

Microorigami: Fabrication of Small, Three-Dimensional, Metallic Structures

Scott T. Brittain,[†] Olivier J. A. Schueller,[†] Hongkai Wu,[†] Sue Whitesides,[‡] and George M. Whitesides^{*,†}

Department of Chemistry and Chemical Biology, Harvard University, 12 Oxford Street, Cambridge, Massachusetts 02138, and School of Computer Science, McGill University, 3480 University Street, Montreal Quebec H3A 2A7, Canada

Received: July 19, 2000

Microcontact printing (μ CP) and wet chemical etching generated two-dimensional (2D) patterns in thin silver films. Electroplating silver onto these patterns increased the structural integrity of the metal layer. Separating the metal film from the substrate resulted in free-standing, 2D structures. Folding of these structures along predesigned “hinges” produced three-dimensional (3D) objects. Additional electrodeposition of nickel welded hinges into position, strengthened the structure, and joined separate pieces. By printing onto cylindrical surfaces, it was possible to generate complex shapes efficiently and to minimize joining steps.

This paper describes a strategy for fabricating small (100 μm –1 mm), three-dimensional (3D), tessellated metallic structures. This strategy takes its inspiration from origami,^{1,2} the Japanese art of paper folding, and converts two-dimensional (2D) patterns to 3D objects by folding. Microfabrication in 3D is difficult using the inherently planar techniques associated with projection photolithography.^{3,4} The most commonly used method for the fabrication of 3D structures—stereolithography^{5,6}—“writes” patterns serially in layers in photosensitive polymers. Other strategies include micromilling using microtool sets^{7,8} and shell plating onto die-cast mandrills.⁹ Ball Semiconductor¹⁰ uses elaborate systems of mirrors to project planar patterns for photolithography onto spherical substrates. Although these methods provide access to complex structures, they are complicated and may be limited in the connectivities of the structures they can generate.

We and others^{11–13} believe that one route to fabrication in the third dimension involves rotation of elements of a planar structure out of that plane. The methods described to date rely on bulk and surface micromachining of silicon to carve out plates and hinges from rigid crystals and glasses. Here we describe a different strategy for fabrication of 3D metallic structures. In this strategy, microcontact printing (μ CP) and wet chemical etching¹⁴ generate 2D patterns in thin silver films; electroplating onto these patterns increases the thickness and structural integrity of the metal layer; separating the metal film from the substrate results in free-standing, 2D structures. Folding of these structures along predesigned lines of perforations that act as “hinges” produces 3D objects. Further electrodeposition welds hinges into position, strengthens the structure, and joins separate pieces. By printing the original, planar pattern on cylindrical surfaces, it is sometimes possible to generate complex shapes efficiently and to minimize joining steps.

Results and Discussion

Folding of a Planar Object into a 3D Structure and Consolidation of this Structure by Electrodeposition. Figure 1 illustrates the general strategy of microorigami. Microcontact printing (μ CP) using an elastomeric stamp transfers a layer of hexadecanethiol to a silver-coated substrate. The hexadecanethiol forms a self-assembled monolayer (SAM) on the surface of the silver. This SAM acts as a nanoscopic resist to subsequent wet chemical etching using aqueous ferricyanide solution. The resulting patterned, interconnected, conductive, thin silver film serves as the cathode in an electrodeposition step. An electroplated layer of silver $\sim 25 \mu\text{m}$ thick strengthens the patterned film and enables removal of the planar, silver object from the surface of the substrate.

The object comprises a single-layer array of rigid plates fabricated in a ductile metal film (silver) connected by weaker, perforated lines of the same metal. This type of structure folds easily at the perforated lines; that is, these lines act as “hinges.” The folds can generate either of two types of topographies: a “ridge fold” results in a convex crease that bends outward and forms a ridge; a “valley fold” results in a concave crease that bends inward like a groove. A series of folds transforms the planar film into a 3D object. A final electrodeposition step using a structural metal (nickel, for example) “welds” the hinges in place, joins elements that are separated in the starting pattern, heals any stress-induced fissures, and consolidates the structure.

