Artificial muscles with silicone-gold nanocomposite electrodes

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Implanting metal ions into elastomers creates highly stretchable electrodes for tunable optics, beam steering, and cellular manipulation.

The term ‘artificial muscles’ was coined to describe a range of electroactive polymer (EAP) actuators with muscle-like properties such as high flexibility, strain (over 100%), and energy density. One type of EAP, the dielectric elastomer actuator, consists of a soft elastomer sandwiched between two compliant electrodes generally made of carbon powder (see Figure 1). When a voltage is applied between the electrodes, an electrostatic force is generated that compresses the elastomer thickness, expanding it in-plane. Depending on the boundary conditions, many different actuators and sensors can be made—from large active fins for blimps and haptic systems, to centimeter-scale walking, grasping, and swimming robots.

As compliant electrodes must conduct well at strains over 30%, be softer than the elastomers, and patterned on the micron scale, miniaturizing EAP devices is a challenge. Some groups have succeeded in patterning carbon powder, but this method is not generally cleanroom-compatible. The seemingly obvious solution of thin metal traces is not acceptable as such metal lines break at only 3% strain and are much too stiff. Our approach, to batch-fabricate arrays of miniaturized polymer actuators, is based on highly stretchable electrodes made by low-energy ion-implantation into the elastomer.

We formed 20–50nm thick nanocomposites where gold ions were embedded in a silicone matrix (see Figure 2). The gold conducts by ohmic contact between particles, which are able to slide within the polymer matrix to allow conduction at up to 175% strain without stiffening the actuator. We achieved micron-scale control of the electrode dimensions using implantation through a shadow mask. This also allowed the nanoparticles to adhere to any surface, permitting 3D patterning of the electrodes for microfluidics.

We used these compliant electrodes to make EAP actuators. Depending on electrode shape and membrane size, several actuation modes are possible. For example, the basic device is a silicone membrane (20μm thick) with micro- to millimeter-scale ion-implanted electrodes on both sides, and it is bonded to a glass substrate with through-holes (see Figure 3). The electrically-induced deflection of the ‘buckling-mode’ actuator (3mm in diameter)—see Figure 4—demonstrated out-of-plane

Figure 1. The basic principle of dielectric elastomer actuators. When high voltage is applied between the flexible electrodes, the electrostatic pressure compresses the elastomer. Removing the voltage returns the device to its initial configuration.
Figure 2. Cross-sectional transmission electron microscopy image of the nanocomposite formed by gold ion implantation into a polydimethylsiloxane (PDMS) elastomer. The gold nanoparticles form a conducting network even when the elastomer is stretched to twice its original length.

Figure 3. Schematic cross-section of a buckling-mode dielectric elastomer actuator. The implanted electrodes are on the top and bottom of the elastomer.

Figure 4. Buckling mode actuators at 0 and 1600V. This is the same device shown in Figure 3. The implanted electrodes are not visible as they are nearly transparent. Device diameter is 3mm.

Figure 5. Chip containing an array of 72 100×200μm² polymer actuators, each of which can apply uniaxial strain to the single muscle attached to it.

Displacement greater than 25% of the device diameter. This is well above what is possible with conventional microelectromechanical systems. High efficiency was possible at this small scale because the compliant electrodes did not significantly stiffen the membrane. Additionally, response time was below 1ms. We have used such devices as building blocks to make arrays of tunable acoustic filters, two-axis beam steering mirrors, micropumps, and, because the electrodes are 50% transparent, tunable lenses (1mm in diameter).

We also used the ion-implantation technique to study the effects of mechanical strain on living cells. We fabricated hundreds of independent actuators on a single chip, each being the size of a single cell and designed to operate in an incubator with cell growth medium (see Figure 5). Individual live muscles cells were attached to each artificial muscle actuator, which applied periodic mechanical strain, thus replicating the environment of repeated stretching of a beating heart. This provided a novel tool to study the effects of mechanical strain on cellular proliferation and differentiation.

By using ion implantation to make stretchable electrodes on elastomers, we demonstrated that it is possible to form arrays of micro- to millimeter-sized artificial muscle actuators. The electrodes themselves show great potential for use in flexible electronics and rollable displays. We are currently optimizing the
arrays of cell stretchers to increase strain and array size as well as developing integrated strain sensors. We are also working on chip-scale integrated microfluidic devices that combine dozens of active polymer pumps and valves.

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References