EuroEAP 2013
International conference on Electromechanically Active Polymer (EAP) transducers & artificial muscles
Zurich, 25-26 June 2013

Organized and supported by 'European Scientific Network for Artificial Muscles – ESNAM' (www.esnam.eu)
COST Action MP1003

Poster ID:
1.3.4

Chip-scale array of artificial muscles for investigation of cell mechanotransduction properties

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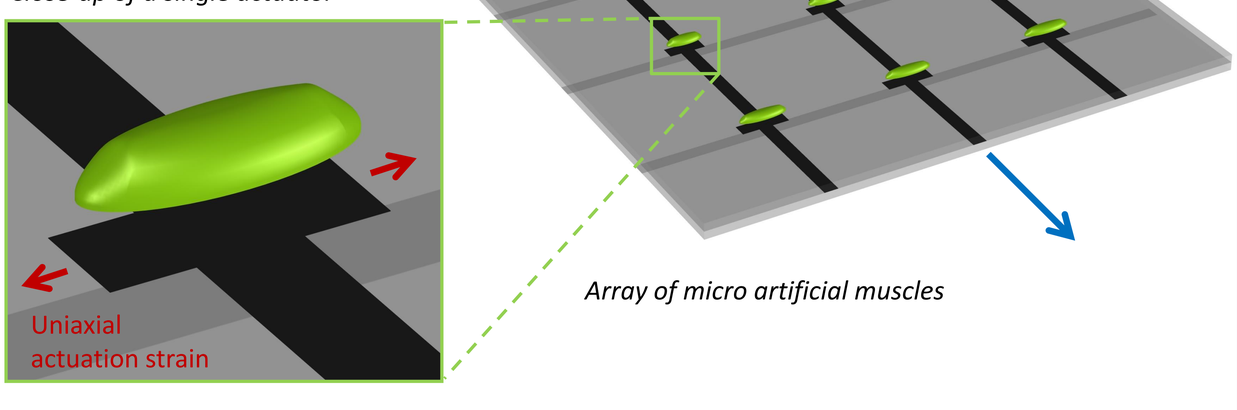
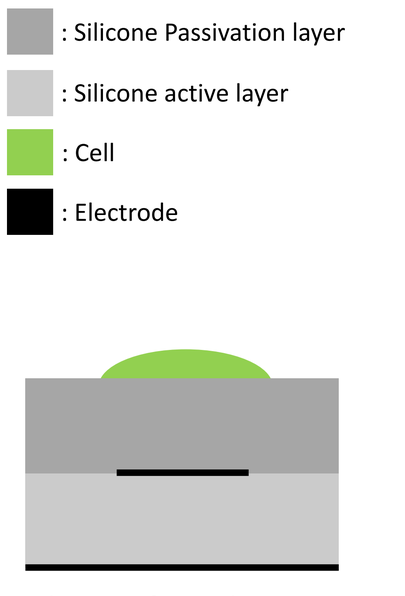
Abstract
We present an array of dielectric elastomer actuators for investigation of cell response to periodic mechanical strain (cell mechanotransduction). Several technologies can be used for this type of study [1-3]. We previously reported on a first generation of 100µm x 100µm dielectric elastomer actuators that enable high-throughput studies on very small cell cultures. That first generation had a limited lifetime when operating in liquid and showed strain non-uniformity across the actuator array. A new generation of devices was fabricated and the packaging was optimized to facilitate its use with biological instrumentation. The current system consists of 9 actuators, each 500µm x 500µm on a single PDMS membrane, in a compact package that is compatible with standard cell incubators. The device was successfully operated for over 100'000 cycles and shows excellent uniformity across the array.

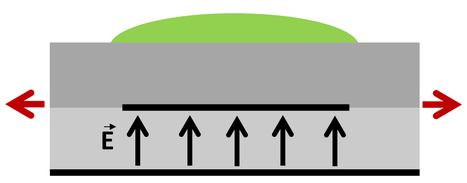
Design and working principle

We demonstrate an array of uniaxial actuators which can be used to apply mechanical stress on small population or single cells while maintaining a high throughput.





