

High-field deformation of elastomeric dielectrics for actuators

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Abstract

This paper investigates the use of elastomeric dielectric materials with compliant electrodes as a means of actuation. When a voltage is applied to the electrodes, the elastomeric films expand in area and compresses in thickness. The strain response to applied electric fields was measured for a variety of elastomers. A nonlinear, high-strain, Mooney–Rivlin model was used to determine the expected strain response for a given applied field pressure. Comparing this analytical result to with experimentally measured strains, we determined that the electrostatic forces between the free charges on the electrodes are responsible for the observed response. Silicone polymers have produced the best combination of high strain and energy density, with thickness strains up to 41% and elastic energy densities up to 0.2 MJ/m³. Response times of 2 ms have been experimentally measured. This paper also reports recent progress in making highly compliant electrodes. We have shown, for example, that gold traces fabricated in a zig-zag pattern on silicone retain their conductivity when stretched up to 80%, compared to 1–5% when fabricated as a uniform two-dimensional electrode layer. Optimal loading of dielectric elastomers can have a significant impact on performance: and the paper describes techniques which that can increase output up to a factor of 5 compared to neutral loading conditions. Lastly, the paper briefly discusses the performance of various actuators that use dielectric elastomer materials. The technology appears to be well-suited to a variety of small-scale actuator applications. © 2000 Published by Elsevier Science B.V.

Keywords: Electroactive polymers; Artificial muscle; Electrostrictive polymers; Polymer actuators

1. Introduction

In many small-scale systems, such as micro robots and other portable or mobile microdevices, the need for improved actuators is particularly critical because conventional electromagnetic actuators generally have poor efficiency at small scales. There has been much recent interest in electroactive polymers as actuator materials. In general, polymers are attractive as actuator materials because they are lightweight, easily fabricated in various shapes, and low cost. Within the general category of polymers, the many different possible approaches to actuators include electrostrictive polymers [1–5], piezoelectric polymers [6], shape memory polymers [7], electrochemically actuated conducting polymers [8–13], polymer-based air-gap electrostatic devices [14], and so forth.

Actuators and actuator materials have several important performance parameters including energy density, specific energy density, strain, actuation pressure, response time,

and efficiency. To this list must be added practical considerations such as environmental tolerance, fabrication complexity, and reliability. Given this range of performance measures, it is not surprising that different applications depend more heavily on only one or a few performance parameters. Nonetheless, we consider a useful, general purpose actuator technology to be one with good overall performance, as opposed to excellent performance in one or two parameters and poor performance in others. This view is supported by the dominance of electromagnetic technology on macro scales where electromagnetic actuators have good overall performance, as well as by the good overall performance of natural muscle in nature over a wide range of size scales.

This paper describes an approach to electroactive polymer actuators that uses the deformation of dielectric elastomers. The actuator performance of these materials is similar in many respects to the performance of natural muscle. For this reason, dielectric elastomer actuators can be regarded as a type of *artificial muscle*. The principle of operation is shown in Fig. 1. An elastomeric polymer is sandwiched between two compliant electrodes. When a

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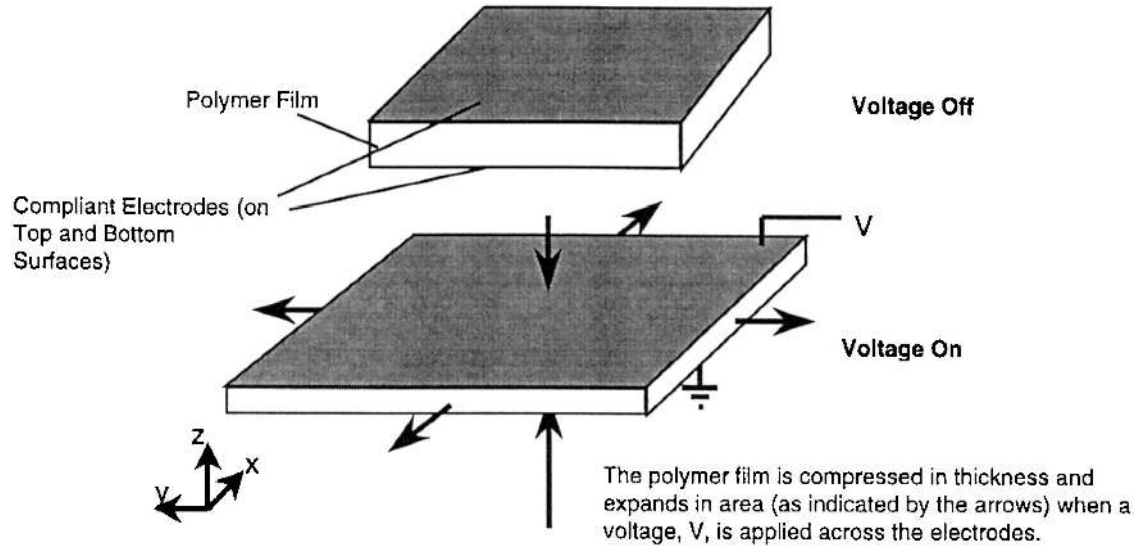


Fig. 1. Principle of operation of dielectric elastomers.

voltage difference is placed across the top and bottom electrodes, the polymer is squeezed in thickness and stretched in area by the electric field pressure.

The derivation of the electrostatic model of actuation is described by Pelrine et al., [15]. The effective actuation pressure, p , is given by

$$p = \varepsilon \varepsilon_0 E^2 = \varepsilon \varepsilon_0 (V/z)^2, \quad (1)$$

where E is the electric field, ε is the dielectric constant, ε_0 is the permittivity of free space, V is the voltage, and z is the polymer thickness. Note that this pressure is greater, by a factor of 2, than that arising from the commonly used equation for Maxwell's stress in a dielectric of a rigid plate capacitor. The greater pressure is due to the compliance of the electrodes, which allows both the forces of attraction between the oppositely charged electrodes and the forces tending to separate the charges on each electrode to couple into the effective pressure normal to the plane of the film.

