DEVELOPMENT OF A SCALABLE SOFT FINGER GRIPPER FOR SOFT ROBOTS

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ABSTRACT

Soft robotics is vastly drawing attention, especially concerning their unique characteristics. Soft robots could be used to enhance motion as a soft exoskeleton, as soft prosthetics, or function as grippers for lifting objects. A challenge to the fabrication and actuation of conventional Dielectric Elastomer Actuators (DEAs) is that they require a pre-stretch over an external rigid frame. Moreover, the external rigid frame can hardly bend, causing the actuation to be limited to planar. In this research, we characterized a silicone-based elastomer electrically and mechanically as a substitute for conventional elastomers. Then, we developed a fabrication process and implemented a backbone structure to achieve soft and scalable finger grippers capable of lifting and holding arbitrary objects without needing an external frame.

KEYWORDS

Dielectric Elastomer Actuators, Soft Robotics, Soft Grippers, Artificial Muscles, Electroactive Polymers

INTRODUCTION

Soft grippers have the potential to mimic muscles to create artificial hands or to replace rigid body robots [1, 2]. Dielectric elastomer actuators, known as artificial muscles, are a subset of electroactive polymer actuators driven by electrostatic force. In their simplest form, they are made of a thin layer of soft and non-conductive elastomer sandwiched between two compliant layers of electrodes. When the electrodes are connected to a high voltage, and the electric field is applied through the dielectric elastomer, the attraction force between opposite charges results in compression stress, known as the Maxwell stress. As a result of the Maxwell stress, the elastomer contracts in thickness and expands in the area. Concerning the expansion of the area with respect to the changes in the thickness, one can assume a constant volume to a good approximation [3].

$$p = \varepsilon_r \cdot \varepsilon_0 \cdot E^2 \qquad (1)$$

$$S_z = -\frac{p}{Y} = -\left(\frac{\varepsilon_r \cdot \varepsilon_0}{Y}\right)\left(\frac{U}{z}\right)^2 \qquad (2)$$

Here, p is the Maxwell stress, ε_r is the relative permittivity of the elastomer, ε_0 is the vacuum permittivity, z is the thickness of the elastomer, E is the electric field, S_z is the thickness strain, and Y is Young's modulus of the elastomer. Eq. (1) and (2) reflect the mechanical and electrical properties of the elastomer, which mainly affect the performance of the actuator. The equations indicate that, on the one hand, the elastomer must have a relatively low Young's modulus, high relative permittivity, and high electrical breakdown (E_{BD}). On the other hand, the electrodes are only meant to deliver charges; thus, any contribution to the total mechanical resistance is considered a disadvantage. The electrodes must have no thickness and zero mechanical resistance in an ideal case.

On top of the material properties, the design of an effective actuation mechanism is of great importance. DEAs, in their simplest form, perform a planar actuation; therefore, a mechanism is required to translate it to more complex actions like bending or twisting. One example at the application level is a gripping actuator. There are many valuable efforts to design and fabricate a soft gripper. Wang et al. [4] have recently presented a DEA gripping tool with two fingers. They optimized a mechanism to translate the planar actuation into the gripping force. They used the conventional VHB^{TM} 4910 tape from *3M^{TM}, Ltd.* for the elastomer and used carbon grease to apply conductive layers. The gripper ultimately managed to apply 100.2 mN gripping force.

In this research, we present an alternative method and a set of materials to overcome some limitations of the performance of a soft gripper. Although showing outstanding actuation qualities, the acrylic VHB^{TM} 4910 tape is highly dependent on a rigid external frame, and its thickness is only defined by the amount of pre-stretch over the frame. This approach limits the application field. A general strategy to gain higher actuation force and motion is to stack the elastomers and electrodes to make multi-stacked or multi-layered actuators. The carbon grease is relatively thick and does not cure well; therefore, it is not the best option for the strategy of multi-stacking. We revised the choice of materials to overcome these barriers, which resulted in a multi-layered, ultra-thin, and compliant actuator. Then, we revised the fabrication process and introduced the backbone structure to produce bending actuators utterly independent from any external frames.

