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Arrays of 100 µm x 100 µm dielectric elastomer actuators to strain the single cells

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Abstract

Dielectric Elastomer Actuators (DEA) are compliant devices capable of generating large percentage strains with sub-second response times. Miniaturizing DEAs is challenging principally because of the need for µm-scale compliant electrodes. Employing low-energy gold-ion implantation into a 30 µm thick membrane of Polydimethylsiloxane (PDMS), we have patterned 100 µm wide compliant electrodes and fabricated arrays of 100 µm x 100 µm DEAs reaching up to 80% in-plane strain at 4 kV. The actuators are designed to be used to stretch single biological cells attached on top of them in order to study mechanotransduction at the individual cell level. In order to have a continuous ground electrode on which the cells will be cultured, a passive 20 µm thick PDMS layer is bonded on top of the actuator array. In this configuration, 37 % strain on the actuators is observed at 3.6 kV. We show that the actuation strain is tunable from uniaxial to biaxial by anisotropically prestretching the elastomer membrane.

*Keywords:*Dielectric elastomer actuator; Microactuator; Single cell stretcher; Tissue engineering.

1. Introduction

Dielectric elastomer actuators (DEAs) consist of a soft thin elastomer sandwiched between two compliant electrodes. Subjected to a high voltage between the electrodes, the Maxell stress squeezes the elastomer, which being incompressible, expands in the in-plane directions. Miniaturization of DEAs is challenging principally due to the difficulties in patterning carbon-based compliant electrodes. Aschwanden et al. have used a stamping technique to pattern 100 µm wide carbon powder electrodes on PDMS [1]. Lotz et al. have sprayed graphite powder over a shadow mask in order to fabricate mm size stacked actuators [2]. Pimpin et al. have shown buckling mode micro-actuators using patterned metal electrodes on elastomers [3], but these electrodes still have an important impact on the stiffness of the polymer membrane. In earlier work, our group has demonstrated the effective miniaturization of DEAs using electrodes made by low-energy (5 keV) gold ion implantation through a steel shadow mask into PDMS [4-6].

In this work, we have further miniaturized the electrodes to fabricate an array of 100 µm x 100 µm actuators. The actuators will be used by our collaborators to stretch single cells attached on top of them in order to study the effect of mechanical stimulation on the single cell behavior. Uni-axially pre-stretching the elastomer membrane up to 175 %, we were able to achieve 80% in-plane strain at 4 kV. This strain is reduced to 37% at 3.6 kV after a 20 µm thick passive PDMS layer coated on top to have a continuous ground electrode where the cells will be cultured shielded from electric fields.

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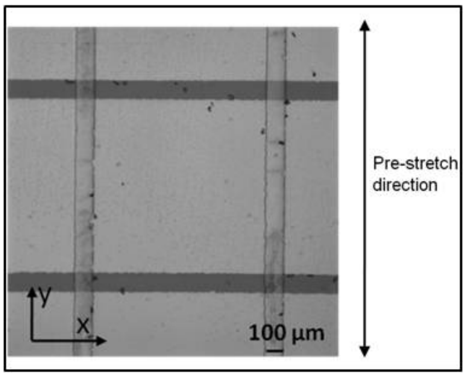
2. An array of 100 µm x 100 µm dielectric elastomer actuators

2.1. Fabrication

The first step in fabricating an array of dielectric elastomer actuators is to prepare a thin PDMS membrane. The two components of Sylgard 186 from Dow Corning Co. is mixed with a 10:1 mixing ratio and diluted with isooctane (PDMS : Solvent 10 : 9 weight) to reduce its viscosity. The mixture is degassed for 30 minutes and casted using a universal applicator over a polyimide support film. The film is cured at 100ºC for 40 minutes and pre-stretched uniaxially with different percentages ranging (λ_p) from 0 to 175 % and fixed on a frame. As the elastomer is incompressible, its thickness reduces with the factor of $1+\lambda_p$.

Finally two perpendicular arrays of 100 µm wide compliant electrodes are patterned by implanting the gold ions into the PDMS membrane using a filtered cathodic vacuum arc source. A 70 µm thick shadow mask is used to minimize the effect of mask's aspect ratio on the ions concentration.

A top view of a portion of the array showing four actuators is shown in Fig 1a. The bright lines are the ion implanted electrodes on top layer of the PDMS membrane, while the darker lines represent the electrodes on the bottom. The actuators are at the intersection of the electrodes, where the high electric field exists as shown in the schematic cross section view of the device in Fig 1b.