For small strains with free boundary conditions, the polymer thickness strain, s_z , is given by

$$s_z = -p/Y = -\varepsilon \varepsilon_0 (V/z)^2 / Y, \quad (2)$$

where Y is the modulus of elasticity. The model for large strains with more realistic constrained boundary conditions, such as those required to drive a load, is more complex. However, this simple case illustrates the influence of the electrical and mechanical properties of the polymer on actuation performance. The model also assumes that the elastomer is an ideal rubber, that is, that the rubber is incompressible and has a Poisson's ratio of 0.5.

One of the more useful metrics for comparing actuator materials, independent of size, is the energy density of the material. The *actuator energy density* is the maximum mechanical energy output per cycle and per unit volume of material. The actuator energy density depends on the loading conditions as described in Section 7. For small strains

with free boundary conditions, the actuator energy density, e_a , of the material can be written as

$$e_a = p s_z = Y s_z^2 = (\varepsilon \varepsilon_0)^2 (V/z)^4 / Y. \quad (3)$$

Conventionally, the *elastic energy density* $e_e = 1/2 Y s_z^2$ is often used. However, for large strains with a linear stress–strain relation this formula must be modified because as the thickness strain becomes increasingly negative, the film flattens out and the area over which the pressure must be applied increases. A more detailed derivation for large strains gives the formula for the elastic energy density of materials with a linear stress–strain relation as

$$e_e = Y [(s_z - \ln(1 + s_z))]. \quad (4)$$

This equation agrees with the more common formula at small strains but is significantly higher for strains greater than 20%.

2. Experimental procedure for measuring material performance

The experiments in our study were designed to measure the response of different polymer materials to applied electric fields. The purpose of the experiments was to identify the most promising polymers, compare the polymer actuator's performance to that of other actuator technologies, and determine the validity of our electrostatic model of actuation.

The measurement of the performance of different polymer materials is complicated by the fact that several of the polymer materials evaluated are relatively soft, with elastic moduli below 1 MPa. Therefore, the constraints on the polymer film must be carefully controlled. The situation is further complicated by the fact that film samples are often

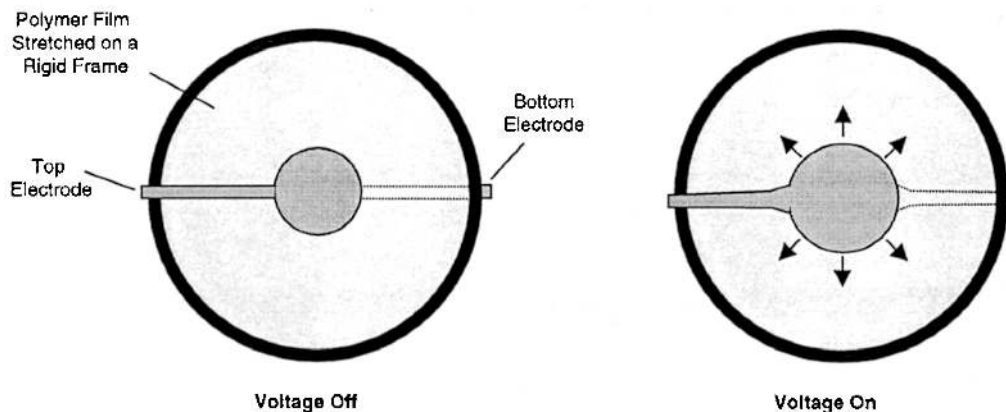


Fig. 2. Experimental setup (top view).

quite thin. We therefore used optical methods to measure the strain condition of the polymer film.

The measurement configuration is shown in Fig. 2. A thin film of a polymer is stretched uniformly across a circular hole in a rigid frame. Electrodes are applied to a relatively small circular area at the center of this frame. When a voltage is applied to the electrodes, the film between the electrodes expands in area and contracts in thickness. This expansion in area is measured with an optical microscope, a video camera, video digitizing hardware, and digital measurement software. The software measures the amount of motion of identifiable features on the surface of the electrodes (such as texture features) when a voltage is applied. By comparing the location of the features at a given voltage to the locations at zero voltage, we determine the in-plane strain at a given voltage. The magnification of the microscope and resolution of the video camera are such that a single pixel represents only a small portion of the observed motion. Most measured motions were on the order of tens of pixels. Photographs of one such experiment with Dow Corning HS3¹ silicone are shown in Fig. 3.

The effects of creep and mechanical hysteresis on the measured strain were minimized by obtaining the strain reading immediately following the application of the voltage. The voltage was brought to zero between each measurement. Any effects of electrical hysteresis on the strain measurement were assumed to be insignificant compared to the total measured strain.

Films of the polymers were prepared by dissolving the uncured polymer in a suitable solvent, such as naphtha for the silicone rubbers (polydimethyl siloxane). The polymer solution was then spun onto a disk at a speed appropriate to give a thin uniform coating. This operation was performed in a clean room, to minimize the introduction of particulates into the film. The sample was then allowed to

dry, to remove the solvent. Certain polymers were further cured at elevated temperatures according to the manufacturers' specifications for a complete cure. Film samples varied from 1 to 100 μm in thickness, depending on the properties of the film. In general, film thickness was chosen to give a maximum sustainable voltage between 1 and 10 kV.

The selection of electrode materials is an area of ongoing research and is discussed in Section 6. For our measurements we wanted a thin, extremely low-modulus electrode that provided uniform charge distribution over the surface of the film under the electrodes. In most cases, ultrafine graphite powder and carbon blacks were brushed onto the surface of the film through a stencil. For many of the silicones that are capable of undergoing extremely large strains, it was necessary to coat these electrodes with a mixture of silicone-polymer-based graphite grease and carbon-filled silicone (Chemtronics CW7200 and Stockwell RTV 60-CON, respectively) in order to ensure full coverage at large strains.

