Pressure-driven devices with lithographically fabricated composite epoxy-elastomer membranes

Kyle Campbell
Department of Physics, University of California, San Diego, 9500 Gilman Drive, La Jolla, California 92093

Uriel Levy and Yeshaiahu Fainman
Department of Electrical and Computer Engineering, University of California, San Diego, 9500 Gilman Drive, La Jolla, California 92093

Alex Groisman[a)]
Department of Physics, University of California, San Diego, 9500 Gilman Drive, La Jolla, California 92093

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The authors describe the fabrication and applications of composite membranes with lithographically defined pieces of rigid UV-cured epoxy grafted inside a flexible polydimethylsiloxane membrane. The pattern of epoxy in the membrane defines its mode of deformation under pressure. They constructed and characterized two devices with the composite membranes. In one device, the grafted pieces of epoxy focus the pressure-induced membrane extension to a thin strip, and in the other device, the epoxy pattern generates in-plane rotation of the membrane under pressure. The proposed composite membranes can be used in pressure-driven actuators and adaptive optical devices. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2361169]

Thin flexible membranes made of a silicon elastomer polydimethylsiloxane (PDMS) have been used to create microrelief on spherical and cylindrical surfaces[1,2] and also integrated into micromachined devices to produce pressure-actuated valves,[3–5] check valves,[6,7] and adaptive lenses.[8] The manner of deformation of a plain membrane under pressure is defined by the shape of the frame it is attached to, allowing for very limited tunability. Here we describe the fabrication and applications of composite membranes with pieces of rigid UV-cured epoxy grafted inside PDMS. The dimensions and positions of the epoxy parts are defined with a high precision by UV lithography. Patterning the soft membrane with the rigid epoxy makes its mode of deformation under pressure highly adjustable. To demonstrate applications of the composite membranes we constructed and characterized two devices that we call stretcher and rotator (Fig. 1). In the stretcher, the grafted pieces of epoxy focus the pressure-induced extension of the membrane to a thin strip of PDMS. In the rotator, the epoxy patterning causes in-plane rotation of a central area of the membrane when pressure is applied.

Both the stretcher and the rotator consist of $\sim$750 μm thick composite PDMS-epoxy membranes (with $\sim$200 μm thick pieces of epoxy grafted in them) bonded to identical $\sim$5 mm thick PDMS supports, which have rectangular openings in the middle and 1 mm thick glass windows glued to their back sides [Fig. 1(c)]. The side of a PDMS support bonded to the membrane has an $\sim$100 μm deep lithographically defined indentation around the opening. The indentation has a shape of a rectangle with rounded corners. The composite membranes in both devices contain identical epoxy frames [Figs. 1(a) and 1(b)] with inner dimensions 0.5 mm smaller than the corresponding dimensions of the indentations in the supports, 22 and 32.4 mm along the x and y directions, respectively. The frames are aligned concentrically with the indentations [Fig. 1(c)]. Therefore, the edges of the contact area between a frame and a support are set by boundaries of the indentation. In contrast, the edges of the deformable area of the membrane are set by the inner boundaries of the epoxy frame, making the mode of deformation of the membrane insensitive to small ($<$250 μm) misalignments of the membrane with respect to the indentation. The mode of membrane deformation under pressure is defined by the epoxy parts inside the frames, which are different in the stretcher and rotator. All epoxy parts are perforated, and the holes are filled with PDMS to ensure grafting of epoxy with PDMS. The air pressure in the cavity between the membrane and the glass [Fig. 1(c)] is adjusted through a via in a sidewall of the support.

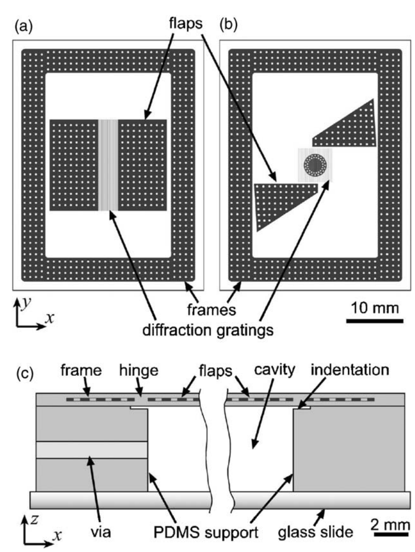

FIG. 1. Composite membrane devices, the stretcher and rotator. [(a) and (b)] Schematic drawings of the composite membranes in the stretcher and rotator, respectively. Dark areas correspond to epoxy parts inside the membranes. (c) Schematic drawing showing a cross section of a device.

