A review on dielectric elastomer actuators, technology, applications, and challenges

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APPLIED PHYSICS REVIEWS—FOCUSED REVIEW

A review on dielectric elastomer actuators, technology, applications, and challenges

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This paper reviews the developments in dielectric elastomer actuator technology for several applications. Dielectric elastomers are a variety of electroactive polymer that deform due to the electrostatic interaction between two electrodes with opposite electric charge. Dielectric elastomers have been subject of much interest and research over the past decade. In earlier years, much of the focus was on actuator configurations, and in more recent years the focus has turned to investigating material properties that may enhance actuator performance. This review outlines the operating principle and actuation mechanisms behind this actuator technology, highlights some of its advantages over existing actuator technologies, identifies some of the challenges associated with its development, and examines the main focus of research within this field, including some of the potential applications of such an actuator technology. © *2008 American Institute of Physics*.
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I. INTRODUCTION

An actuator is a mechanical device for moving or controlling a mechanism or system. Traditional actuators include pneumatic actuators, electronic actuators, motors, and hydraulic cylinders. The weight, limited size, complex transmission, and restrictive shape of such actuators have led researchers to investigate alternative technologies for various applications. Electroactive polymers (EAPs) are polymers that respond to electrical stimulation with a significant size or shape change and are emerging as a new class of actuation material. In particular, EAPs are most often compared with actuator technologies such as electroactive ceramics (EACs), shape memory alloys (SMAs), and McKibben actuators. Comparisons are drawn with these particular technologies, since EAPs potentially have a similar application set to these already established actuator technologies. For example, a comparison of the properties of EAPs and widely used transducer actuators, outlined in Table I, drawn up and presented by Bar-Cohen at a short course on EAPs in San Diego, March 2004, highlights the advantages of EAPs as an actuator technology in the area of artificial muscle development.

EAPs can outperform these existing technologies in a number of metrics. EAPs are superior to McKibben actuators, which employ heavy electric motors and pneumatics. In addition, they do not exhibit the unpredictable movement and slow response speed, characteristic of SMAs, and the fragility and small actuation strain capabilities of EACs. The most attractive characteristic of EAPs is their ability to emulate the operation of biological muscle in high fracture toughness, large actuation strain, and inherent vibration damping. It is this ability that has been the driving force

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TABLE I. Comparison between EAP and widely used transducer actuators.

Property	EAP	SMA	EAC
Actuation strain	Over 300%	<8% (short fatigue life)	Typically 0.1%–0.3%
Force	0.1–25 MPa	200 MPa	30–40 MPa
Reaction speed	μ sec to min	millisecond to minute	microsecond to second
Drive voltage	1–2.5 g/cc	5–6 g/cc	6–8 g/cc
Consumed power	Ionic EAP: 1–7 V Electronic EAP: 10–150 V/μm	5 V	50–800 V
Fracture behavior	Resilient, elastic	Resilient, elastic	Fragile

behind much of the research in the field. Reported actuated elastomers with strains greater than 100% accelerated this field of research in 2000.[1]

This review continues with an overview of existing EAP technologies with a particular focus on the dielectric elastomer variety. Dielectric elastomer actuation mechanisms and configurations are outlined, and existing and potential applications are discussed. Technological challenges faced by such an actuator technology are highlighted. Finally to conclude, the future developments in this area are discussed.

The aim of this review is to familiarize the reader with recent developments in the area of dielectric elastomer actuator technology and in so doing encourage further research in this field to overcome some of its challenges and also to inspire new and creative applications for this alternative and exciting actuator technology.

II. ELECTROACTIVE POLYMER TECHNOLOGY OVERVIEW

EAPs can be categorized into two major classes: ionic and electronic. An electric field or Coulomb forces in general drive electronic EAPs, while the actuation mechanism for ionic EAPs involves the diffusion or mobility of ions.