Measurement of the strains can serve as a basis of comparison between different polymers. For actuator designs, however, it is most useful to compare materials on the basis of energy density, since some materials may be capable of higher strains and others capable of higher pressures. Additionally, elastic energy density is typically used as a means of comparison between different actuator

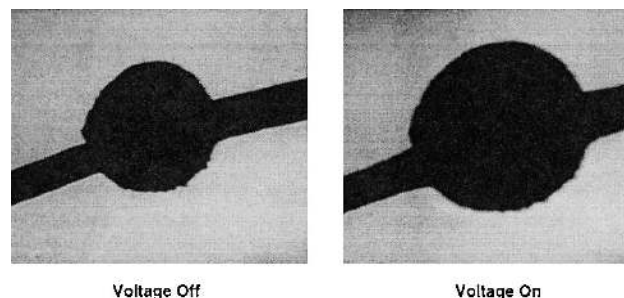


Fig. 3. Experimental results: HS3 silicone showing approximately 68% area strain (41% thickness strain).

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materials. In order to determine the elastic energy density of the material from the measured strain, it is necessary to characterize the elastic properties of the polymers and accurately model the constraints of the experimental setup. Another motivation for modeling the mechanical pressures from the measured strains is that to be able to compare our measured polymer performance with that suggested by the electrostatic model described in Eq. 1. The verification of this model has important implications for material selection and actuator design.

The tensile elastic modulus was obtained by measuring the force on a thin strip of polymer material at different linear strains. The compressive modulus was assumed to be equal to the tensile modulus.

The constraints on the measured strain of the experimental setup may can be considered analytically, due to the high degree of symmetry of the setup. However, the highly nonlinear nature of the elastic behavior of most polymers and the large strains make the analysis more difficult. A finite element analysis with a Mooney–Rivlin material model was used to account for both of these effects [16,17].

3. Dielectric elastomer material performance

As seen from Eqs. 1–3, the ideal dielectric elastomer material, with maximal energy density, has a high dielectric constant ϵ , a high breakdown strength (V/z), and a low modulus of elasticity Y . For most applications, desirable material properties also include low viscoelastic losses, a wide range of temperature and humidity tolerance, and

ease of fabricating thin films. Table 1 shows the measured performance of some of the polymers we have tested.

The table shows measurements of strain, electric field, modulus, and dielectric constant. We used Eq. 1 to measure the pressure, and the measured strain and estimated pressure from Eq. 3 to estimate the elastic energy density. In general, the pressure estimated using by means of the electric field pressure from Eq. 1 is in reasonable agreement with mechanical models such the finite element analysis with by means of a Mooney–Rivlin material model described in Section 4. The only major exceptions in Table 1 are the entries for polyurethane and fluoroelastomer, where the field pressure is a factor of 2–3 below that of the mechanical models. However, the polyurethane tested was relatively conductive and has a low melting temperature, suggesting that resistive heating and softening may adversely affecting the mechanical model's estimate of pressure. Similarly, the fluoroelastomer exhibited significant creep, which again could adversely affect the mechanical model estimate of pressure. Alternatively, it is possible that for these materials other actuation mechanisms add to the pressure estimated with Eq. 1. Polyurethane, in particular, has been reported to have an abnormally large response to electric fields [1] and to heating [7].

The coupling efficiency, k^2 , deserves some comment. The square of k is used for consistency with the conventional nomenclature for piezoelectrics. The electromechanical coupling factor is defined as follows: $k^2 = \text{energy converted into mechanical work per cycle} / \text{electrical energy applied per cycle}$.

Electromechanical coupling efficiency is an important parameter for many applications. Materials with low cou-

Table 1
Maximum response of representative elastomers

Polymer (specific type)	Elastic energy density (J/cm^3)	Pressure (MPa)	Strain (%)	Young's modulus (MPa)	Electric field ($V/\mu m$)	Dielectric constant (at 1 kHz)	Coupling efficiency, k^2 (%)
Silicone Nusil CF19-2186	0.22	1.36	32	1.0	235	2.8	54
Silicone Dow Corning HS3 (centrifuged to remove particulates)	0.026	0.13	41	0.125	72	2.8	65
Polyurethane Deerfield PT6100S	0.087	1.6	11	17	160	7.0	21
Silicone Dow Corning Sylgard 186	0.082	0.51	32	0.7	144	2.8	54
Fluorosilicone Dow Corning 730 (centrifuged to remove particulates)	0.055	0.39	28	0.5	80	6.9	48
Fluoroelastomer Lauren L143HC	0.0046	0.11	8	2.5	32	12.7	15
Isoprene Natural Rubber Latex	0.0059	0.11	11	0.85	67	2.7	21

Average engineering modulus at the maximum strain.

pling efficiencies are difficult to operate efficiently even without any intrinsic energy loss mechanism, because low coupling requires a large amount of electrical energy (relative to the work output) to be removed or recovered from the actuator after each cycle. Even with high-efficiency circuits (e.g., 90% efficient) recovery, if the coupling is too low, too much energy is lost in the recovery electronics relative to the work output per cycle.

Coupling efficiency is often difficult to measure directly, but we can use the electrostatic model (in which the permittivity of the material does not change) to estimate the coupling efficiency of dielectric elastomers, based on the capacitance change for the given strain. That is, the capacitance, C , varies as

$$C = \epsilon \epsilon_0 A/z = \epsilon \epsilon_0 U/z^2, \quad (5)$$

where U is the total volume of the material. Note that the last equality uses the constant volume property of elastomers, i.e., $Az = U$ is approximately constant throughout the actuation. Using Eq. 5 with a constant charge drive gives the percentage change in electrical energy at the assumed strain, starting at State 1 and actuating to State 2, as follows.

$$\begin{aligned} \Delta E/E_1 &= (E_2 - E_1)/E_1 \\ &= ((Q^2/C_2) - (Q^2/C_1))/(Q^2/C_1) \\ &= (z_2^2 - z_1^2)/z_1^2 = 2s_z + s_z^2, \end{aligned} \quad (6)$$

where we have used $z_2 = z_1(1 + s_z)$. Our best dielectric elastomers typically have low viscoelastic losses, so that the change in electrical energy is approximately equal to the work output, taking into account a minus sign ($s_z < 0$), i.e.,

$$k^2 = -2s_z - s_z^2. \quad (7)$$

Eq. 7 is an approximation but indicates that dielectric elastomer materials with a strain of 32% can have a coupling efficiency of up to approximately $k^2 = 54\%$ ($k = 0.73$), a value compared value with those of most piezoelectric materials and other field-actuated actuator technologies.