Microorigami using Planar Substrates: the Arch and Bird. As demonstrations, we have prepared two microorigami figures, the “arch” and the “bird” (Figure 2). The arch requires a transformation from a plane to a quasi-hemicylindrical shell. The uniformity of folding angles and panel sizes/shapes results in a symmetrical structure. The corrugation developed in this object on folding increases the structural stability of the metal film. The final silver arch is shown in Figure 3. The bird illustrates that a range of folding angles and panel sizes/shapes can produce more elaborate structure (Figure 2). In this origami figure, some panels have been folded under others. These

* Corresponding author. E-mail: gwhitesides@gmwgroup.harvard.edu.

[†] Harvard University.

[‡] McGill University.

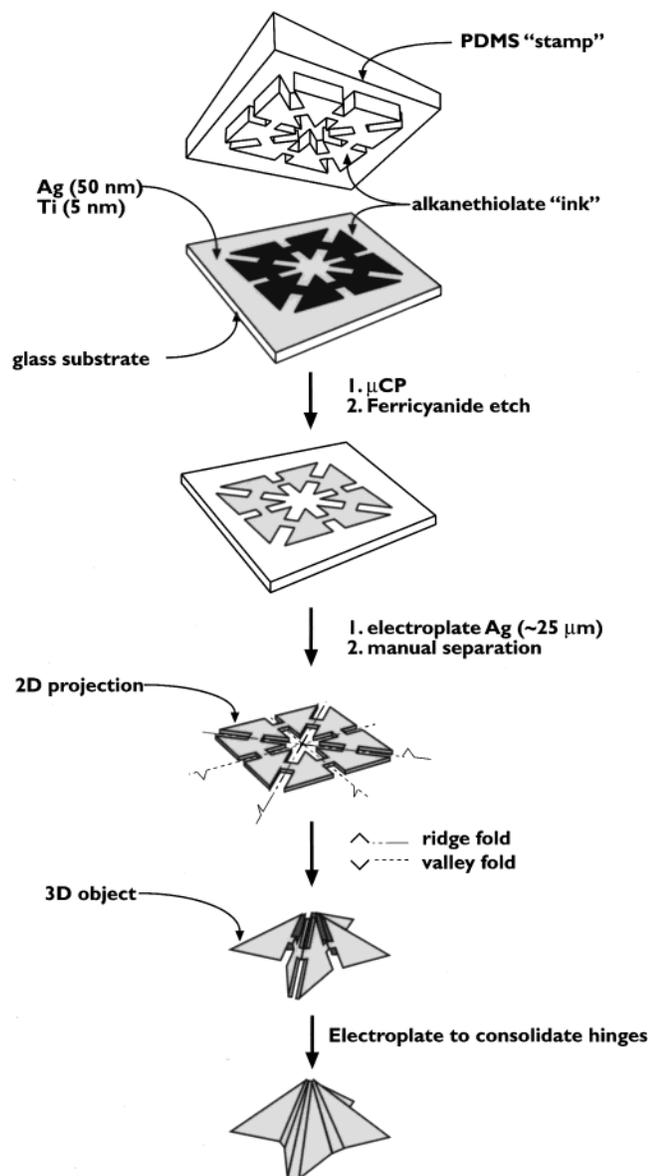


Figure 1. General method of microorigami. Microcontact printing (μ CP) of an alkanethiol "ink" with an elastomeric poly(dimethyl siloxane) (PDMS) stamp formed a patterned self-assembled monolayer (SAM) on the surface of the silver-coated glass substrate. Immersion of the substrate in an aqueous ferricyanide removed the areas of underivatized silver; immersion in 1% HF solution removed the exposed titanium adhesion layer. Electrodeposition of a layer of silver onto the conductive metal pattern strengthened the 2D structure. Weak adhesion between the evaporated and electroplated silver layers enabled mechanical separation of the 2D structure from the glass substrate. We introduced folds in the structure manually along perforated "hinges" using tweezers. Combinations of mountain and valley folds produced the final, 3D object. An additional electroplating step filled in the perforations between adjacent plates, effectively "welding" the structure into the final, 3D shape. In this and subsequent figures, the perforations, which are drawn disproportionately large, are removed for clarity once the fold has been performed.

"pushed" folds introduce multiple layers into the object that increase the complexity beyond that of a simple shell structure (Figure 3). Pushed folds also increase the complexity of the fabrication process and require finesse to achieve manually. Accomplishing these types of folds using automated micromanipulators will require careful design.