A. Electronic electroactive polymers

1. Electrostrictive relaxor ferroelectric polymers

Piezoelectricity is a coupling between a material's mechanical and electrical behavior. When a piezoelectric material is squeezed, an electric charge collects on its surface. Ferroelectricity is the reverse effect of piezoelectricity. The application of an electric field causes aligning of polar domains and, as a direct result, crystal elongation. This reversible alignment of polar groups produces a contraction of up to 10% in the direction of the electric field. Ferroelectric polymers can be operated as actuators in air, vacuum, or water. Since piezoelectricity is a linear effect, where not only does the material experience a strain upon application of voltage, a voltage signal is also induced when a stress is applied. A significant hysteresis effect is present in ferroelectric polymers. Subsequently a large field must be applied in the opposite direction to the original to reverse the polarization, resulting in substantial energy being expended, which does not produce any mechanical work. Polyvinylidene flouride (PVDF) and its copolymers are the most exploited materials in the ferroelectric group. Much of the pioneering work in this area has been carried out by Zhang *et al.*[2] Electrostrictive poly(vinylidene-flouride triflouroethylene) has been used to realize a microfluidic pump.[3]

2. Dielectric elastomers

Dielectric elastomer actuators consist of a polymer film sandwiched between two compliant electrodes. A voltage difference is applied between the compliant electrodes, causing compression in thickness and stretching in area of the polymer film. Figure 1 shows the actuation of a circular dielectric elastomer.[4] Dielectric elastomer actuators are a subject of interest to many research groups and are discussed in greater detail in Sec. III.[5–8]

3. Electrostrictive graft elastomers

Electrostrictive graft elastomers are polymers that consist of two components, a flexible macromolecule backbone and a grafted polymer, that can be produced in a crystalline form. Here we consider electrostrictive graft elastomers as an electronic EAP in its own right; however, since its actuation mechanism is electrostrictive in nature, it is fundamentally the same as ferroelectric polymers described in Sec. II A 1. The copolymer polyvinylidene-fluoride-trifluoroethylene permits operation as a piezoelectric sensor and as an electrostrictive actuator.[9] Electrostrictive graft elastomers have achieved strain levels of up to 5% with a relatively large force and a response speed in the region of milliseconds.[10] The most significant disadvantage of this type of actuator is the high voltage requirement (150 MV/m), which is charac-

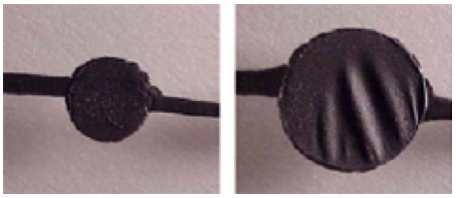

FIG. 1. (Color online) Circular dielectric elastomer actuator, unactivated (left) activated (right) (see Ref. 4).

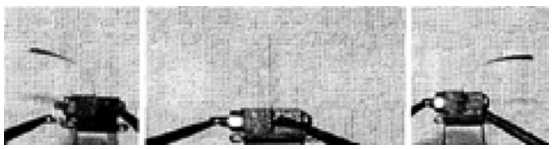

FIG. 2. An electrostrictive graft elastomer, bimorph actuator excited in one direction, unexcited, and excited in the opposite direction from left to right respectively (see Ref. 9).

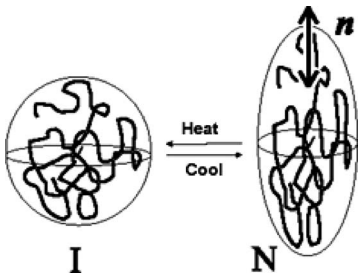

FIG. 3. Polymers are on average spherical in the isotropic (i) state and elongate when they are cooled to the nematic (n) state. The director n points along the long axis of the shape spheroid (see Ref. 11).

teristic of almost all actuator varieties in the electronic EAP group. Figure 2 depicts the actuation of an electrostrictive graft elastomer.