Finally, we note that previous analysis indicates that strains of around 33% would be the maximum achievable under DC test conditions with linear materials and free boundary conditions [15]. As the polymer contracts in thickness, with a constant voltage the electric field pressure increases. Beyond 33% thickness strain, the material undergoes an electromechanical instability and locally contracts rapidly in thickness until breakdown occurs. This phenomenon is similar to “pull-in” instabilities (e.g., as reported by Gupta and Senturia [18]) in conventional, air-gap electrostatic actuators. We have not absolutely confirmed that electromechanical instability limits the actuator performance of dielectric elastomers, but the fact that a number of materials with very different elastic moduli have peak strains in the range 25–35% suggests that such instability may be a limiting factor.

It is important to note that the 33% strain instability is subject to a number of qualifications that may allow higher performance to be achieved. In particular, the 33% strain value does not apply to polymers having nonlinear moduli of elasticity (as all polymers do to some extent), nor does it apply to actuators where part of the strain is caused by dynamic or static loading constraints. Indeed, the peak 41% thickness strain we have measured using HS3 silicone indicates that the 33% “limit” is not fundamental but is rather a practical limitation that may apply to some materials under certain loading conditions.

Nusil CF19-2186 silicone rubber has the highest measured energy density and strain of the elastomers tested. Other materials such as polyurethane can achieve higher actuation pressures at lower voltages, due to their greater permittivity (the dielectric constant of polyurethane is roughly 7, compared to 3 for silicones). However, silicone has better coupling efficiency as well as other properties, including low creep and excellent tolerance to temperatures and humidity, that make it more attractive as an for many actuator applications. Consequently, most of our actuator development has focused on the use of silicones.

4. Validation of electrostatic model

Fig. 4 shows the measured strain of a silicone rubber film (Dow Corning HS3) as a function of the applied electric field, is compared to the strain that would be expected based on the pressure from the electrostatic model described by Eq. (1). As can be seen, there is very close agreement between the measured strain and that predicted by the model.

Also shown in Fig. 4 is a curve of representing the strain that would be expected from a test sample with free boundary conditions. This curve illustrates the importance of accurately modeling the constraint conditions. The curve also suggests that actuators with different constraints might be able to undergo greater strains than the constrained sample films.

5. Comparison to with competitive technologies

Table 2 shows several characteristics of dielectric elastomer materials and other electric actuation technologies, including several electroactive polymer technologies.

As can be seen in Table 2, dielectric elastomers are not the best technology in any single measure of performance. However, their overall performance, and in particular their high specific energy density and high efficiency is encouraging enough to suggest that it they can be used competitively in energy-efficient actuators that are lightweight and compact, relative to common actuation technologies such as electromagnetics and piezoelectrics.

Dielectric elastomer actuators do have one notable characteristic that may be considered a disadvantage in certain

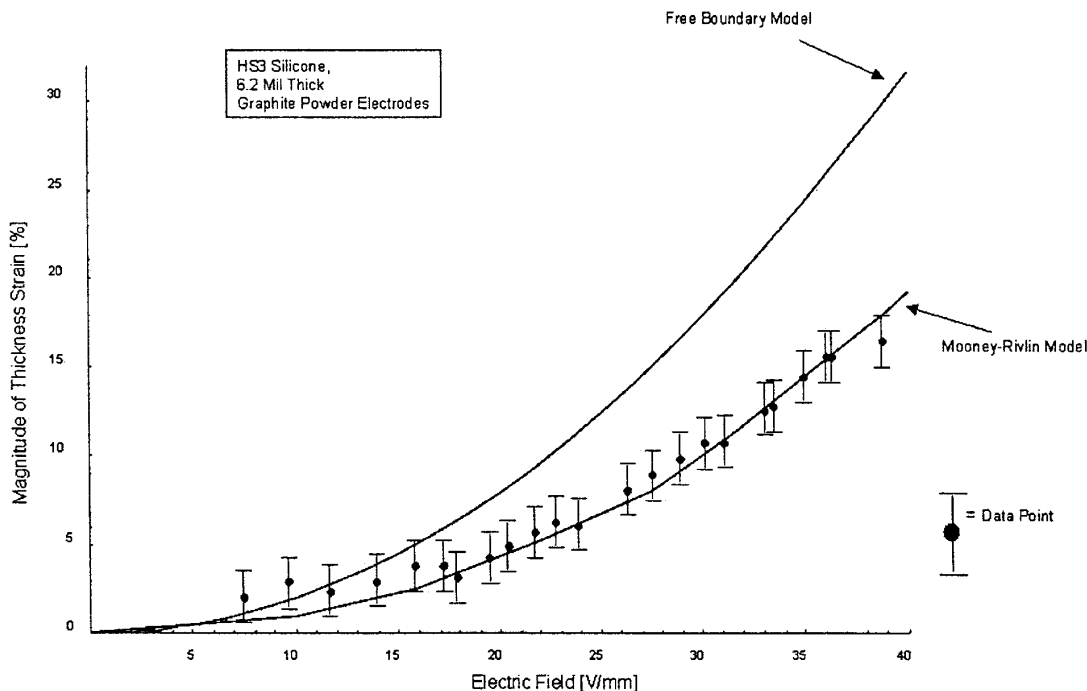


Fig. 4. Response of silicone rubber to an electric field; comparison with electrostatic model.

applications. In general, these actuators operate at relatively high voltage (e.g., typically as high as 100–4000 V, depending on material thickness and properties). This high voltage adds makes the actuators' electronics more complex than those of electromagnetic and other low-voltage drives. However, we note that voltage amplifiers can be made quite small (e.g., we have demonstrated $4 \times$ high-voltage multipliers with components roughly 5 mm^3), so the disadvantage is not fundamental, but rather an issue of designing suitable components and circuits with the desired voltage and power ratings. High-voltage operation can be an advantage in some applications, since it allows for more efficient transmission of the electrical energy through thin wires and less-than-perfect connectors.

