of Young's moduli and ratio of thicknesses  $m$  of the two bilayer materials. Then

$$\rho = \left[ \frac{d_2}{6\varepsilon} \right] \cdot \left[ \frac{n^2 m^4 + 4nm^3 + 6nm^2 + 4nm + 1}{nm(1+m)} \right] \quad (1)$$

where  $d_2$  is the thickness of the bottom layer and  $\varepsilon$  is the stress-induced strain [4]. The folding angle is  $\theta = w/\rho$ .



**Figure 5** Stress induced actuation. (a) Chromium on silicon nitride. (b) Chromium on gold, attached to rigid segments made out of SU-8.

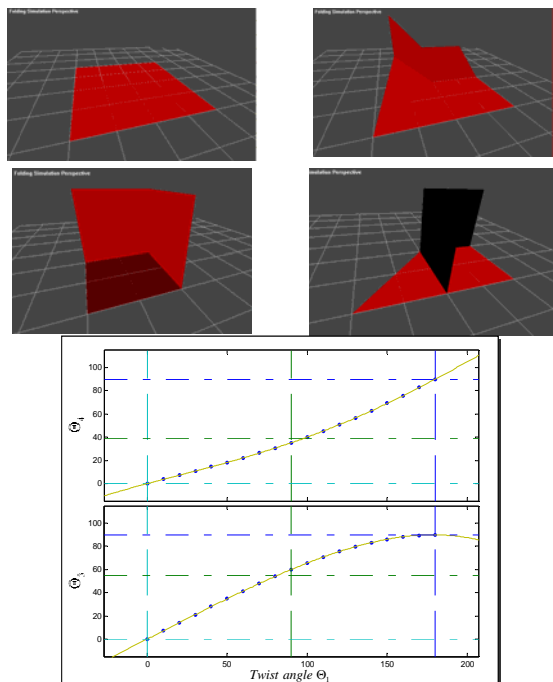
Figure 5(a) shows a bilayer fabricated by evaporating chromium over LPCVD stoichiometric silicon nitride ( $n=1.93$ ) deposited on single crystal silicon. The layer thicknesses were 100nm and 200nm, respectively. For the calibrated value  $\varepsilon=0.026$  of our LPCVD machine, the theoretical radius of curvature predicted by (1) is  $\rho \approx 20\mu\text{m}$ . In the experiment, the bilayer curled into a complete loop with  $\rho \approx 18\mu\text{m}$  upon release from the substrate.

Figure 5(b) shows the result of folding a different bilayer, made out of evaporated chrome on gold using the process described in Section II. In this case, the bilayer was attached to two patterned rigid SU-8 segments.

#### IV. KINEMATIC MODELING

Modeling the kinematics of origami structures is necessary to verify two desirable properties: (i) integrity, *i.e.* ensure that the structure is not torn at its hinges during folding; and (ii) compatibility, *i.e.* avoidance of collisions between segments during folding. Note that the integrity concern does not arise in robotic manipulators, for example; in origami, it is essential because of the 2D nature of the segments. Prior works have used affine transformations [5] and pseudo-triangulations [6] to model folding and unfolding. We used screw calculus [7] because it is computationally convenient. Its dual twist calculus permits the straightforward derivation of the dynamical model as well.

Our model begins by attaching a closed “skeleton” structure to the origami segments. The skeleton is then broken into two parts and forward kinematics are performed in the part that contains the actuation mechanism. The second part is constrained by the integrity condition, and so its motion is estimated via inverse kinematics. Singularity in the inverse kinematics of the second part indicates that kinematic integrity is violated in the given structure. Kinematic compatibility is ensured by tracking the segment edges (this function has not yet been implemented in our software tool).



**Figure 6** Five-segment origami mechanism (actuation sequence shown clockwise on top) and the folding angles of two of the segments in response to actuation of the diagonal joint.

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Figure 6 shows an example of a five-segment origami structure, and the folding angle progression as the diagonal joint is actuated. Our approach is presently limited to similar single-vertex structures [5,6].

## VI. CONCLUSION

The preliminary results from the material, actuation, and modeling work presented herein show great promise for the use of Nanostructured Origami in 3D nano-manufacturing. Possible applications with immediate value are miniature 3D electrochemical storage devices [2] embedded in general-purpose microsystems (e.g., distributed sensors), multi-layer diffractive optics, etc.

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