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Microfabricated suspensions for electrical connections on the tunable elastomer membrane

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Electrical connections through microfabricated suspensions on a pneumatically pumped elastomer membrane were demonstrated. A method to fabricate the suspensions on the elastomer membrane was developed. The elastomer membrane was 1 mm in diameter and 120 μm in thickness. Resistances of the microfabricated suspensions measured across the elastomer membrane were within 1% difference when the membrane's center deflection ranged from 0 to 100 μm, which corresponded to a numerical aperture change from 0 to 0.2 as well as a 2.6% elongation of the elastomer. © *2004 American Institute of Physics*. [DOI: 10.1063/1.1835553]

Elastomer based devices open many applications in microfluidics[1,2] as well as tunable microoptical components.[3,4] Integration of semiconductor devices such as microfabricated devices, photodetectors, and integrated circuits with elastomer could open applications such as *in vivo* biocompatible sensors, wide field-of-view optical sensors, spherical imagers…etc.; however, there is not yet a report of integration of functional semiconductor devices with elastomer structures. The main challenges are the compatibility between the elastomer processing and the state-of-the-art microfabrication technologies as well as the electrical connection methods on top of the elastomer structures.

It has been shown that metal thin films could be direct deposited onto the elastomer membrane;[5] however, due to the large thermal coefficient differences between the metal and the elastomer, the metal films will wrinkle or buckle after the deposition. Metal-film pattern transfer using stamps was also demonstrated;[6,7] however, none of the above approaches proved reliable electrical connections under elastomer elongation. It was shown that direct-deposited gold thin films on the elastomer could still exhibit electrical conductivity under elongation up to 22%;[8] however, the resistance degraded rapidly as a function of the elastomer deformation and is not reliable for signal transduction.

In this letter, we reported the integration of microfabricated suspensions on top of the elastomer membrane as the electrical connection pathways. A fabrication method has been developed to integrate silicon-based semiconductor layers on top of the elastomer membrane. Consistent resistances of the microfabricated suspensions across the elastomer membrane were measured under different pneumatic pumping pressures to confirm electrical connections through the microfabricated suspensions under membrane deflection.

Single crystal silicon blocks arranged in an octagonal array connected by S-shaped microfabricated suspensions were designed to be placed on top of the membrane. The scanning electron microscope (SEM) picture of the fabricated device was shown in Fig. 1. The array and the microfabricated suspensions were coated by Cr/Au thin films to verify electrical connections across the membrane. The elastomer membrane was spin coated on a silicon wafer. A through hole was etched from the backside of the wafer using the elastomer as the stop layer. A pneumatic pump was connected to the through hole and pressures were applied to deflect the membrane as well as the silicon blocks.

Polydimethalsiloxane (PDMS) is an attractive microfabricated membrane material because of its low Young's modulus, chemical inertness, and bio-compatibility. The relationship between the thin circular membrane center deflection w_0 and the applied uniform pressure P can be approximated by the following equation:[9]

$$w_0 = 0.662a\left(\frac{\text{Pa}}{Eh}\right)^{1/3}, \qquad (1)$$

where a is the membrane radius, E and ν are the Young's modulus and the Poisson's ratio of the membrane material, respectively, and h is the thickness of the membrane. We used E of 0.75 MPa, ν of 0.48 for PDMS dependent parameters.[10] The membrane thickness is 120 μm and the radius is 500 μm. This gives us the center membrane deflection of 270 μm when the applied pressure is 100 KPa.

The S-shaped microfabricated suspensions are designed to provide good electrical connections across the structure under membrane deflection because it exhibits low spring constants in all different directions.[11] In this letter, the material of the S-shaped suspensions is made of silicon dioxide. The thickness of the oxide is 1 μm. The short arms are 10 μm in width and 20 μm in length while the long arm is 10 μm in width and 30 μm in length as shown in Fig. 1. This would give a spring constant of 7.3 Nt/m in direction perpendicular to the membrane and 424 Nt/m along the stretching axis.