Figure 3 also shows the effect of electroplating a metal shell over the entire surface of a folded bird. This operation closes the gaps between perforations and increases the overall film

thickness. Since nickel is stiffer and less ductile than silver, the nickel-coated structures are much stronger than their silver precursors.

Microorigami using Cylindrical Substrates: the Torus.

To produce an object that encloses space (e.g., a continuous shell) from a planar template, the template must wrap around and connect to itself at some point. For example, a toroidal shell can be thought of as a cylindrical shell connected end-to-end. The cylindrical shell can be further decomposed into a planar sheet rolled and joined along a seam. Cylindrical shells with more complex topographies—for example, a chain of tetrahedral shells—require multiple connecting points (qQ , rR , ...) to be joined after initial folding of a planar sheet (Figure 4a). The alignment required for this joining is difficult. These connections can, however, also be made before the sheet is folded (Figure 4b). Using this strategy, we first rolled the planar sheet into a cylinder and then joined the connecting points (qQ , rR , ...) along the seam. Crimping of the cylinder in two orthogonal directions that are both orthogonal to the axis of the cylinder produces a tetrahedral shell.¹⁵ A series of such crimps along the length of the cylinder results in the desired chain of tetrahedral shells.

Implementing the strategy described in Figure 4b involves an initial transfer of a planar pattern directly to a cylindrical substrate using μ CP (Figure 5). This printing step is topologically analogous to rolling a sheet into a cylinder. After the cylindrical substrate makes one entire rotation across the stamp, the pattern meets along its edge, and all necessary interconnects form in one simple step. Wet chemical etching develops the pattern, electroplating strengthens the patterned metal film, and dissolution of the cylindrical substrate releases the free-standing, quasi-3D template. Crimping of this template along the specified perforated hinges produces the desired chain of tetrahedral shells. Suturing the chain end-to-end with platinum wire followed by an electroplating step joins the ends and completes the toroidal shell.

Conclusions

The method described provides a strategy for fabricating tessellated, 3D, metallic surfaces, but uses planar methods of lithography (high-resolution printing,¹⁶ photolithography, soft lithography, electrodeposition) that make the fabrication of even very complex 2D patterns straightforward. Microelectrochemistry enables joints and joins to be welded and heals defects introduced during bending or crimping. The use of nonplanar substrates with suitable topographies/symmetries can, in some instances, enable difficult interconnects to be made simply and directly on the substrate.

The range of microspheres that can be formed using the strategy described here is large: conformal mapping¹⁷—the mapping of 2D patterns onto 3D surfaces—and cylindrical buckling¹⁸ have been extensively studied. The major limitations to this method are practical ones: the difficulties of folding and connecting. In its present configuration, we fold the structures manually, and the method is thus limited to tessellations having millimeter dimensions. We can envision using microtools^{19,20} to manipulate hinges and assemble components. We^{21,22} and others^{23,24} have also developed methods of self-assembly that use minimization of surface free energy to accomplish folding. These methods are particularly attractive for their simplicity and for their ability to scale to small dimensions. We suggest that they will be useful in fabricating small, lightweight structures: components of MEMS, small antennas, components of micro air vehicles, and microchemical reactors.