4. Liquid crystal elastomers

Liquid crystal elastomers (LCEs) consist of crystal molecules (mesogens) appended to a compliant polymer backbone. A soft backbone permits the mesogens to reorient while preventing free flow of molecules. Reorientation of mesogens can occur by thermal or electrical means. This reorientation of mesogens induces stresses on the backbone resulting in a bulk strain of the LCE. Due to heat diffusion, thermally actuated LCEs are relatively slow, particularly the relaxation process ($\sim$10 s) and requires active cooling. The actuation mechanism involves a change in average molecular shape from spherical to spheroidal as the polymer transitions from the nematic to the isotropic phase.[11] Electrically actuated ferroelectric liquid crystals have an intrinsic polarization of their mesogens. Upon application of an electric field, realignment of the mesogens causes bulk stresses and strains in the material (Fig. 3). The required applied fields (1.5–25 MV/m) are lower compared with ferroelectric polymers and dielectric elastomers, thus demanding decreased applied voltage levels for the same thickness of material. However, achieved strains of 4% at 1.5 MV m^{-1} for electrically activated LCEs are much smaller compared to the typical 35%–45% strains achieved for thermally activated LCEs.[12,13]

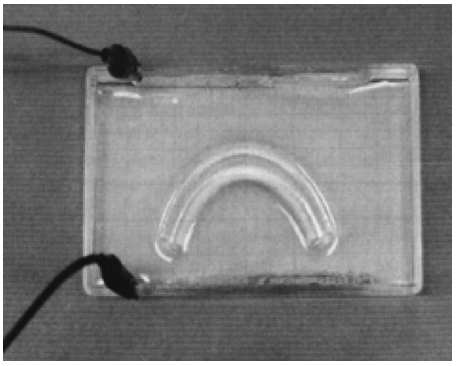

FIG. 4. Bending of a polyacrylic acid gel rod sodium hydroxide. dc applied field, cathode (negative) at bottom. Gel swells on the anode side and bends toward the cathode (see Ref. 14).

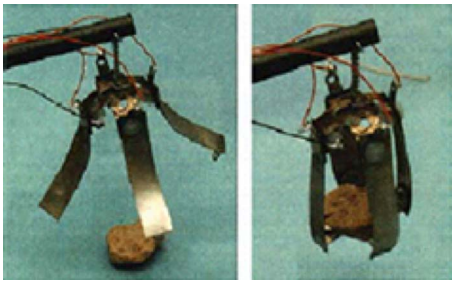

FIG. 5. (Color online) Four-finger IPMC gripper lifting a rock (see Ref. 16).

B. Ionic electroactive polymers

1. Ionic gels

Application of voltage to ionic gels (IGLs) such as polyacrylic acid gel causes movement of hydrogen ions in or out of the gel, thus changing the environment from acid to alkaline causing the gel to become dense or swollen accordingly. Under activation, polyacrylic acid gels bend with a concave positive side if the gel is in contact with the anode, a process which is driven by the build up of acidity. If the gel has no contact with either electrode the gel strip bends with a concave negative side (as illustrated in Fig. 4), the bending being induced by a difference in ion diffusion rates in the gel, and in the electrolyte.[14] While the voltage requirement for actuation of IGLs is low the diffusion of ions results in slow operation. Polyacrylonitrile with conductive fibers is an example of such a material. IGLs have been used to construct an artificial uretheral sphincter,[15] but for the most part they are at the prototype stage of artificial muscle development.

2. Ionic polymer metal composites

Ionic polymer-metal composites (IPMCs) are a variety of EAP, which bend in response to a relatively low activation voltage. The base polymer provides channels for the mobility of cations in a fixed polymer network of negative ions on interconnected clusters. Chemical electroding of polymer films is achieved by dispersing metal ions throughout the hydrophilic regions of the polymer surface, which are subsequently reduced to zero-valence metal atoms. An IPMC consists of a polymeric electrolyte sandwiched between two layers of thin metal. A field induced change in ion concentration, which attracts water molecules to one side of the polymer, results in deflection of the layered structure toward one of the metal electrodes. Nonuniform distribution of water produces swelling on one side of the actuator while the other side experiences contraction. IPMC does not produce linear actuation, only bending. Restoration of the initial external conditions returns the gel to its original volume. A milestone was reached in the field of EAPs in 2003 with the emergence of the first commercial product. This product is a fish robot, which is driven by an IPMC type EAP and energized via electromagnetic induction coils in the upper and lower sections of the water tank, which induce power onto a coil inside the fish. The fish robot and the water tank were developed by Eamex, Japan and manufactured by Daiichi Kogei, Japan. IPMCs are also showing potential as robotic grippers, as depicted in Fig. 5.[16]