Side view of a single actuator at rest



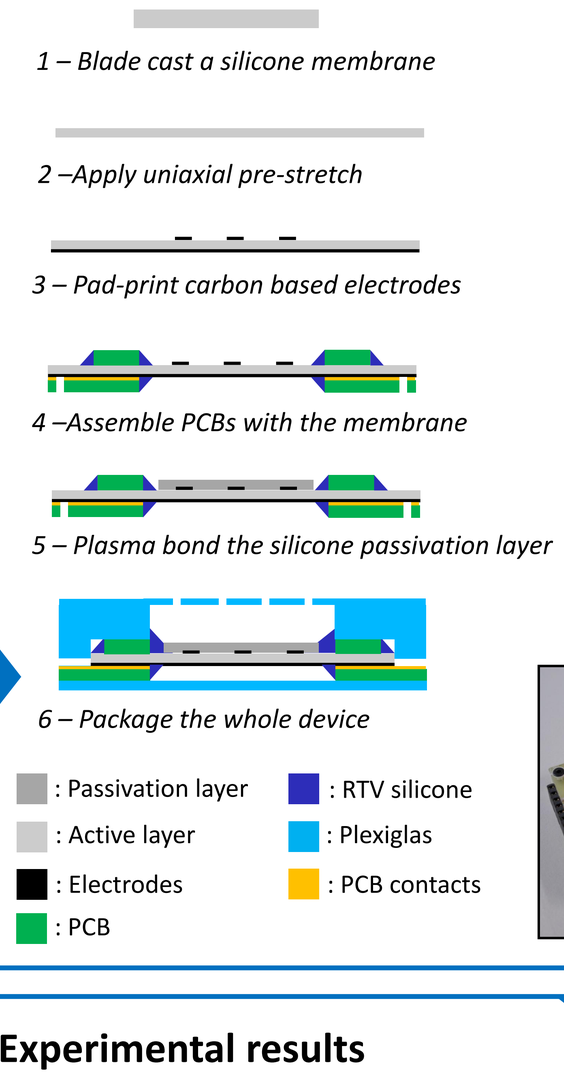
Side view of a single actuator when actuated

Design
- 500 µm wide compliant electrodes are patterned on both sides of a 30 µm thick silicone (Sylgard DC 186) membrane with a uniaxial pre-stretch.
- An array of chip-scale actuators is thereby created by the electrodes overlaps.
- A 30 µm thick passivation silicone (Sylgard DC 186) membrane covers the active membrane and top electrodes to ensure a biocompatible environment for the cells.

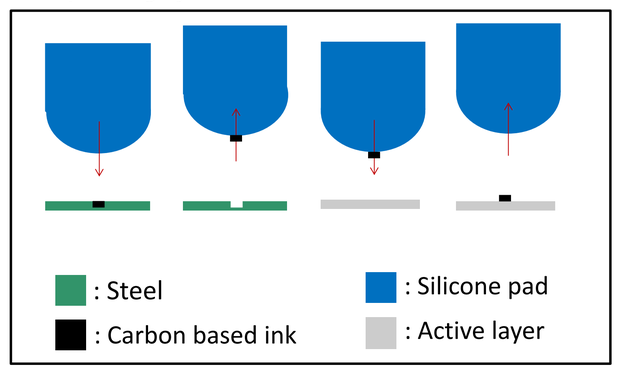
Design highlights
- This simple design allows to achieve high density of actuators. The maximum density depends on the size of actuators active area.
- Silicone membranes, unlike the commonly used 3M™ VHB™ tape, exhibit low viscoelasticity which allow to work at relevant biological frequencies (up to a few Hz).
- The design allows to apply a gradient of stress across the array of actuators. Different and complementary measurements can therefore be realized in parallel.

Working principle
- A high voltage difference (3 kV) is applied between the top and bottom electrodes. (Top electrodes are set to ground in order to minimize the electric field in the cells surroundings.)
- The applied electric field generates electrostatic forces which induce Maxwell stresses inside the silicone membranes. In reaction, the incompressible polymer deforms in the plane perpendicular to the electric field.
- Uniaxial pre-stretch of the active membrane allows to achieve quasi-uniaxial strain actuation in the orthogonal direction.