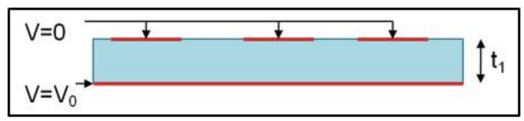


Fig. 1. a) Top view of a portion of the device showing four actuators. The bright horizontal lines are the 100 µm wide ion implanted electrodes on the top side of the PDMS membrane and the dark vertical lines are the bottom electrodes. The actuators, where the electrostatic pressure is applied, are at the intersection of the electrodes.

b) Cross section of the arrays of actuators. Two perpendicular arrays of 100 µm wide electrodes are patterned on both sides of a pre-stretched membrane.

2.1. Characterization

Different sets of actuators are fabricated on uni-axially pre-stretched membranes as the pre-stretch ratio ranges from 0 to 175%. Pre-stretch is applied in the y-direction. When a high voltage is applied to the electrodes, the electrostatic pressure on the actuators squeezes the membrane leading to in-plane expansion. The images captured before and after actuation are analyzed with the ImageJ software to compute the in-plane strains. Fig 2, shows the x-axis strain perpendicular to the pre-stretched direction versus the applied nominal electric field. The electric field is computed by dividing the applied voltage to the thickness of the membrane at the pre-stretched state. The maximum applied voltage was 4 kV.

The maximum actuation strain of the dielectric elastomer actuators is increased from 8% for a non-stretched membrane up to 80% for a 175% pre-stretched membrane. The main reason is that the sustainable electric field is increased retarding the onset of the electromechanical instability [7]. At higher electric field and thus higher strain, the elastomer, being hyperelastic, softens resulting in a higher slop in the strain-electric field curve after 10% strain. The stress strain curve of our PDMS membrane (100 µm thick) obtained by pull-test is plotted in Fig. 3 and confirms that the elastomer softens at around 10% strain and gets stiffer at higher stretch ratios. This is the principle to tune the ratio of the in-plane actuation strains; the membrane is anisotropically pre-stretched to have different stiffness and thus different actuation strains in the two in-plane axes [8].

Fig. 4 and Fig. 5, show that the in-plane strains are identical for a non-stretched membrane while the in-plane strain along the pre-stretched direction is much less for a 175% uni-axially pre-stretched membrane.

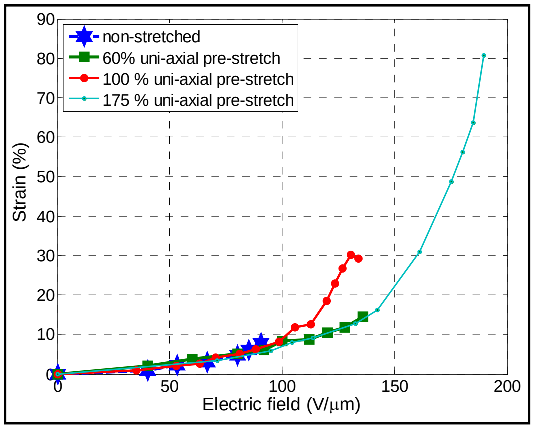


Fig. 2. The x-axis strain of the actuator versus the applied electric field. The x-axis strain is increased up to 80% by pre-stretching the membrane in the y axis.

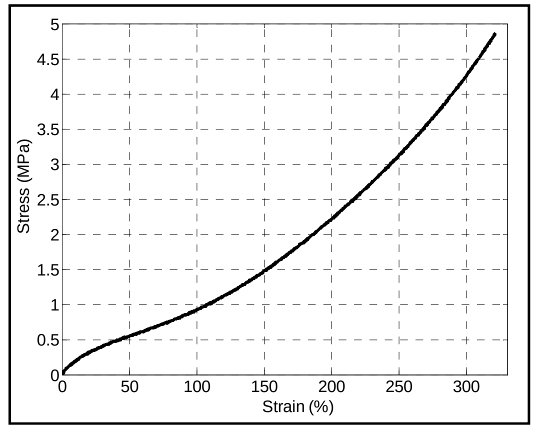


Fig. 3. Stress-strain behaviour of a PDMS membrane (100 µm thick) measured by Instron 3343. The slope of the curve represents the elastomer's stiffness, which is a function of the stretch ratio.

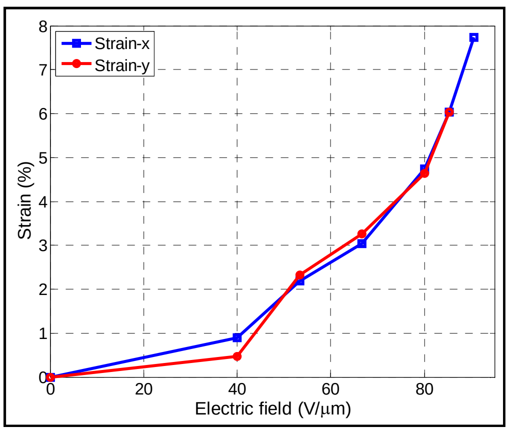


Fig. 4. Y-axis and x-axis strain of the actuator versus the applied electric field on a non-stretched membrane. The biaxial strain achieved is due to the isotropic stiffness of the membrane.