One other potential disadvantage is that dielectric elastomers are intrinsically a variable capacitive drive. After actuation, capacitive electrical energy remains on the actuator. In this respect, dielectric elastomers are similar to piezoelectric and conventional, air-gap electrostatic actuators. For maximum efficiency, energy recovery circuits are needed; but within the class of actuators that require energy recovery circuits, dielectric elastomers are attractive because of their high electromechanical coupling (discussed in Section 3).

6. Dielectric elastomer fabrication issues

Dielectric elastomer actuation technology can borrow many techniques and materials from the microelectronics and microelectromechanical systems (MEMS) communi-

ties. The materials used are relatively low cost and commercially available. However, many features of the technology require unique materials and actuator designs.

Elastomer films can be made by casting, dipping, spin coating, or spraying. Spin coating generally yields the best-performing films because the spin coating process is able to fabricate films of high uniformity. Spin coating is also the preferred process for the thinnest films: we have demonstrated the fabrication and actuation of $1\text{-}\mu\text{m}$ -thick silicone films. The fabrication procedure for making spin-coated actuator films is the same as that for the polymer samples described above.

A key feature of dielectric elastomer technology is the use of compliant electrodes. If the electrodes cannot stretch in at least one planar direction of the film while its thickness contracts, actuation is dramatically reduced because the polymer is essentially incompressible, i.e., its bulk modulus is much greater than its elastic modulus. Fortunately, for energy efficient operation the compliant electrodes need not be very conductive, due to the high-voltage, low-current drive typical of electrostatic devices.

As noted above, the selection of electrode materials remains an ongoing area of research. The more successful materials have typically been based on small particles of carbon such as powdered graphite, carbon black, and carbon grease. These materials can be deposited directly on the film in a screen-printing process, or they can be sprayed on the film with a fast-evaporating carrier liquid.

Carbon-based electrode materials work reasonably well but have drawbacks. In particular, it is difficult to get a smooth, uniform electrode from carbon particles. This is

Table 2
Comparison of dielectric elastomers with other actuator technologies

Actuator type (specific example)	Maximum strain (%)	Maximum pressure (Mpa)	Specific elastic energy density (J/g)	Elastic energy density (J/cm ³)	Coupling efficiency k^2 (%)	Maximum efficiency (%)	Specific density	Relative speed (full cycle)
Dielectric elastomer artificial muscle — Silicone	32	1.36	0.22	0.2	54	90	1	Fast
Dielectric elastomer artificial muscle — Polyurethane	11	1.6	0.087	0.087	21	80	1.1	Fast
Electrostrictor polymer (P(VDF-TrFE) [3]	4	15	0.17	0.3	5.5	–	1.8	Fast
Electrostatic devices (integrated force array) [2]	50	0.03	0.0015	0.0015	50 (est.)	> 90	1	Fast
Electromagnetic (Voice Coil) ^a	50	0.10	0.003	0.025	n.a.	> 90	8	Fast
Piezoelectric — ceramic (PZT) ^b	0.2	110	0.013	0.10	52	> 90	7.7	Fast
Piezoelectric — Single Crystal (PZN-PT) [20]	1.7	131	0.13	1.0	81	> 90	7.7	Fast
Piezoelectric — Polymer (PVDF) ^c [25]	0.1	4.8	0.0013	0.0024	7	–	1.8	Fast
Shape memory alloy (TiNi) [21]	> 5	> 200	> 15	> 100	5	< 10	6.5	Slow
Shape memory polymer (Polyurethane) [7]	100	4	2	2	–	< 10	1	Slow
Thermal (Expansion) ^d	1	78	0.15	0.4	–	< 10	2.7	Slow
Electrochemo-mechanical conducting polymer (polyaniline) [8]	10	450	23	23	< 1	< 1	~ 1	Slow
Mechano-chemical polymer/gels (polyelectrolyte) [22]	> 40	0.3	0.06	0.06	–	30	~ 1	Slow
Magnetostrictive (Terfenol-D, Etrema Products) [26]	0.2	70	0.0027	0.025	–	60	9	Fast
Natural muscle (human skeletal) [22]	> 40	0.35	0.07	0.07	n.a.	> 35	1	Med

^aThese values are based on an array of 0.01-m-thick voice coils, 50% conductor, 50% permanent magnet, 1-T magnetic field, resistivity of 2 Ω /cm, and 40,000 W/m² power dissipation.

^bPZT B, at a maximum electric field of 4 V/ μ m [19].

^cPVDF, at a maximum electric field of 30 V/ μ m [25].

^dAluminum, using a temperature change of 500°C.