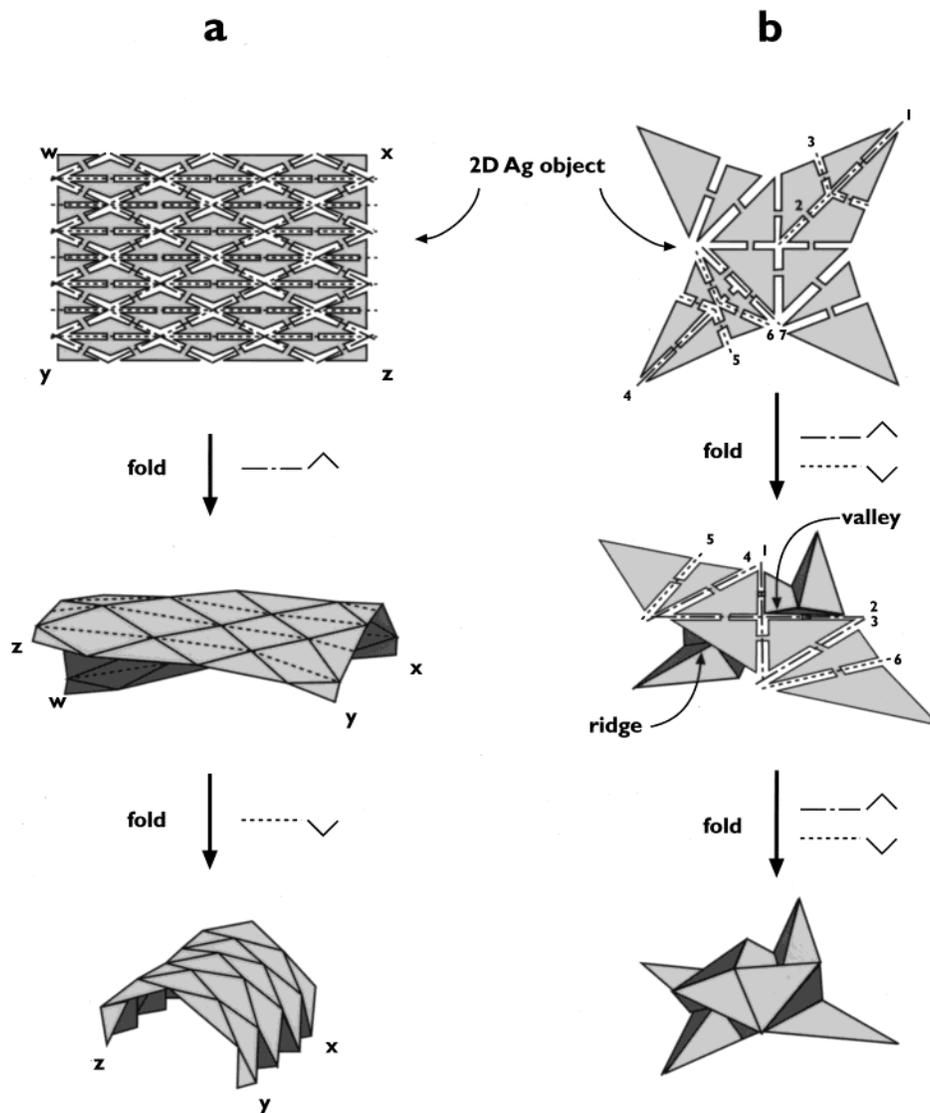


Figure 2. Patterns of folds used for two microorigami figures. (a) The diagonal ridge folds are performed first and cause the planar film to curl. Incorporation of the lengthwise valley folds completes the corrugated arch. (b) The “pushed” folds that create the nose and tail of the bird are performed first, creating a dimpled area near the tail and a multilevel zigzag surface near the nose. The simple folds required for the wings and body complete the bird. The numbers indicate the order of folding in each panel.

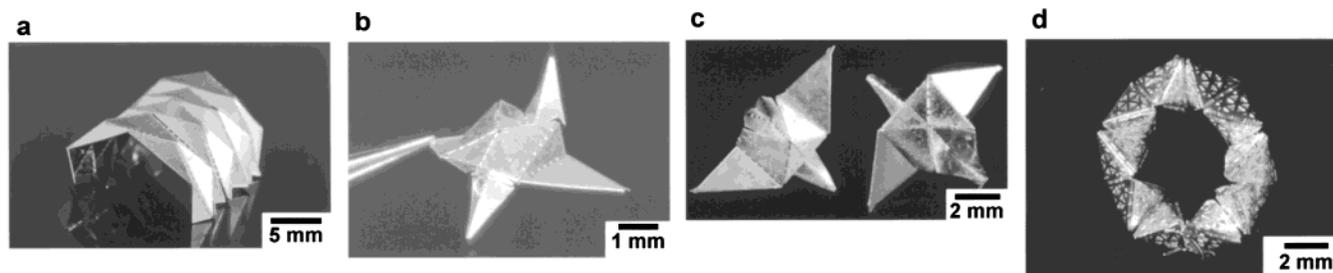


Figure 3. Photographs of tessellated, 3D objects fabricated using microorigami. (a) Corrugated arch. (b) Bird (tweezers shown at left). (c) Birds shown before (left) and after (right) final consolidation by electroplating. Note that the electroplated film has filled in the perforations that make up the hinges. (d) Torus composed of tetrahedra joined along edges.

Acknowledgment. This work was supported by the National Science Foundation (ECS97-29405) and the Defense Advanced Research Projects Agency. It also used MRSEC Shared Facilities supported by the NSF under award DMR-9400396.