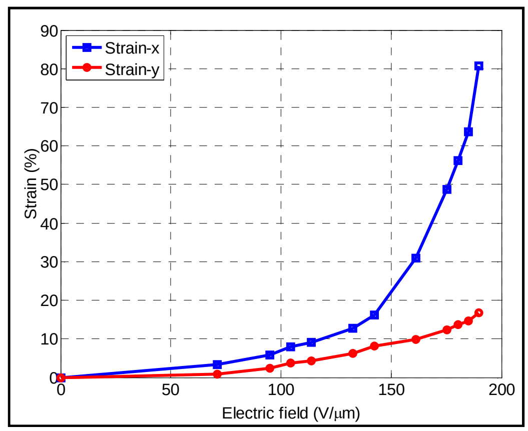


Fig. 5. Y-axis and x-axis strain of the actuator on a 175 % pre-stretched membrane along the y axis versus the applied electric field. The ratio of the strains is increased up to 4.8 due to the anisotropic stiffness of the pre-stretched membrane.

3. An array of 100 µm x 100 µm actuators with a passive layer

The array of micro-actuators are developed to stretch individual biological cells attached on top of them in order to study the effect of mechanical stimulation on the cell behaviour such as differentiation, proliferation and calcium signalling. Since the cells will be immersed in a cell culture medium, which is a conductive liquid, the whole top layer will be grounded and it is not possible to have patterned 100 µm wide electrodes on top, as the liquid would act as one large continuous electrode. To overcome this, another thin passive PDMS layer is coated on the actuator array and grounded. The same PDMS mixture is diluted with 200 % weight ratio isooctane and sprayed on the top layer while the contact pads are protected. This layer is cured at 60ºC for 5 hours. This low curing temperature is required to avoid rupturing the highly pre-stretched membrane. For this experiment, we deposited a blanket electrode on top by ion implantation.

Fig. 6 shows a simplified cross section of the device, which includes three different sections of the electric field. There is a high electric field on the pre-stretched 100 µm^2 area (E_1), a lower electric field along the 100 µm wide high voltage electrode (E_2) and a zero electric field over the actuator. Thickness of the passive layer (t_2) should be high enough to reduce the E_2 to the sustainable region for the non-stretched coated PDMS layer, while the pre-stretched membrane is operating at the higher electric fields.

The in-plane strain perpendicular to the pre-stretching direction for an actuator on a 160% uni-axially pre-stretched membrane is measured versus the electric field and is plotted in Fig. 7. The actuation strain increases up to 37% at the electric field of 170 V/µm, corresponding to a voltage of 3.6 kV.

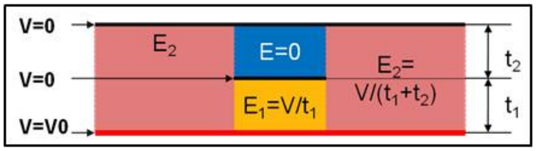


Fig. 6. Schematic cross section of the actuators with addditonal passive layer on top (thickness t_2), showing different electric field in different cross-secttions.

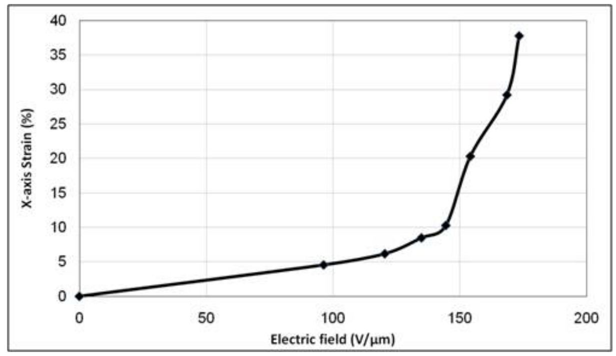


Fig. 7. x-axis strain versus the applied electric field for a 100 µm wide actuator with a passive layer on top. The membrane was pre-stretched 160 % in the y direction.

4. Conclusions

In this paper, we have presented an array of 100 µm x 100 µm dielectric elastomer actuators capable of generating up to 80 % uni-axial strain at 4 kV. Two perpendicular arrays of 100 µm wide compliant electrodes are patterned by low-energy ion implantation on both surfaces of a thin pre-stretched PDMS membrane. Uni-axial actuation is achieved by uni-axial pre-stretching the elastomer in the perpendicular axis. The actuators are fabricated to stretch individual cells attached on top of them to study mechanotransduction in the single cell level. To have a continuous ground electrode where the cell will be cultured, a 20 µm thick passive PDMS layer is spray coated on top. In this case, the actuation strain is up to 37% at 3.6 kV.

Acknowledgements

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