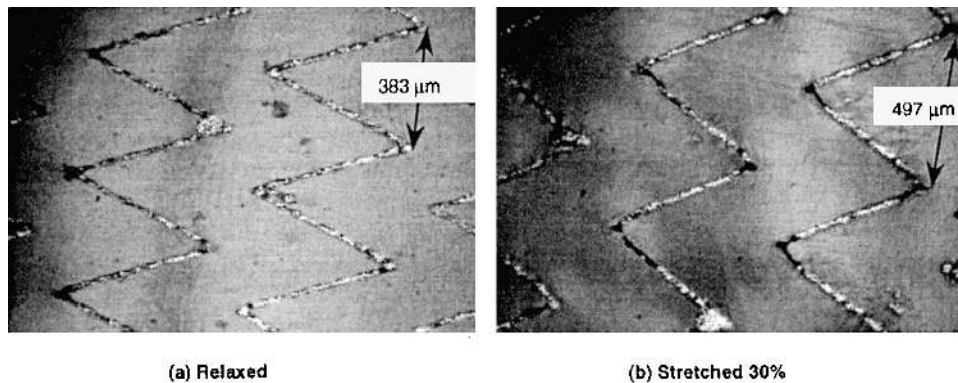


Fig. 5. Zig-zag gold electrodes undergoing large strains.

not an issue for single-layer actuators, or for multilayer actuators that are mechanically assembled from single-layer films. However, ideally one would like to be able to fabricate multiple layers of dielectric elastomers and their electrodes in situ. To do this, however, one needs an extremely smooth electrode to prevent local thinning of the elastomer deposited on top of the electrode.

One approach is to use sputter-deposited, ultrathin gold (with thicknesses below $0.1 \mu\text{m}$), for compliant electrodes. Unfortunately, uniform gold electrodes easily crack, and strains greater than about 4% are difficult to achieve with this technique. Recently, we have demonstrated that patterned, rather than uniform gold electrodes can remain conductive at much greater film strains. Zig-zag patterns of gold traces deposited on silicone film, such as those shown in Fig. 5, remain highly conductive at film strains up to 80%. The gold traces are sputtered uniformly on the film, then patterned via photolithography. Photolithography on soft polymers has not been reported in the literature; therefore, it was necessary to refine the processes. We have successfully fabricated gold traces with line widths as small as $5 \mu\text{m}$.

The zig-zag traces carry charge out onto the film, but a second electrode material is needed to carry the charge in between the zig-zag traces, for uniform distribution over

the surface of the polymer. Fortunately, this problem is easy to address, because the resistivity of the second electrode material can be quite high. For a $50\text{-}\mu\text{m}$ -thick silicone film with $500\text{-}\mu\text{m}$ trace spacing, for example, the surface resistivity to achieve a 100 Hz response can be as high as $10^{10}\text{--}10^{11} \Omega/\text{square}$ (based on the RC time constant of the film). Indeed, we have shown that even ambient air is sufficiently conductive to carry charge between finely spaced metal traces. In contrast, the maximum surface resistivity of a uniform electrode (without gold traces) for a 10 cm^2 piece of film of the same thickness would need to be about 4000 times lower for in give the same 100 Hz response.

The use of electrodes having two different conductivities can improve reliability and robustness. The electrode materials can be configured as *structured electrodes*, as illustrated in Fig. 6. Note that with structured electrodes, no matter where a breakdown occurs, the electrical breakdown current must pass through the low-conductivity material before it can reach a high-conductivity trace. The low-conductivity material thus limits breakdown current and localizes the breakdown effects to prevent catastrophic failure. The material also limits leakage current and helps maintain efficiency even in the presence of breakdowns. For example, with a surface conductivity of $10^{11} \Omega/\text{square}$,

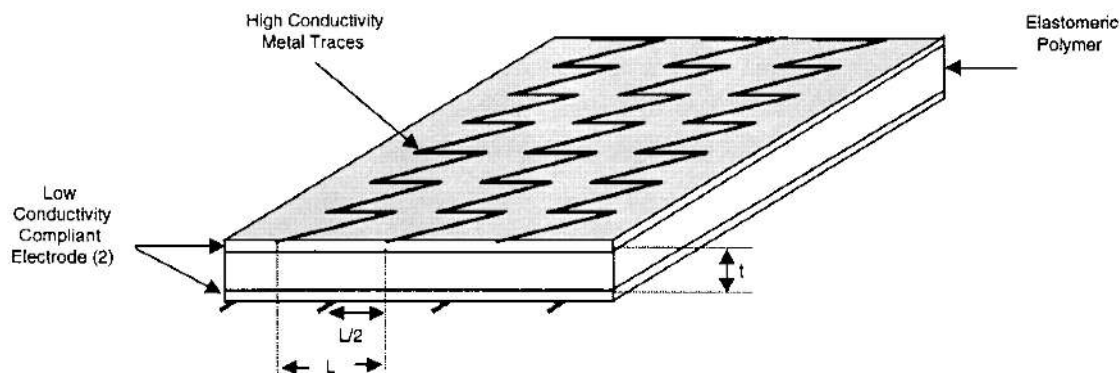


Fig. 6. Structured electrodes.

even at an operating voltage of 1000 V the power loss from a breakdown is only 10 μW , a negligible amount for most applications.

Another way to limit breakdowns is to use self-healing electrodes. Self-healing electrodes are well known in the manufacturing of certain types of capacitors. However, capacitors do not stretch, and therefore the choice of electrodes is less restricted. We have demonstrated self-healing gold, conductive polymers, and carbon-based electrodes. Studies of promising conductive polymer electrodes have focused on solvent-based solutions of doped polyaniline, although numerous ionically conductive materials have also been evaluated. The self-healing property is less dependent on the material than it is on the electrode and film thicknesses. This observation is not surprising, since self-healing generally works by locally vaporizing the electrode material during breakdown. Thus, electrode materials can usually be made self-healing if they can be used in sufficiently thin layers. Unfortunately, most of the self-healing electrode materials capable of undergoing large strains (such as conducting polymers) have not shown good long-term performance on silicone. One possible reason for this poor performance appears to be the poor adhesion of the polymer to the silicone. Another possible reason is that the film area in the vicinity of the electrode defect experiences both an electric field concentration and a stress concentration. These factors may combine to allow the defect to propagate from the initial location. The development of self-healing electrodes remains an area of active research.