Supporting Information Available: All experimental details, including preparation of glass substrates, microorigami using planar substrates, and microorigami using cylindrical

substrates. This material is available free of charge via the Internet at <http://pubs.acs.org>.

References and Notes

- (1) Mitchell, D. *Mathematical Origami: Geometrical Shapes by Paper Folding*; Tarquin Publications: Cambridge, 1997.
- (2) Gross, G. M.; Silverman, E.; Palubniak, N. *Paper Creations: Easy-to-Make Paperfolding Projects*; Friedman/Faifax Publishers: New York, 1997.

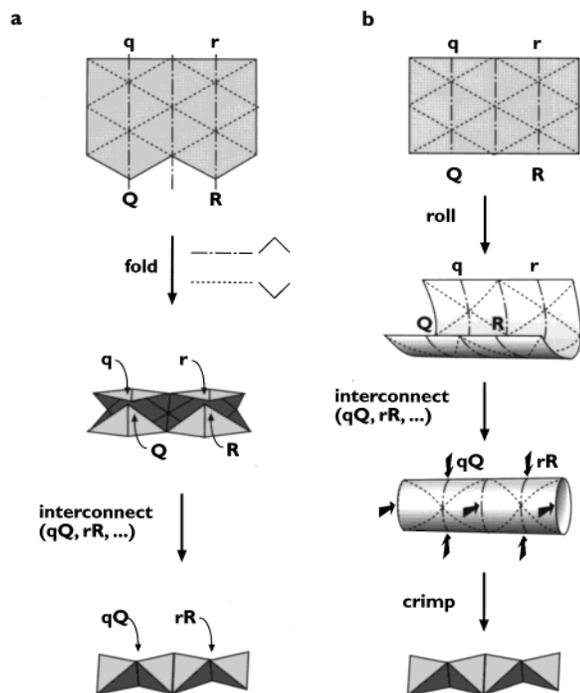


Figure 4. Two strategies for converting a planar sheet into a chain of interconnected tetrahedral shells. (a) Interconnects made after the folding step. Introduction of the indicated folds causes the sheet to curl along its long axis. Points q and Q , and r and R , can be joined to form the array of tetrahedra. (b) Interconnects made before the folding step. Points q and Q , and r and R , meet along the seam of the rolled sheet; joining of the edges along the seam forms a cylinder. Crimping at the locations and in the directions indicated by the arrows creates the concave folds shown by the dash-dotted lines. Simultaneously, the crimping induces the formation of convex folds along the dotted lines. This strategy results in the formation of the desired array of tetrahedral shells.

- (3) Kovacs, G. T. A.; Petersen, K.; Albin, M. *Anal. Chem.* **1996**, *68*, 407A.
- (4) Madou, M. J. *Fundamentals of Microfabrication*; CRC Press: New York, 1997.
- (5) Calvert, P.; Crockett, R. *Chem. Mater.* **1997**, *9*, 650.
- (6) Neckers, D. C. *CHEMTECH* **1990**, 615.
- (7) Friedrich, C. R.; Vasile, M. J. *J. Microelectromech. Sys.* **1996**, *5*, 33–38.
- (8) Kussel, E. M.; Rachkovskij, D. A.; Baidyk, T. N.; Talayev, S. A. *J. Micromech. Microeng.* **1996**, *6*, 410–425.
- (9) Suzuki, H.; Ohya, N.; Kawahara, N.; Yokoi, M.; Ohyanagi, S.; Kurahashi, T.; Hattori, T. *J. Micromech. Microeng.* **1995**, *5*, 36–40.
- (10) Ball Semiconductor Inc. Site. <http://www.ballsemi.com> (accessed Sept 2000).
- (11) Friedberger, A.; Muller, R. S. *J. Microelectromech. Sys.* **1998**, *7*, 315–319.
- (12) Pister, K. S. J.; Judy, M. W.; Burgett, S. R.; Fearing, R. S. *Sens. Actuators, A* **1992**, *33*, 249–256.
- (13) Reid, J. R.; Bright, V. M.; Butler, J. T. *Sens. Actuators, A* **1998**, *66*, 292–298.
- (14) Jackman, R. J.; Brittain, S. T.; Adams, A.; Wu, H.; Prentiss, M. G.; Whitesides, S.; Whitesides, G. M. *Langmuir* **1999**, *15*, 826–836.
- (15) Lobkovsky, A.; Gentges, S.; Li, H.; Morse, D.; Witten, T. A. *Science* **1995**, *270*, 1482–1485.
- (16) Qin, D.; Xia, Y.; Whitesides, G. M. *Adv. Mater.* **1996**, *8*, 917.
- (17) Krantz, S. G. *Am. Sci.* **1999**, *87*, 436.

