MICROACTUATORS BASED ON ION-IMPLANTED DIELECTRIC ELECTROACTIVE POLYMER MEMBRANES (EAP)

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ABSTRACT

We report on the first ion-implanted dielectric electroactive polymer actuator that was successfully microfabricated and tested. Ion implantation is used to make the surface of the polymer locally conducting. Implanting the compliant electrodes solves the problem of how to microfabricate patterned electrodes having elasticity close to that of the insulating elastomer. Dieletric EAP actuators combine in an exceptional way high energy-density, while allowing large amplitude displacements [1,2]. The ion-implant approach avoids the deposition of metal electrodes on the polymer, normally accompanied with an undesired stiffening of the membrane. The actuator consists of a 35-µm thick ion implanted PDMS membrane bonded to a silicon chip containing a hole. We observed 110-µm vertical displacements of a square membrane measuring 1 mm^2.

INTRODUCTION

Microactuators based on stiff materials such as silicon generally have a very limited out of plane displacement~~s~~. Using elastic materials such as elastomers instead allows much larger displacements as shown for macro-sized, dielectric elastomer actuators (DEA) [1,3]. However, the several attempts conducted worldwide to down scale these devices to the mm or µm range have encountered major difficulties, mostly related to the micropatterning of sufficiently compliant electrodes [2,3]. We propose here a novel method to microfabricate compliant electrodes by using implantation of metal ions into polymers to make the elastomer locally conductive without significantly increasing its stiffness. By implantation of specific micrometer-sized areas, one can create and individually address many independent large displacement DEAs on a single chip, allowing for complex actuation schemes.

The working principle of a dielectric EAP is based on the compression of a dielectric elastomer membrane produced by the electrostatic pressure of compliant soft electrodes. The compression of the elastomer results in an elongation of the elastomer without a change in volume (Figure 1).

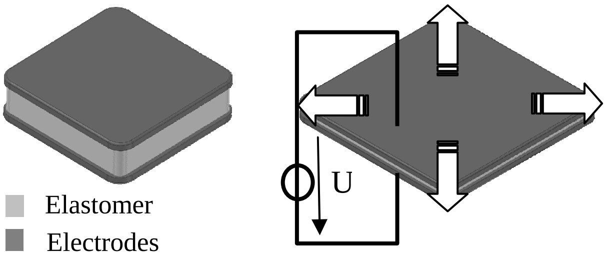

Figure 1: Dielectric EAP principle [1]. When a voltage is applied to the electrodes, the dielectric pressure squeezes the elastomer dielectric (right side). The volume of the dielectric being quasi constant, the whole structure stretches. Maximum strains of over 100 % are reported [1,2].

Depending on the boundary conditions and on the material properties of the membrane, the membrane either elongates in-plane, buckles, or bends (Figure 2) [2]. A DEA consists of a dielectric EAP membrane fixed to a rigid body on well-defined locations [1]. The membrane motions are translated into actuation of stiff structures such as robotic arms, grippers and orientating devices or are directly used to interact with liquid, gases or even the human body [1].

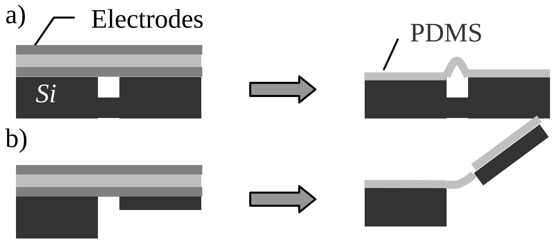

Figure 2: Two different actuation modes of a DEA [2]. a) When electrodes are deposited on both surfaces of the elastomer, the membrane elongates and then eventually buckles when actuated. b) In case of a buried electrode, the membrane deforms continuously when actuated.

Macro size dielectric EAP are based on unstructured compliant electrodes connected by wires [1,2]. To reduce the size of the device and increase functionality and integration, it is extremely useful to pattern the electrodes in order to address many dielectric EAPs on a single membrane [4]. Ion implantation will enable to independently address several individual dielectric EAP actuators on one single membrane.