7. Effects of material loading on actuator performance

Dielectric elastomer actuators convert electrical energy to mechanical energy by bringing opposite charges on the two sides of the film closer together (squeezing) and simultaneously separating similar charges on the same side of the film (stretching). The simplest mode of operation is for the electrostatic pressures to strain the film until the elastomer's elastic stress prevents further expansion. However, this is not the only mode of operation of dielectric elastomers, and other forms of loading may significantly increase performance.

Fundamentally, the conversion of electrical to mechanical energy depends only on geometric changes of the film, independent of how those changes are caused. Virtually any loading or constraint that increases the film thickness will convert electrical to mechanical energy.

Many actuator applications are suitable for a resonant mode of operation. With resonance, the inertial forces of the system act to strain the elastomer beyond the strains that can be achieved off resonance. Let G be the ratio of the resonant amplitude to the amplitude below the resonant frequency at the same voltage. We have typically measured $G = 3.5$ to 4.5 , using silicone elastomers. For small

strains, these values corresponds to roughly 3.5 to 4.5 more electrical energy converted to mechanical energy at resonance than would be converted off resonance. The measured increase in strain amplitude is about half of what would be expected, based on the measured viscoelastic losses in the silicone alone. These measurements suggest that current configurations have an appreciable amount of additional damping from the electrodes, the connection points, and/or air damping.

The analysis of strains obtained from loaded films at resonance that output useful work (as opposed to film that only move) is more complicated. Detailed analysis indicates that for ideal loading, under the assumptions that damping loss is proportional to the amplitude squared and that electrical-to-mechanical energy conversion is proportional to the amplitude, the maximum output at resonance is given by:

$$W_r = W_o G^2 / (4(G - 1)), \quad (8)$$

where W_r is the ideal work output per cycle at resonance and W_o is the work output per cycle below resonance. For a film with $G = 4.5$, Eq. (8) indicates that the work output can be as much as 45% greater at resonance than off resonance.

Another way to increase strain at any frequency is to couple the film to a mechanism which that compensates for the increase in elastic energy with strain. It was noted previously that for small strains the elastic energy density is given by $e_e = 1/2 Y s_z^2$. The elastic energy of the film is the film's elastic energy density multiplied by the film volume, U . Suppose that we couple the film to a mechanism whose energy, when expressed in terms of film strain, is $0.5 K s^2$, where K is an effective spring constant. This type of coupling could be achieved, for example, by attaching a narrow strip of film to a spring, so that film strain causes the spring to elongate or contract. In this case, the total energy of the system, e_T , is given by:

$$e_T = 0.5(UY + K) s^2, \quad (9)$$

If K is a positive spring constant, then the coupled mechanism has made the total system stiffer because the total stored energy increases more quickly with strain, s , than it would for $K = 0$. However, if k is a negative spring constant, then the total system is softer. If $K < -(UY)$, the system is unstable because the total spring constant $(UY + K)$ is negative. In this case, a small disturbance in strain causes the system to go to infinite strain (i.e., break the film or reach a mechanical stop). However, if $-(UY) < K < 0$, then the total spring constant is positive; the system is stable (i.e., it returns to zero strain after a disturbance); and the system is softer than it would be without the added mechanism. For K slightly greater than $-(UY)$, very little added energy is needed to strain the

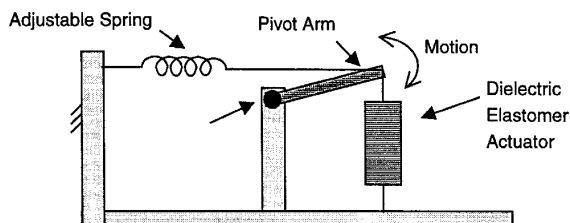


Fig. 7. Simplified over-center mechanism.

film, because the increase in the elastic film energy is compensated by a decrease in the mechanism energy. In effect, the film behaves as if its elastic modulus were much lower.

Mechanisms with negative spring constants are well known in the field of mechanical design. In general, any mechanism that is intrinsically unstable in a given range of motion has a negative spring constant. Two examples are bellville springs in their unstable range, and over-center mechanisms. An example of an over-center mechanism is shown in Fig. 7.

This analysis implies that by coupling a dielectric elastomer film to a mechanism having the proper negative spring constant, we can significantly increase the strain of the film beyond that of a similar film that has free boundary conditions or is neutrally loaded ($K = 0$, but with a constant preloading force). To test this concept, we coupled a silicone elastomer strip with electrodes to an adjustable over-center mechanism. Fig. 8 shows data taken with this apparatus: when coupled to the over-center mechanism at a given electric field, the film had approximately five times the strain it had when neutrally loaded.

Over-center mechanisms are useful for demonstrating the effect of coupling to a mechanism with a negative spring constant, and they may be useful for some applications. However, they are cumbersome for many applications, and especially small-scale applications. More recent and as yet untested designs use two films configured so that each film acts as the negative spring constant mechanism for the other film.

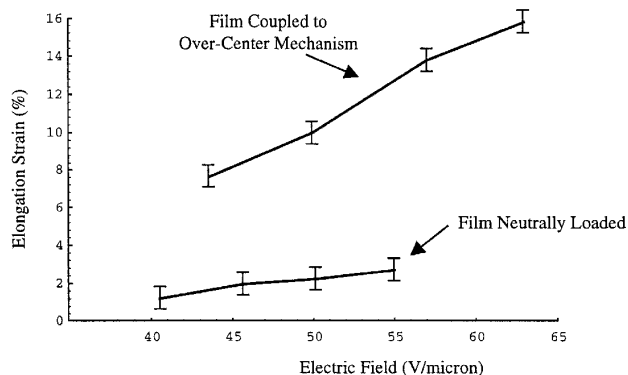


Fig. 8. Strain response of a silicone film coupled to an over-center mechanism.

8. Dielectric elastomer actuators and actuator design

A wide variety of dielectric elastomer actuator configurations have been demonstrated. Several are analogous to well-known piezoelectric configurations; others take advantage of the unique capabilities of high-strain polymer actuators. Here we briefly describe three such actuators that illustrate the range of possible designs.