a)Author to whom correspondence should be addressed; electronic mail: agroisman@ucsd.edu

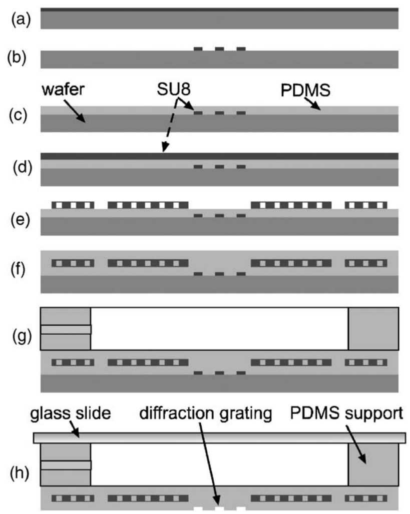

FIG. 2. Fabrication of a composite membrane device is shown step by step from top to bottom.

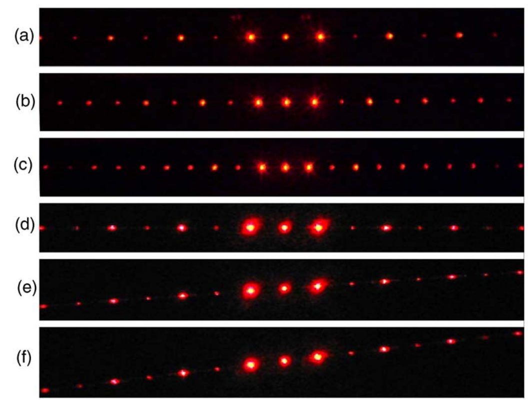

FIG. 3. (Color online) Photographs of diffraction patterns generated at different pressures P by the diffraction gratings engraved in the membranes of the stretcher [(a)–(c)] and of the rotator [(d)–(f)]. The pressures are (a) 0, (b) 0.75 psi, (c) 1.5 psi, (d) 0, (e) 0.75 psi, and (f) 1.5 psi.

Fabrication of the composite membranes (Fig. 2, see supplemental materials for more details) started with coating a silicon wafer with a 0.6 μm thick layer of UV-curable epoxy SU8 and patterning it through a photomask to produce a diffraction grating relief [Figs. 2(a) and 2(b)], similar to the fabrication protocol in Ref. 1. The wafer was coated by an $\sim$200 μm layer of PDMS [GE RTV 615, 25:1 mixture of parts A and B, Fig. 2(c)] that was cured and then spin coated with an $\sim$200 μm layer of SU8 epoxy [Fig. 2(d)]. The SU8 layer was exposed to UV light through another photomask and developed to generate the rigid epoxy parts of the composite membranes with lithographically defined dimensions and positions [Fig. 2(e)]. Next, the wafer was coated with another layer of PDMS that when cured produced a flat-parallel composite membrane with a total thickness of $\sim$750 μm [Fig. 2(f)]. (The membrane thickness inside the frames varied within $\sim$5%, between 730 and 770 μm.) To complete a device, the membrane was bonded to a PDMS support [Fig. 2(g)], separated from the wafer, and the support was bonded to a glass slide [Fig. 2(h)].