MATERIAL CHARACTERIZATION

VHB^{TM} 4910 is an acrylic adhesive commercially available as double-sided tape. It is available only in viscoelastic form, so one should adjust the thickness by stretching the tape and fixing it to an external rigid frame. The stretched area should not contact other parts; otherwise, it sticks. Then, the carbon grease must be applied to the exposed surfaces, and the following elastomer layers should get stretched in the same way and placed onto the last layer. The method of stretching can cause inaccuracy in achieving the desired thickness, making it difficult to stack the layers accurately. In addition, the tape can mainly function in a straight planar form, and any curvature needs another rigid external support. Thus, one cannot have the tape in a stably curved form.

Considering all the mentioned limitations, we took another approach in this research and implemented a silicone-based elastomer. We mixed the ECOFLEX^{TM} 00-10 with 10% SILICONE THINNER^{TM} from *Smooth-On, Inc.*, and we characterized the elastomer electrically and mechanically. We refer to the compound as Ecoflex10T.

Table 1: Properties of the elastomers

Material	**ε_r**	**E_{BD} ($V\mu m^{-1}$)**	**Y (kPa)**
Ecoflex10T	4.4 @ 20 Hz	22	58
Ecoflex^{TM}10	3.5 @ 20 Hz	38	57
VHB^{TM} 4910 [5]	3.2 @ 1 kHz	25	n.a.

As indicated in Table 1, the properties of Ecoflex10T are comparable to VHB^{TM}. We also learn from characterization results that adding the thinner to the silicone improves the dielectric constant though decreasing the electrical breakdown strength. Since

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the ultimate goal of this project is to develop DEAs driven by the lowest possible voltage, we avoid working with very high voltages close to the breakdown voltages. Therefore, the addition of the thinner is favorable. Moreover, uncured Ecoflex10T is liquid; hence, it is suitable for fabrication methods such as molding and spin-coating.

The results of the elastic behavior of cured Ecoflex10T are shown in Figure 1. Accordingly, Young's modulus for very high strains is 58 kPa, while this value for lower strains less than 300% is 14 kPa. For this measurement, Ecoflex10T was molded into standard dog-bone test specimens according to ISO 37:2017-11 [6].

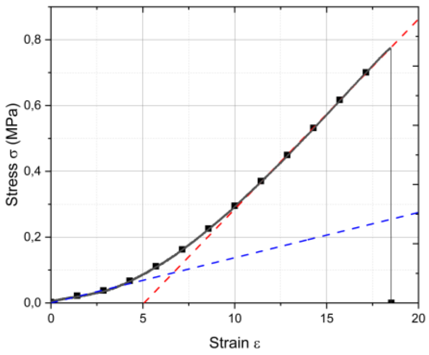

Figure 1: Stress-strain curve of the specimen made of Ecoflex10T, and the linear fits for strains less than 2 and higher than 10.

FABRICATION METHOD

Elastomer

In this research, the spin-coating method was chosen to deposit the elastomer layers one after the other. In this method, the Ecoflex10T was cured in the oven at 85°C right after deposition onto a handling wafer. The amount of the deposited material and the spin-coating parameters would determine the thickness of the cured layer. The elastomer thickness is critical as the Maxwell stress correlates proportionally to the inversed squared of the thickness. In addition, the thickness of the thinnest elastomer determines the maximum allowed voltage to prevent an early-stage breakdown.

Lee, Kim et al. [7] have derived a formula for the spin-coating parameters which control the film thickness. We developed a recipe for every desired film thickness based on this formula. For instance, the rotation speed of 250 rpm for 23 s would result in a thickness of 545 ± 30 µm for 6 grams of Ecoflex10T (with the density of 987 kg.m^{-3} and the viscosity of 6.7 Pa.s). With this repeatable and reproducible method, we obtained layers as thin as 42 µm (Figure 2).

$$h = \frac{h_0}{\sqrt{1+\frac{4\rho\omega^2 h_0^2 t}{3\eta}}} \tag{3}$$

Here, h_0 describes the initial thickness of the coating material. ρ is the density, η is the viscosity of the liquid, and t represents the duration of spinning [7].