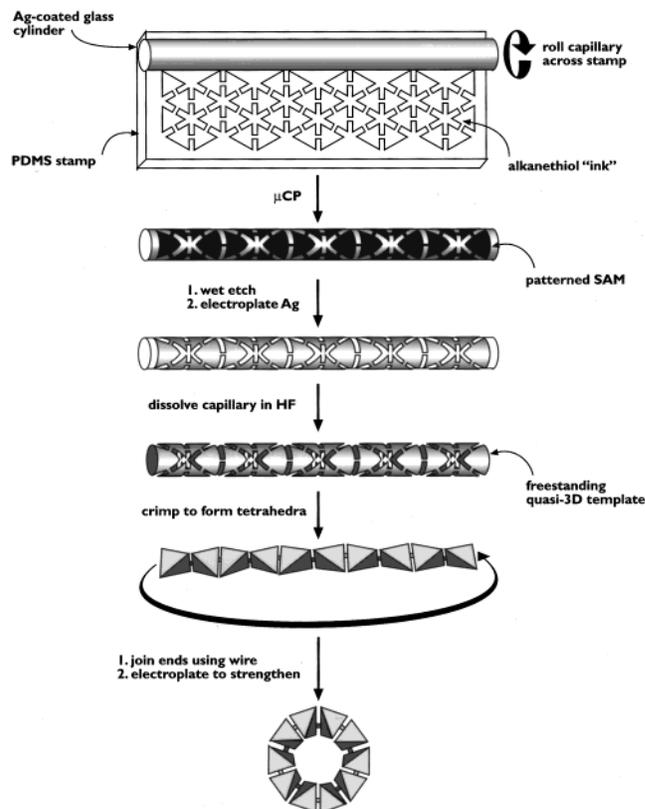


Figure 5. Microorigami using cylindrical substrates. Microcontact printing of hexadecanethiol on the surface of the silver film was achieved by rolling the capillary across the surface of a poly(dimethyl siloxane) (PDMS) stamp “inked” with an ethanolic solution of hexadecanethiol. Careful alignment of the capillary with the stamp ensured that the printed pattern matched with an error of $<5 \mu\text{m}$ along the “seam”, and a continuous, interconnected, patterned SAM resulted. The SAM acted as a resist against subsequent wet chemical etching of areas of underivatized silver using an aqueous ferricyanide solution. A brief, subsequent etch in 1% aqueous HF solution removed exposed areas of the titanium adhesion layer. Electrodepositing additional silver strengthened the patterned metal film. Dissolving the glass capillary in 49% aqueous HF solution released the free-standing, quasi-3D template. Crimping the cylinder along orthogonally oriented, perforated hinges using tweezers shaped the tetrahedral shells (as described in Figure 4b). The ends of the chain of tetrahedra were sutured together using a fine wire and welded by electrodeposition of an additional layer of silver over the entire structure.

- (18) Stewart, I. *Sci. Am.* **1999**, 100.
- (19) Gonzalez, C.; Smith, R. L.; Howitt, D. G.; Collins, S. D. *Sens. Actuators, A* **1998**, *66*, 315–332.
- (20) Schomburg, W. K.; Maas, D.; Bacher, W.; Bustgens, B.; Fahrenberg, J.; Menz, W.; Seidel, D. *J. Micromech. Microeng.* **1995**, *5*, 57–63.
- (21) Tien, J.; Breen, T. L.; Whitesides, G. M. *J. Am. Chem. Soc.* **1998**, *120*, 12670–12671.
- (22) Breen, T. L.; Tien, J.; Oliver, S. R. J.; Hadzic, T.; Whitesides, G. M. *Science* **1999**, *284*, 948–951.
- (23) Syms, R. R. A. *Sens. Actuators, A* **1998**, *65*, 238–243.
- (24) Green, P. W.; Syms, R. R. A.; Yeatman, E. M. *J. Microelectromech. Sys.* **1995**, *4*, 170–176.