The stretcher [Fig. 1(a)] has two rectangular epoxy flaps separated from the frame by 750 μm wide strips of PDMS, which act as flexible hinges. When the interior of the device is pressurized and the membrane is inflated, the flaps are lifted by turning about the edges of the frame. Young's modulus of the SU8 epoxy [4–5 GPa (Ref. 9)] is about four orders of magnitude higher than that of PDMS in the membrane (measured at 0.3 MPa). Thus, a substantial part of the membrane extension occurs between the flaps in the narrow central strip of PDMS [Fig. 1(a)] that has a width x_0 $=3.5$ mm when the device is not pressurized. The composite membrane in the rotator [Fig. 1(b)] has a circular piece of epoxy in the middle and two trapezoidal flaps adjacent to the frame. The epoxy patterning has central but not axial symmetry. When the membrane is inflated and the flaps are lifted, the tips of the flaps apply a torque to the circle, making it rotate clockwise in the plane of the membrane. To evaluate the extension of the central PDMS strip in the stretcher and rotation of the central area of the membrane (with the epoxy circle in it) in the rotator, we studied the diffraction of light in the gratings engraved on the surface of PDMS in these two areas [Figs. 1(a) and 1(b)]. Both gratings had $\sim$12.5 μm wide, 0.6 μm deep grooves parallel to the longer side of the frame and a period of 25 μm. They were illuminated with an $\sim$1 mm wide, 632.8 nm HeNe laser beam Application of air pressure to the stretcher caused reduction of the distance between maxima of diffraction [Figs. 3(a)–3(c)], whereas the pressure applied to the rotator caused rotation of the whole diffraction pattern without its appreciable deformation [Figs. 3(d)–3(f)].

For small diffraction angles, the period of the grating and the distance between adjacent diffraction maxima at a given pressure, d and X, respectively, are connected to those at zero pressure, d_0 and X_0, respectively, by the equation $d/d_0=X_0/X$. We measured X at various air pressures P and calculated the relative extension of the central PDMS strip in the stretcher as $\Delta x/x_0=X_0/X-1$. Elevation h of the center of the membrane as a function of P was measured in a separate test. Dependence of $\Delta x/x_0$ on h is shown in Fig. 4(a) along with the corresponding dependence for a plain $\sim$750 μm thick PDMS membrane (without any epoxy pieces in it) attached to the same support.

Because of the flexibility of the epoxy flaps (Fig. 1), the xz-plane profile of the inflated composite membrane was close to an arc with a chord of a constant length, l_0 $=22$ mm. The radius of the arc, r, can be estimated from r^2 $=(l_0/2)^2+(r-h)^2$ as $r=(l_0^2/4+h^2)/(2h)$, and the contour length of the inflated membrane in the xz plane can be estimated as $l=2r\sin^{-1}(l_0/2r)$. The ratio between Δx and $\Delta l=l$ $-l_0$ found at different P was consistently 0.44±0.01, suggesting that the 3.5 mm wide central strip of PDMS contributed $\sim$44% of the total extension of the membrane. The rest of the membrane extension originated from elongation of the strips connecting the flaps with the frame and from slippage of PDMS along the flaps and the frame. The ratio of $\Delta x/x_0$ to the estimated relative extension of the whole membrane, $\Delta l/l_0$, at different P was consistently at 2.7±0.1. It was the same as the ratio between $\Delta x/x_0$ for the composite membrane and for the plain PDMS membrane at equal h [Fig. 4(a)]. The high values of the two ratios indicate that the introduction of the epoxy flaps leads to substantial enhancement of the membrane extension in the narrow central strip of PDMS.

Dependence of $\Delta x/x_0$ on P in the composite membrane device was close to linear [inset in Fig. 4(a)]. At low pressures ($P\leqslant 1$ psi), the ratio between $\Delta x/x_0$ measured at a given P for the composite and plain membranes was $\sim$1.6, indicating that the stretching of the central strip of PDMS in