Electrode

As a substitution for the carbon grease, we chose the method of dry-brushing the carbon black powder directly onto the elastomer layer with a soft brush. This method was suggested by H. Shigemune et al. [8]. The deposition of the patterned electrode layer was through a polymethyl methacrylate (PMMA) mask. The pattern was first lasered out using a CO_2 laser (*VersaLaser^{TM}, Universal Laser Systems, Inc.*) from the 4-inch PMMA wafer with a 0.5 mm thickness (Figure 3). Then, the mask was placed directly onto the cured layer of elastomer, and with a soft paintbrush, the carbon black powder (*P250, Ensaco*®) was applied to the exposed parts of the Ecoflex10T through the mask. Finally, the remaining carbon black powder was blown away, and the next layer of Ecoflex10T was applied directly onto the electrode layer. It is noteworthy that polymerization of Ecoflex10T is relatively quick (30-minute pot life), so for every elastomer layer, a fresh uncured Ecoflex10T should be prepared.

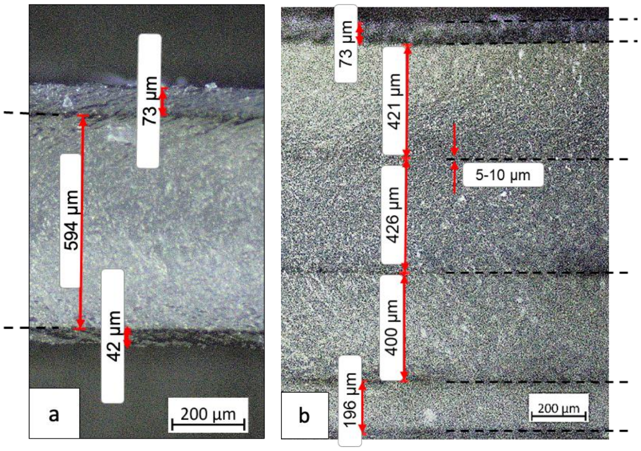

Figure 2: Cross-section view of the actuators under the microscope. The dashed lines indicate the position of the electrode layer with a thickness of less than 10 µm (a) a single layer actuator (b) an actuator with three active layers.

The carbon black powder showed excellent adhesion to the Ecoflex10T, resulting in a uniform and evenly distributed electrode layer. The electrode layer remains conductive even when the actuator is deformed. The final actuator was cut into thin slices for the thickness measurement and observed under the measurement microscope (*Scope.A1, ZEISS*). As indicated in Figure 2, the electrode layer thickness is between 5 µm to 10 µm. The first and the last layer of the actuator are covered with very thin passivation elastomer layers to protect the actuator and the surrounding objects from any unwanted contact. When the layer deposition is over, the actuator is cut out and connected to the contact pins (Figure 3). The thickness and the weight of the actuator are dependent on the number and the thickness of the layers. For comparison, the single layer actuator was 1.46 mm thick and had 1.51 g mass, while a 5-layered actuator was 3.84 mm thick and had 4.57 g mass (Figure 4).

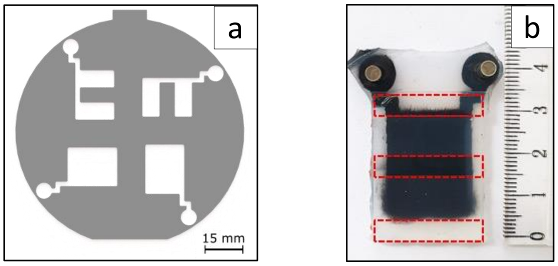

Figure 3: (a) A PMMA mask used for patterning the carbon black powder with a soft brush onto the elastomer (b) The final bending actuator (4 cm × 3 cm) with the full-rectangle design cut out from the wafer. The red dashed lines indicate the position of the transparent PMMA backbone structure.