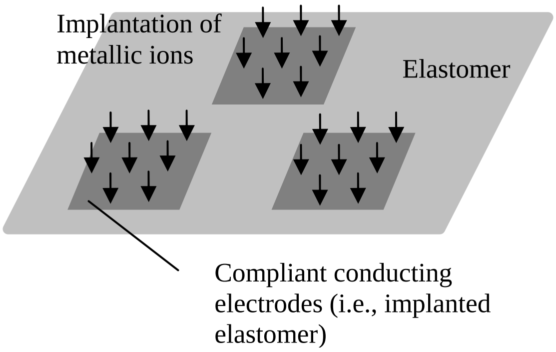

Figure 3: Implantation of metallic ions into elastomeric membranes to create localized compliant electrodes and EAPs.

The field of ion implantation in polymers is still not established. A few publications report on resistivity reduction by ion implantation into polymers [4]. These studies concern rigid polymers such as PET. DEA micro-actuators based on ion implantation have never been reported in the literature.

In order to create micro DEAs, we combined ion implanted membranes with micromachined silicon substrates. The silicon structure supports the membrane on specific locations and defines the boundary conditions.

DESIGN AND BACKGROUND

The actuators reported in this article were designed to create a buckling of the ion implanted DEA membrane when actuated. The EAP membrane is fixed to the silicon and covers an opening to define the boudary conditions, as shown schematically in Figure 2a. A similar macro-scale diaphragm actuator is reported in the literature [2,5].

Vertical displacements of about 10% of the diameter were reported on the macro scale [2]. Micro fabricated DEA membranes showed displacements limited to about 1.5% of the diameter size [3]. This lower value was attributed by the authors to the use of stiff metallic compliant electrodes [3]. We expect implanted compliant electrodes to be more compliant than evaporated metallic electrodes.

Another factor limiting the displacement can be the electrical field strength and a local collapse of the membrane that can occur for contraction above 30%. Usually PDMS field strengths provided by manufacturers are much lower than the one reported for similar materials but tested for membranes thinner than 100 μm (over 100 MV/m [6]).

Because of the symmetry of the device, the direction of displacement (buckling), i.e. upward or downward, is related to the boundary conditions and possible strain gradients in the membrane. One can break the symmetry by having one of the implanted conducting layers buried inside the PDMS. This geometry favours one direction of displacement.

Orifices having more than two axis of symmetry, such as square or circular geometries, favour the first buckling mode while in other geometries higher order buckling modes will occur. The first buckling mode enables the largest vertical displacements. Rectangular and square orifices were designed ranging from 1 to 3 mm^2.

Based on displacement values reported for a similar type of actuator larger in size [7], a square diaphragm of 1 mm^2 is expected to lead to a vertical displacement of about 100 μm.

FABRICATION

For the actuator reported here, the dielectric consists of a PDMS membrane bonded to a silicon chip with through holes ranging from 1 to 3 mm^2. KOH wet etching was used to process the large holes and deep reactive ion etching (DRIE) for the small ones. We fabricated ion-implanted membranes in a chip-scale process for test purposes. Ion implantation was carried out on both sides of the PDMS membranes.

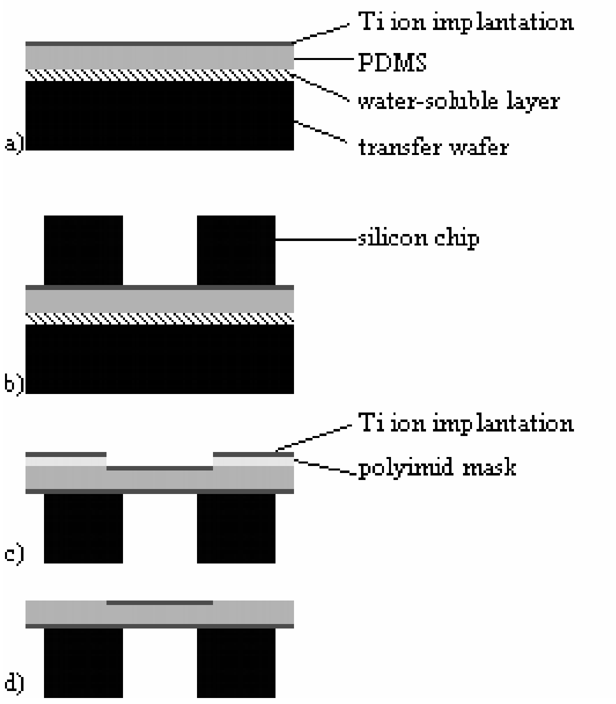

Figure 4: Process flow of the fabrication of ion implanted PDMS diaphragm dielectric EAP actuators.