The fabrication started with a bare 4 in. double-side polished ⟨100⟩ silicon wafer. PDMS elastomer (Sylgard 184, Dow Corning) was prepared according to the technical notes provided by the vendor.[12] The elastomer was spun on the wafer at a speed of 800 rpm for 2 min. The final membrane thickness was 120 μm as measured by a stylus profiler. The membrane was then cured on a 90 °C hot plate for 15 min and diced into chips with 1 cm × 1 cm in size. Another 4 in. silicon-on-insulator (SOI) wafer with 10 μm single crystal silicon (SCS) layer, 1 μm oxide layer and 525 μm handle layer was also diced into the chips with 1 cm × 1 cm in size. Both the SOI chip and the elastomer-on-silicon chip were

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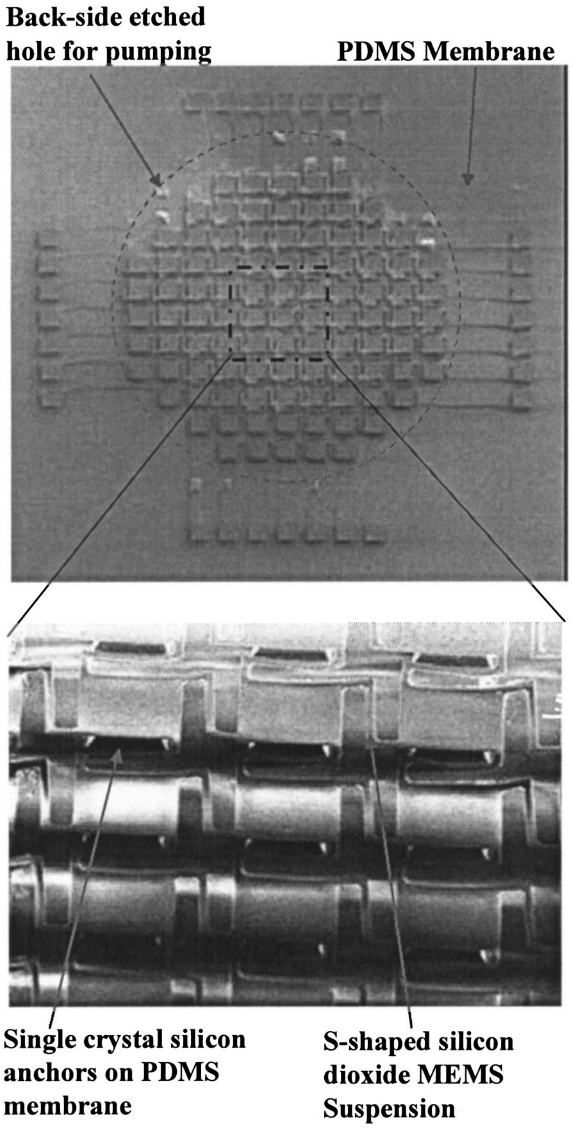

FIG. 1. Scanning electron microscope (SEM) picture of the fabricated device. All the square patterns were anchored on the elastomer membrane through covalent bonds while the S-shaped microfabricated flexures were released. The through hole for pumping the whole array is shown as the dotted line and cannot be seen in SEM because it is buried under the elastomer membrane.

then loaded into a Plasma Therm parallel plate etcher with SCS and elastomer sides up. After treating both chips with oxygen plasma at 2 Torr under 40 W rf power for 40 s, the SCS surface was placed on top of the elastomer by hand without applying any additional force. Due to cross-linking between the hydroxyl dangling bonds on both surfaces,[13] the SOI chip and the elastomer-on-silicon chip were irreversibly bonded.

The composite chip was then encapsulated inside the elastomer by putting the chip into the elastomer bath and curing it on a 90 °C hot plate for 2 h. A 1 cm × 1 cm window was cut using a razor blade to expose the SOI handle layer while all other surfaces remain sealed inside the elastomer. The encapsulated composite chip was then bathed in the 5% tetramethyl ammonium hydroxide at 80 °C for 8 h to release the SOI handle layer and expose the oxide layer. The chip then was retrieved from the encapsulation manually.