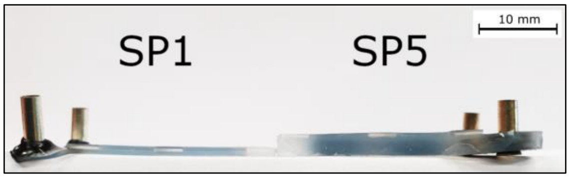

Figure 4: Side view of a single layer (SP1) and a 5-layered (SP5) actuator.

BENDING MECHANISM

When the voltage is applied to the electrodes, the Maxwell stress causes the actuator to shrink thickness. Since the elastomer volume is assumed to remain constant, the actuator surface increases accordingly. A single layer actuator with symmetrical passive layers deforms only in a planar direction as the active area's top and bottom surface expand to the same degree. In case one side, either top or bottom surface, has a higher mechanical resistance, the deformation would be asymmetrical, i.e., the surface with higher resistance would expand less than the other. As a result, the actuator bends towards the stiffer side.

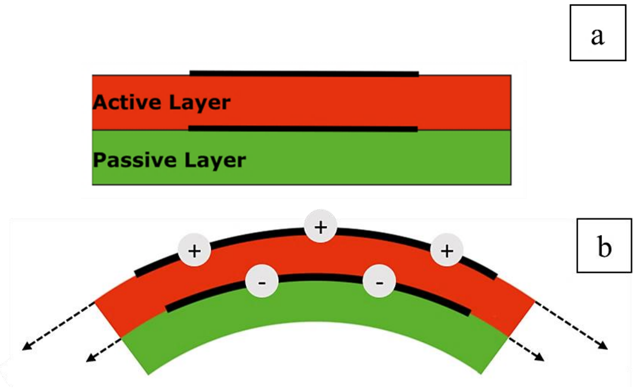

Figure 5: Schematic of the bending mechanism. The area sandwiched between electrode layers is called an active area. As the bottom surface had more resistance due to the thick passive layer, the top surface expands more and bends the actuator.

The mechanism, shown in Figure 5, was the inspiration for the development of bending actuators in this research. Accordingly, we introduced a so-called backbone structure to the last layer. The backbone structure consists of small thin, and rigid parts made of PMMA. As shown in Figure 6, the pieces are placed in the passive layer, increasing the mechanical resistance on that side. The advantage of this mechanism is that the stiffer parts are embedded in the soft actuator, and there is no need for any external support. The bending motion is only possible when the actuator is independent of external rigid frames.

The backbone structure also inhibits the bending in the non-desired direction. Figure 6 illustrates the schematic cross-section of a single layer actuator. The transparent backbone structure in a bending actuator is shown with red dashed lines in Figure 3. All results were achieved with actuators of the same lateral structure but with different numbers of active layers.

Figure 6: Schematic of the cross-section of the bending actuator. (a) the passivation layer (b) PMMA backbones (c) elastomer layer (d) electrode layer (e) active elastomer layer for actuation.

RESULTS

Eventually, the bending actuator was connected to the measurement setup, hanging from the contact pins, and a laser sensor (*scanCONTROL 3002-25/BL, Micro-Epsilon*) was placed in front of the actuator to capture the deflection.

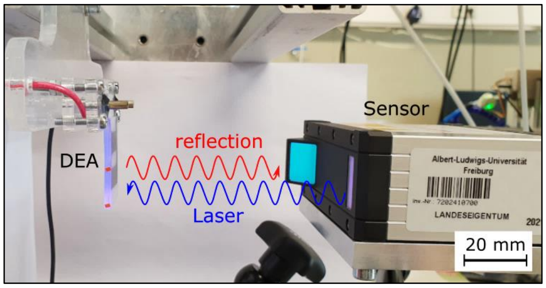

Figure 7: Capturing and measuring the bending line with the laser sensor.