The 35-μm-thick PDMS membranes were made by spinning soft PDMS (SmoothOn, Dragon Skin) onto a transfer silicon wafer having a thin homogenous acrylic sacrificial layer soluble in water [8] (Figure 4a). The ion implantation was carried out in a filtered cathodic vacuum arc implanter at the CAFI (Le Locle, Switzerland) with an acceleration voltage of about 5 kV. We used such a low energy in order to minimize the damage of the PDMS surface and to implant ions to a depth of about 50-nm. The implantation was simulated with the software SRIM (developed by J.F. Ziegler).

The implanted side was bonded or glued with PDMS on the pre-processed silicon chips (Figure 4b). Bonding with plasma O_2 during 6 to 18 s resulted in inconsistent adhesion in the implanted areas. Therefore, in the more recent chips the plasma bonding process was replaced by gluing using as an adhesive the identical PDMS used for the membrane.

Once the silicon chips were fixed to the PDMS membrane, the PDMS membranes were cut manually around the silicon chips with a cutter and detached from their silicon support by dissolving the acrylic sacrificial layer.

Finally, the top side was ion implanted using a polyimide shadow mask to define the top electrode geometry (Figure 4c). For testing, the polyimide was detached (Figure 4d).

Since the instrument can only implant ions into a surface of about 1 cm^2, we used a chip-scale process. However, wafer scale processing tests are planned with similar approach in the near future.

Two different sizes of chip and orifices were fabricated. First a large chip having a rectangular orifice of 1.5 x 2 mm^2 was fabricated using plasma O^2 for bonding the membrane (Figure 5). Then ion implanted membranes were fixed by gluing on smaller chips having an orifice of 850 x 850 μm^2 (Figure 6).

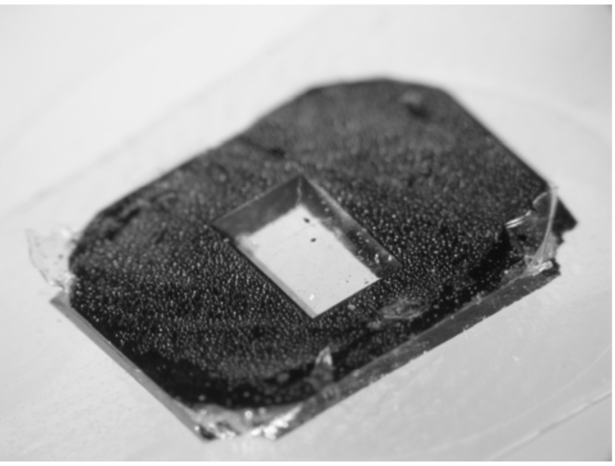

Figure 5: The first microfabricated DEA demonstrator consisting of a 35-µm PDMS membrane bonded on a KOH wet etched rectangular cavity. The Si chip measures 9 x 6.5 mm^2 and has an orifice of 1.5 x 2 mm^2.

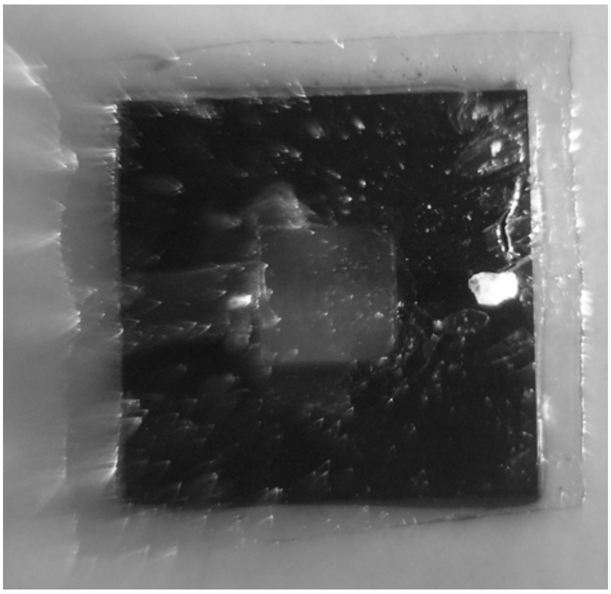

Figure 6: The second microfabricated DEA demonstrator consisting of a 35-µm PDMS membrane bonded on a DRIE etched square cavity. The Si chip measures 2.5 x 2.5 mm^2 and has an orifice of 850 x 850 μm^2.