8.1. Unimorph and bimorph actuators

Unimorph and bimorph actuators are similar to their piezoelectric counterparts and work well with dielectric elastomer materials. Applications for unimorph and bimorph actuators include oscillating micro fans, displays, and low-force robotic elements such as grippers. Dielectric elastomers produce higher strains than with competing piezoelectric materials, so that higher bending angles can be achieved with shorter devices and without resorting to submicron film thicknesses. Bending angles approaching 360° have been achieved with 5-mm-long unimorphs. Fig. 9 shows a photo of a dielectric elastomer unimorph made from silicone. The electrodes are sputtered gold on the stiff unimorph surface and carbon black on the free surface. The sputtered gold is sufficiently stiff, compared to the carbon black, that the strain is much less at the gold electrode than at the carbon black electrode. The result is that the film bends away from the carbon black electrode when a voltage is applied.

8.2. Rolled actuators

Unlike piezoelectric ceramic actuators, dielectric elastomer film can be rolled up to form a linear rolled actuator. Since it is easiest to fabricate and deposit electrodes on a



Fig. 9. Dielectric elastomer unimorph undergoing actuation.

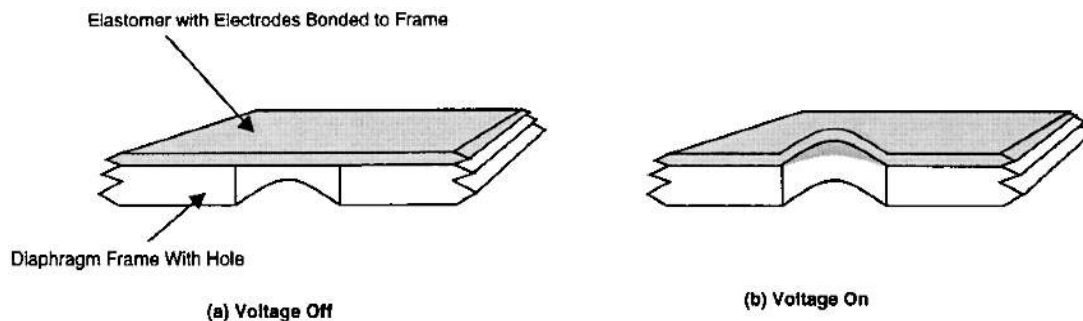


Fig. 10. Cross-sectional view of a diaphragm actuator.

single flat layer of film, rolled actuators are an easy way to squeeze a large single layer of film into a compact shape. Rolled dielectric elastomer actuators are potentially applicable wherever linear actuators and electromagnetic solenoids or voice coils are used, such as in robotic legs and fingers, high-force grippers, and general-purpose linear actuators. Rolled dielectric elastomer actuators have been used in most reliability tests to date; for example, an actuator of this type was demonstrated for more than 10,000,000 cycles without significant performance degradation. Rolled actuators have been fabricated that have maximum strokes of 5–7% of their active lengths. Larger rolls with forces ranging up to nearly 1 N also have been demonstrated.

8.3. Diaphragm actuators

Diaphragm dielectric elastomer actuators work very well, in part because a diaphragm can easily exploit both directions of planar expansion of the film. Fig. 10 illustrates a diaphragm actuator. Diaphragms are particularly well suited to pumps but could also be used for adaptive optics, loudspeakers [23], or controllable surface roughness (e.g., on an aerodynamic surface). For pumps, diaphragm actuators with up to 20 kPa (3 psi) pressure with 3-mm-diameter diaphragms have been demonstrated. Multiple cascaded pumps could be used to increase pressure, or thicker diaphragms could be used. An attractive feature of dielectric elastomer diaphragms (as opposed to competitive piezoelectric diaphragms) is that the displacement can be relatively large without the sacrifice of other performance parameters. Diaphragm motion with dielectric elastomers can easily be 10% or more of the diaphragm diameter. In principle, piezoelectrics could produce large diaphragm motions, but because the intrinsic strain of piezoelectrics is so much smaller than with that of dielectric elastomers, only very thin piezoelectric diaphragms could achieve similar motions with comparable diameters. The use of very thin diaphragms, however, sacrifices other parameters such as pumping pressure or packaging density, and most

piezoelectric diaphragms must use relatively small strokes to avoid these [24].

9. Summary and conclusions

Elastomeric polymers show promise as actuator materials when employed as a dielectric layer between compliant electrodes. Dielectric elastomer materials show excellent overall performance and appear more attractive than many competitive actuator technologies. Strains over 30%, actuation pressures of 1.3 MPa, and energy densities of 0.22 J/cm³ have been demonstrated with silicone rubbers. Response is rapid, and the potential efficiency is high.

Experimental measurements of strain in a variety of elastomeric materials have validated the electrostatic model of electrostriction. Mooney–Rivlin finite element modeling, which can address large strains and elastic nonlinearities, was used to help validate the model. We plan to extend this modeling technique beyond fundamental measurements of stress and strain to actuator design.

The key technical issues for dielectric elastomer technology include the selection of elastomer materials and compliant electrode materials, the fabrication of integrated elastomer–electrode structures, material modeling, and actuator design. Improved elastomer materials are an ongoing area of research, though current performance is already attractive for many applications. Compliant electrodes have been based primarily on carbon particle materials (e.g., graphite, carbon black), but structured electrode approaches using, for example, patterned zig-zag gold traces in conjunction with a low conductivity material may be more promising in the long term. Single-layer elastomer films of excellent quality can be fabricated via spin coating. As to fabrication, some progress has been made in demonstrating in-situ multilayer fabrication, but at present the performance of these films is inferior to that of single layer fabrication. A variety of dielectric elastomer actuators have been fabricated and demonstrated with good performance. These linear actuators have many potential

applications for pumps, robots, and general-purpose linear actuators; their large strain capabilities suggest that that they could be used for muscle-like actuation in small robots.

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