3. Conductive polymers

Conductive polymers (CPs) such as polypyrrole and polyaniline are materials that swell in response to an applied voltage as a result of oxidation or reduction, depending on the polarity, causing insertion or expulsion of ions. Oxidation and reduction occur at the electrodes, inducing a considerable volume change due to the exchange of ions with an electrolyte. Dimensional changes occur primarily due to ion insertion. Electromechanical coupling of CPs is low (<1%), so without substantial input energy recovery, efficiency will also be low. This low coupling, however, is not unique to CPs and is characteristic of other ionic EAPs such as IPMCs and carbon nanotubes (NTs). Very high currents are required in order to operate at high power due to the low electromechanical coupling and low activation voltages. Polypyrrole and polyaniline are the most widely used CPs.

4. Carbon nanotubes

The carbon-carbon bond of NTs suspended in an electrolyte changes length as a result of charge injection, which affects the ionic charge balance between the NT and the electrolyte. Carbon NTs have the potential to provide superior work/cycle and mechanical stress. In addition, the carbon NTs offer high thermal stability at high temperatures (<1000 °C). However, despite these potential advantages, advancement of carbon NTs as an actuator technology has been somewhat hindered by the fact that they are expensive and difficult to mass produce, since fabrication does not always yield a pure sample.

Within the realm of EAP research, much of the focus has been on dielectric elastomers, which fall into the electronic EAP category. The greatest progress in EAP materials development has occurred in the last 15 years with dielectric elastomers (briefly introduced in Sec. II A 2) where effective materials that can induce over 300% strain have emerged.[17] Dielectric elastomer actuators combine high energy density with large displacements, low power consumption, and fast response time, making them very attractive for a wide variety of applications on both the macro- and microscale. The remainder of this paper will focus on dielectric elastomer actuators, their applications, and challenges.

III. ACTUATION MECHANISM AND CONFIGURATIONS

An electromechanical actuation mechanism is a physical process whereby a mechanical system is activated by electricity. Two mechanisms, electrostriction and Maxwell's stress effect, are considered prime contributors to the large electric-field-induced strain exhibited by electronic EAPs. The resulting stresses and strains relating to both mechanisms exhibit a quadratic dependence on an applied electric field. The strain response of an elastomer can be contributed by either one of them, as is the case of dielectric elastomers or both of them, as in polyurethane[18] and graft elastomers. An electromechanical response is the physical response (stress or strain for example) of a mechanical system to electrical stimulation.

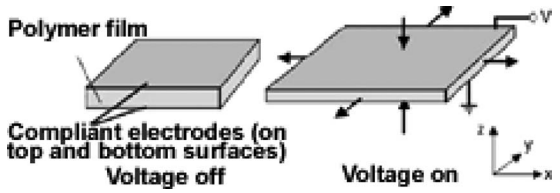

FIG. 6. The dielectric elastomers actuate by means of elecrostatic forces applied via compliant electrodes on the elastomer film (see Ref. 21).

A. Electrostriction

Electrostriction arises due to the change in dielectric properties of the material with strain, i.e., there is a direct coupling between electric polarization and mechanical strain response,[19]

$$S_{\text{electrostriction}} = -Q\varepsilon_o^2(\varepsilon_r - 1)^2 E^2. \quad (1)$$

Equation (1) relates $S_{\text{electrostriction}}$, the strain in the thickness direction of the film due to electrostriction to the electrostrictive coefficient Q the permittivity of free space ε_o, the relative permittivity ε_r, and the applied electric field E. The relative permittivity often referred to as the dielectric constant ε_r is given by the ratio of the permittivity of a material ε to the permittivity of a vacuum ε_o. In order for electrostriction to be present, the material must have some crystallinity in its structure. When the crystallites are converted to other crystallite types with different lattice forms, large macroscopic changes in dimension are observed. The likelihood of an electrostrictive effect being present is indicated by an increase in the dielectric constant of the material when prestrained. Electrostriction contributes largely to the electromechanical response of polyurethane, PVDF and its copolymers, and to a lesser degree in graft elastomers.