OBSERVATIONS AND TESTING

Implanting Ti ions into the PDMS significantly lowered its surface resistivity from a starting value of more than 30 MΩ/square to less than 100 kΩ/square. An investigation of the Ti implanted elastomer showed that the surface was modified. Roughness measurement by AFM showed an increase in RMS roughness from 30 nm to 110-nm for the non-irradiated and irradiated elastomer, respectively .

Electrical contacts between the electrical wires and the surface of the PDMS was ensured with plastic conductive cement (Leit-C-Plast, Neubauer Chemikalien). The surface of the PDMS in contact with the silicon was electrically contacted either through the silicon chip for bonded membranes or on the parts of the membrane protruding from the silicon chip. We encountered some difficulties to contact the PDMS with the cement and are investigating other method of contacting.

For testing the first generation of chips having orifices measuring 1.5 x 2 mm^2 (Figure 5), the actuation voltage was increased up to the dielectric breakdown voltage of about 1.5 kV. The membrane motion was recorded on video. The complex buckling mode observed is attributed to the rectangular shape of the cavity. The maximum displacement estimated on the video was above 30-µm.

At about 1 kV, we observed large local contractions of the PDMS membrane. This behavior is similar to the pull-in effect in electrostatic MEMS [7]. This localized thinning of the membrane is likely to induce dielectric breakdown. We did not yet measure the maximum strain of the membrane, however collapses are reported to occur for contractions above 30% for non pre-stretched elastomers [7]. Therefore the estimate of the dielectric field strength of the PDMS used (SmoothOn, DragonSkin) is 60 MV/m.

The first observations made with micro-DEAs having rectangular openings showed that complex modes of buckling having many maxima of displacement located in different areas could occur. To verify that this behavior is only due to the boundary conditions, which are defined by the shape of the opening and the way the membrane is fixed, actuators having square openings (1 mm^2) were fabricated as well and tested.

The membrane displacement of the second type of chips having square openings were measured with a laser profilometer (UBM Messtechnik GMBH, Figure 7). A step actuation of 0 V to the actuation voltage was made at each measurement point. We observed a maximum displacement of 110-µm, which represents 13 % of the width of the square membrane. This percentage displacement is comparable to the best values reported for macro size diaphragm actuators [7]. Electrical breakdown occurred at about 1.3 kV. The experiments were repeated several times and an increase of the deviation was observed at high actuation voltage. This was due to slow response time that made the maximum displacement measurement difficult. We observed response time of more than one second. The electrical time constant was much lower, so the overlap response time can be attributed to a relaxation phenomenon occurring in the dielectric material.

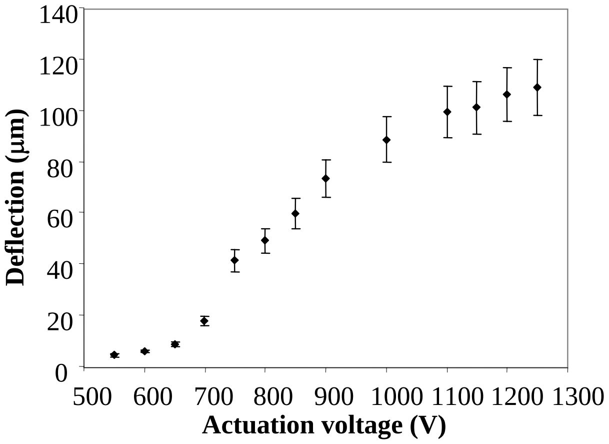

Figure 7: Measured displacements vs. actuation voltages of the center of a square Ti ion implanted diaphragm dielectric PDMS membrane measuring 1 mm^2.

CONCLUSION

To the best knowledge of the authors, this is the first time that micromachined ion-implanted dielectric electroactive polymer membrane (EAP) actuators were fabricated and tested. We measured a ratio of displacement to diaphragm size about 8 times larger than what was reported for a microfabricated dielectric EAP having metal evaporated compliant electrodes [3]. The ratio measured is comparable to the one reported for macro size diaphragm dielectric EAPs [7]. The membrane modes of deformation were observed to be highly linked to the shape of the membrane. A square shape favors the first buckling mode.

Fabrication on the wafer level will enable to individually address a large number of dielectric EAPs on a single membrane.

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