The Cr/Au metal layer to define the octagonal array was then e-beam evaporated on top of the oxide layer following standard lithography and lift-off. The chromium was 10 nm thick and the gold was 100 nm in thickness. The chip was then flipped and backside lithography was carefully conducted to align the center pixel of the array to the center of the membrane. Deep reactive ion etching was used to create holes to expose the elastomer membrane. To create the oxide suspensions, buffer HF (10:1) was used to etch away the 1 μm oxide using the metal as the masking layer. The chip was then put into a XeF_2 chamber[14] to selectively dry etch the SCS layer.

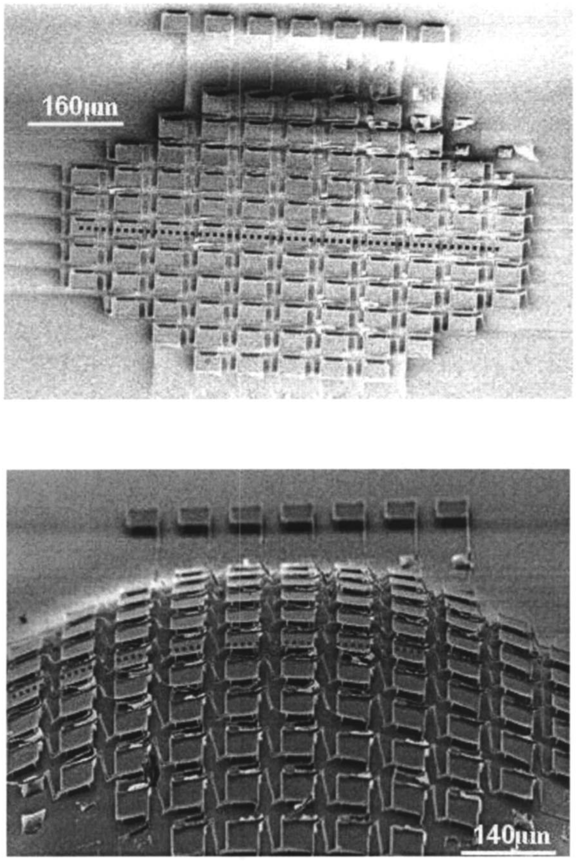

FIG. 2. (a) SEM picture of the fabricated device when there is no pneumatic pressure applied. (b) SEM picture of the fabricated device under 50 KPa applied pressure. To acquire SEM images, ultraviolet (UV) curable polymer was injected to pump the membrane. The device was then cured under a UV lamp for 12 h to fix the shape at this pumping pressure.

Figure 2(a) showed the SEM picture of the device when there was no pressure applied to the membrane. The residues around the octagonal array were due to imperfect fabrication. In Fig. 2(b), under 50 KPa pneumatic pumping pressure, the PDMS membrane was inflated and showed the dome shape as shown by the dotted line. Each pixel of the octagonal array was also deflected because the pixels follow the shape of the membrane deflection through the irreversible bonding between the SCS layer.

Figure 3(a) showed the closer look of the S-shaped suspensions when no pressure was applied to the membrane. Due to stress between the oxide and the SCS layer of the SOI wafer, the microfabricated suspensions were off from their original position and bended upwards. Figure 3(b) showed the SEM picture of the S-shaped suspensions under 50 KPa pump pressure. The S-shaped microfabricated suspensions were stretched due to membrane deflection; however, they remained connected between each pixel.