For characterizing the bending actuator, the bending profile was recorded. Figure 8 depicts the maximum bending angle for a 2-layered bending actuator under voltages up to 8 kV.

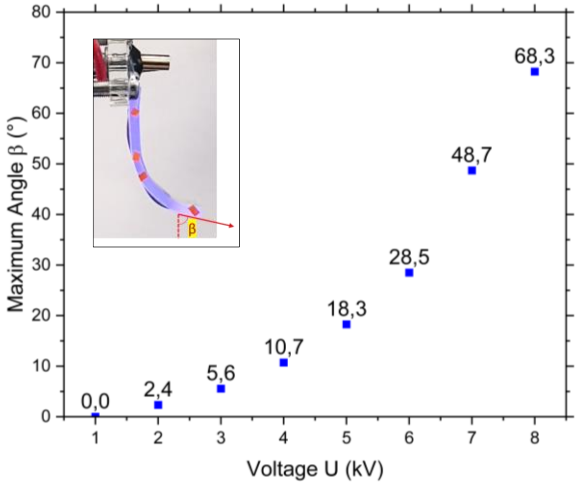

Figure 8: The maximum bending angle (β) for a 2-layered bending actuator.

The soft finger gripper is made of two actuators facing and bending towards each other. The finger gripper can press, hold and lift an object with an arbitrary shape. For the characterization purpose, a basket was designed, and in every measurement step, some incremental weight was added to the basket. The best result was for the fingers with a 5-layered actuator, which held and lifted the weight of 10.29 g (100.9 mN). The setup is shown in Figure 9.

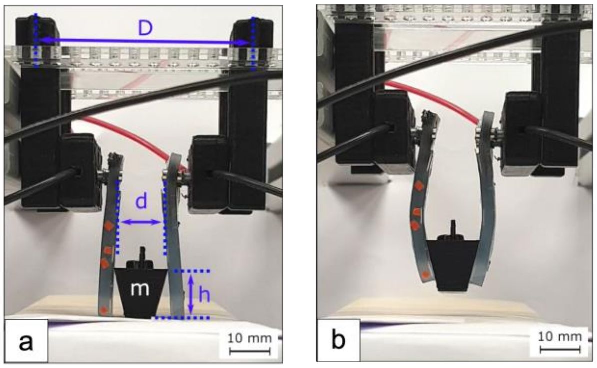

Figure 9: (a) The soft gripper ready for actuation, m_{max}=10.29 g, D = 55 mm, d = 11 mm, h = 14 mm (b) the soft gripper lifting and holding the weight under 8 kV.

CONCLUSION AND OUTLOOK

The key results presented in this paper were the choice of material, the novel actuation mechanism, and the process developed to fabricate the grippers. We deposited the elastomer layers of Ecoflex10T with a spin-coating method and patterned the electrode layers by dry-brushing the carbon black power directly onto the cured elastomer. The thickness of elastomer layers was tunable between 40 µm and 800 µm, and the electrode layer was between 5 µm to 10 µm thick. We also characterized the properties of the elastomer electrically and mechanically (Y = 58 kPa for very high strains and Y = 14 kPa for strains lower than 300%, ε_r = 4.4 @ 20 Hz, and E_{BD} = 22 V.µm^{-1}). This novel fabrication process enables the fabrication of multi-layered bending actuators without external ridged frames.

The bending actuator with two elastomer layers was able to bend up to 68.3°, lifting its weight (W_2 = 22.6 mN), while the 5-layered finger grippers (W_5 = 44.8 mN each) successfully lifted, held, and released the objects up to 100.9 mN. The advantage of this work is the independency from any external frame, scalability, and ease of thickness control for the elastomer layer. This research paves the way for future works for the scientific community to miniaturize the gripper and optimize the backbone structure to realize more complex motions like twisting grippers.

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