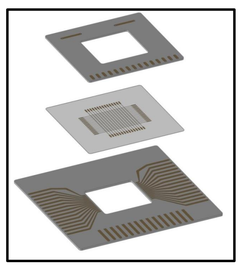
Fabrication process & packaging

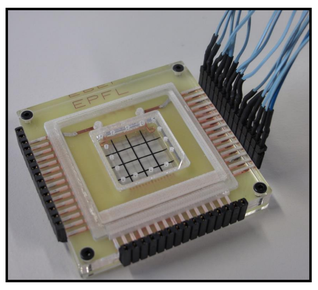


Pad-printing of the electrodes



Connecting the device
- The membrane is squeezed between two PCBs.
- Actuators electrodes are in direct contact with PCBs conductive tracks.



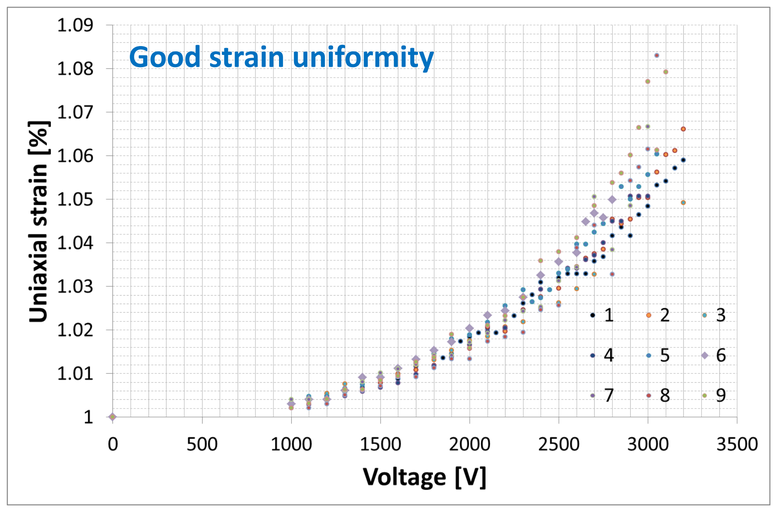


Device packaging
- Compact and robust
- Safe handling (protected circuitry)
- Biocompatible, watertight and grounded reservoir for cell culture.

Experimental results

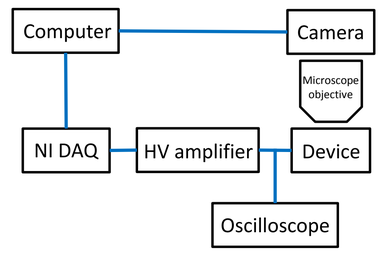
For the device to be a useful tool in biological studies, it is important to have a good control over the induced strain. Spatial and temporal strain uniformity studies were therefore conducted on our device.

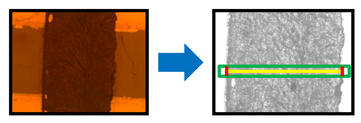
Strain uniformity across an array of 9 actuators



How to measure strain
- Capture images of the actuator under increasing voltages.
- Process images to isolate the top electrode.
- Delimit the electrode borders and measure its width.

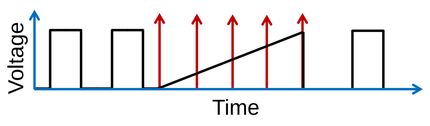
Experimental setup





Strain uniformity of one actuator over time

Shape of the signal used to measure strain uniformity over time



- Square waveform at 1 Hz.
- Every 5000 cycles : linear voltage ramp with capture triggers every 20 V.

Conclusion and outlook

We have successfully fabricated and characterized an array of 9 uniaxial actuator. Experimental results show good strain uniformity across the entire array. The device is still working after more than 100 000 cycles at an actuation frequency of 1 Hz and 3 % strain.

On the short term, future work will focus on characterizing strain uniformity of devices with higher maximum strain. Based on previous work[4], it should be possible to achieve 80% strain. The effect of a cell culture medium (ionic liquid) on top of the passivation layer will also be studied. Different thicknesses, surface treatments and materials will be tested in order to find the best passivation layer.

On the long term, our device will be used to measure strain response of specific cells such as fibroblast and myoblast which are known to exhibit strain dependant behaviour.

References

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Acknowledgments

Participation to this conference was partially supported by COST (European Cooperation in Science and Technology) in the framework of ESNAM (European Scientific Network for Artificial Muscles) - COST Action MP1003.
We acknowledge financial support from the Swiss National Science Foundation grant #200020-140394 and equipment obtained thanks to Swiss National Science Foundation grant #206021-139187.