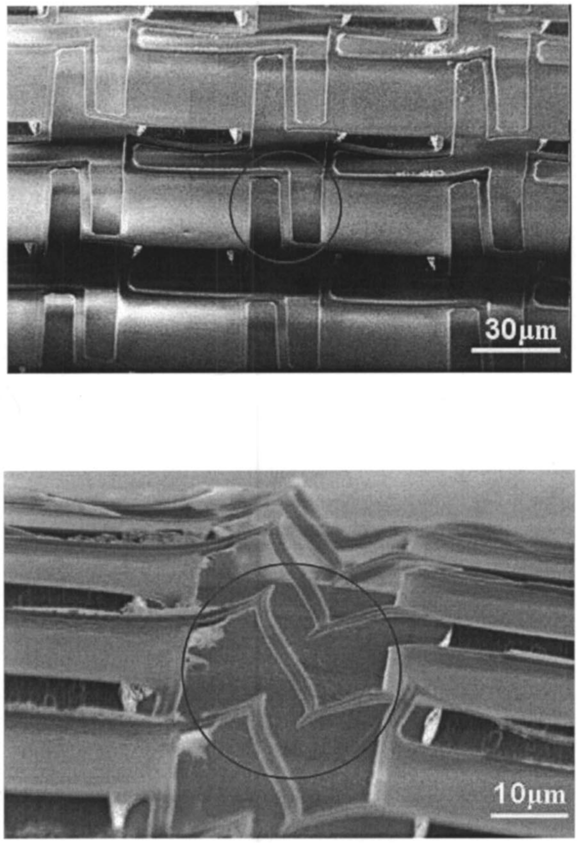

FIG. 3. (a) SEM picture of the S-shaped microfabricated suspensions when no pressure was applied to the membrane. The S-shaped suspensions were bent due to the stress between oxide and the silicon after releasing. (b) SEM picture of the S-shaped microfabricated suspensions when 50 KPa pressure was applied to the membrane. The S-shaped suspensions were stretched but remained connected between each pixel.

To characterize the membrane deflection, white light interferometry (WYKO™) was used to obtain the height difference between the anchor and the center pixel. Figure 4 shows the theoretical and measured membrane deflection versus the pneumatic pumping pressure applied. There existed a deviation between the measured deflection and the theoretical deflection described by Eq. (1). The main reason was the published Young's modulus of the PDMS elastomer varied from 750 KPa to 10 MPa.[5,10] Since we used the lowest Young's modulus for theoretical calculation, we may overestimate the membrane deflection. Figure 4 further shows the measured resistances across the membrane when the pneumatic pumping pressure ranged from 0 KPa to 50 KPa, which corresponded to a membrane deflection from 0 to 100 μm, or a numerical aperture changed from 0 to 0.2, or the PDMS elastomer elongation from 0% to 2.6%. All measured resistances were between 20 and 22 Ω with an average value of 21.1 Ω and a standard deviation of 0.35 Ω. We concluded that consistent and reliable electrical connections were accomplished through the S-shaped microfabricated suspensions.

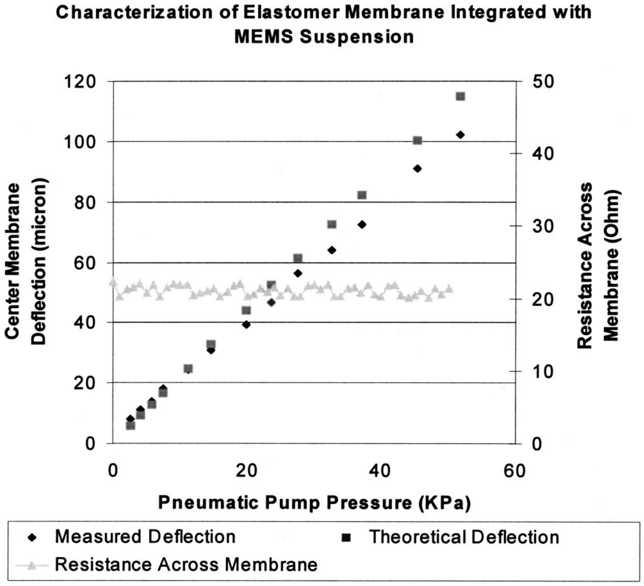

FIG. 4. Measured resistances when pneumatic pump pressures vary from 0 to 50 KPa, which corresponds to the membrane deflection from 0 to 100 μm. The resistances were within 1% difference, proving that consistent and reliable electrical connections were achieved through the S-shaped microfabricated suspensions.

In summary, we have designed and proved electrical connections through microfabricated suspensions on a circular tunable elastomer membrane. At 50 KPa pneumatic pumping pressure, the central membrane deflection was 100 μm, corresponding to a numerical aperture of 0.2, or an elongation of the membrane of 2.6%. The measured resistances were consistent in a range between 20 and 22 Ω when the applied pressures vary from 0 to 50 KPa. The same fabrication processes can be applied to replace mirrors into different functional devices such as photodetectors or field-effect transistor sensors, to open applications such as bio-compatible *in vivo* biosensors, wide field-of-view optical detectors and spherical imagers.

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