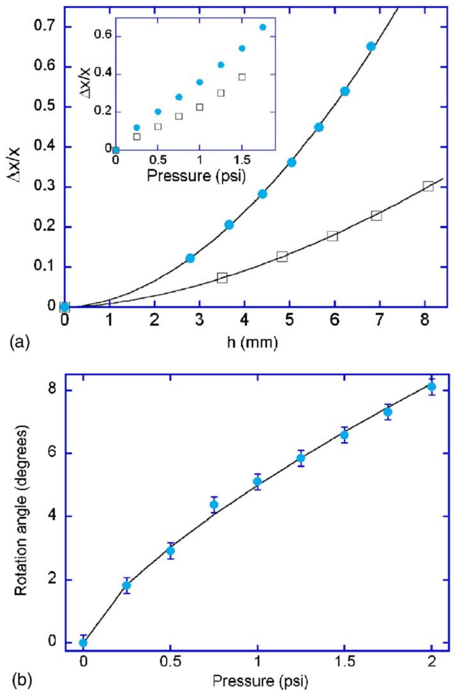

FIG. 4. (Color online) (a) Relative extension of the central strips, $\Delta x/x_0$, as a function of elevation of the center of the membrane, h, for the stretcher (circles) and for the plain membrane device (squares). The continuous lines are power law fits, $\Delta x/x \propto h^{1.9}$ and $\Delta x/x \propto h^{1.7}$, for the composite and plane membrane devices, respectively, shown to guide the eyes. Error bars are smaller than symbols and are not shown. Inset: $\Delta x/x_0$ as a function of pressure P for the stretcher (circles) and for the plain membrane device (squares). Error bars are smaller than symbols and are not shown. (b) Angle of the in-plane rotation φ of the central circle of the composite membrane in the rotator as a function of pressure P applied to the device. The continuous line is a power law fit, $\varphi \propto P^{0.72}$, shown to guide the eyes.

the composite membrane device was significantly more sensitive to pressure. To measure the uniformity of stretching of the central strip of PDMS, we analyzed patterns of diffraction from different regions along the central axis of the strip The variations of $\Delta x/x_0$ along the middle 8 mm of the 14 mm strip were within 1% at 0.5 psi and within 2% at 1 psi ($\Delta x/x_0$ was always a maximum at the center). For the plain membrane, the corresponding variations of $\Delta x/x_0$ were ~10% at both pressures. We also examined the central strip of PDMS under the microscope to evaluate its curvature in the yz plane (Fig. 1). At $P=0.5$ psi the radius of curvature of the middle 8 mm of the strip was ~150 mm for the composite membrane and was ~30 mm for the plain membrane. These last two results show that the epoxy flaps substantially improve the uniformity of extension of the central strip of PDMS and render the extension substantially more unilateral.

The rotation of the diffraction pattern generated by the rotator [Figs. 3(d)–3(f)] was a manifestation of in-plane rotation of the central area of the composite membrane with the epoxy circle [Fig. 1(b)] and did not occur in the device with the plain PDMS membrane. The dependence of the rotation angle φ on P is shown in Fig. 4(b). The angle reached 8° at $P=2$ psi (and $h=8$ mm). At $P=1$ psi and $h=5.6$ mm, φ was 5°, whereas the out-of-plane tilt of the central circle (measured under a microscope) was ~0.8°. The circle thus remained practically parallel to its original orientation at $P=0$ as it elevated and turned in the plane of the membrane. This type of motion of the circle was a consequence of a highly symmetric layout of the composite membrane with respect to its center (the center of the circle). The symmetry in the layout was enabled by the lithographic definition of the dimensions and positions of the frame, flaps, and circle, as well as by the high uniformity of the membrane thickness.

The durability of the devices was tested by putting them through $\sim 2\times 10^5$ cycles of inflation and deflation at $P=0.5$ psi and a frequency of 1 Hz, and measuring $\Delta x/x_0$ and φ as functions of P (for the stretcher and rotator, respectively) after the cycling. The dependences of $\Delta x/x_0$ and φ on P were found unchanged within the experimental error. The response time of the devices to variations of P was measured at ~100 ms for the stretcher and at ~200 ms for the rotator

The UV-curable epoxy SU8 has been used before to produce micromechanical elements[10] as well as complex pressure-actuated devices with moving parts on flexible springs.[11,12] The proposed fabrication technique is different in that it permits lithographic definition not only of individual parts but also of their mutual arrangement in the final functional device, thus allowing building complex multipart micromechanical systems without the need for assembly. The two devices constructed, the stretcher and rotator, demonstrate the usage of the composite membranes in pressure-driven adaptive optical systems, modifying diffraction patterns of light. Deformation of plain PDMS membranes under pressure is uniform, which is beneficial for the transfer of diffraction gratings engraved on the membranes onto spherical and cylindrical surfaces,[1] but allows only limited adaptivity. Epoxy patterning of the composite membranes makes their pressure-induced deformation nonuniform and allows enhancing the extension of the diffraction grating in the stretcher and substituting the extension by rotation in the rotator. The performance of the proposed devices can be enhanced by improving the adhesion between epoxy and PDMS, and the devices can be miniaturized by proportional reduction of dimensions of all their components. A prospective area of applications for the composite membranes is pressure-driven actuators.

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