B. Maxwell stress effect

The Maxwell stress effect is a consequence of a change in electric field distribution inside the dielectric with strain and is solely responsible for the actuation of purely amorphous polymers. Alternatively this may be interpreted as Coulombic attraction between opposite charges on electrodes,[19]

$$S_{\text{Maxwell}} = -s\varepsilon_o\varepsilon_r E^2/2. \quad (2)$$

Equation (2) relates the strain in the thickness direction of the film S_{Maxwell} to the elastic compliance s, the permittivity of free space ε_o, the relative permittivity ε_r, and the electric field E. A study carried out by Ma *et al.* suggests that the field induced strain in acrylic elstomers is due primarily to the Maxwell stress effect, since experimental data closely fits the transverse strain response predicted by Maxwell stress induced strain.[20]

C. Principle of operation

By considering the case of a thin film dielectric elastomer, we can explain the principle of operation of dielectric elastomers, as shown in Fig. 6. A polymer is sandwiched between two compliant electrodes, which are in intimate contact with the polymer film. Applying a voltage difference

between the two electrodes causes compression in thickness and stretching in area of the polymer film. Closer consideration of the principle of operation of the dielectric elastomers unveils their advantage over conventional electrostatic air gap actuators. There are two modes of energy conversion involved in the actuation of dielectric elastomers, compared to just one with electrostatic air-gap actuators. In dielectric elastomer actuators, the electrodes expand in area in addition to coming closer together. Coming closer together converts electrical energy to mechanical energy by bringing opposite charges closer together. The second mode of conversion of electrical energy to mechanical energy lies in the stretching in area of the polymer film. This stretching in area separates like charges, thus reducing electrical energy. Compliant electrodes are the key to this second mode of energy conversion and thus electrostatic air-gap actuators do not experience this mode of conversion, which is due to stretching. Elastomeric materials have a Poisson's ratio of approximately 0.5 and thus dielectric elastomers can only change shape by maintaining a constant volume, consequently the two modes of energy conversion are directly coupled. Stretching in area is mechanically coupled to compression in thickness and vice versa. Thus it makes sense to consider, a single effective actuation pressure as derived by Pelrine *et al.*[21] This actuation pressure p is defined as

$$p = \varepsilon_o \varepsilon_r E^2 = \varepsilon_o \varepsilon_r (V/t)^2. \quad (3)$$

Equation (3) relates the actuation pressure p to the relative permittivity ε_r, the permittivity of free space ε_o, the electric field E, the applied voltage V, and the film thickness t.

D. Configurations

Deformation of dielectric elastomers can be configured in many ways to produce actuation. Dielectric elastomer actuators expand when electrically stimulated and may work in different modes and configurations. Electroded dielectric elastomer films may be stretched over a frame, rolled into a scroll,[22] formed into a tubular shape, or laminated on a flexible substrate to form unimorphs and bimorphs. A number of these configurations have been fabricated using dielectric elastomers and are shown in Fig. 7. Some of these configurations are not uncommon in piezoelectric applications. However, since elastomeric material is much softer, the amount of deformation is much greater allowing for a potentially greater variety of actuator configurations.[23]

Diaphragm actuators can exploit both directions of planar expansion of the film. Such actuators are finding applications as pumps, loudspeakers, in areas such as adaptive optics, controllable surface roughness for aerodynamics and refreshable Braille displays. Goulbourne *et al.* at Pennsylvania State University developed a nonlinear model for dielectric elastomer membranes with the view to potentially developing a cardiac pump.[24] The principle advantage of dielectric elastomer diaphragm actuators over their piezoelectric counterpart is their ability to produce relatively large displacement without sacrificing other performance parameters. Piezoelectrics have a much lower intrinsic strain compared to that of dielectric elastomers and consequently only very thin

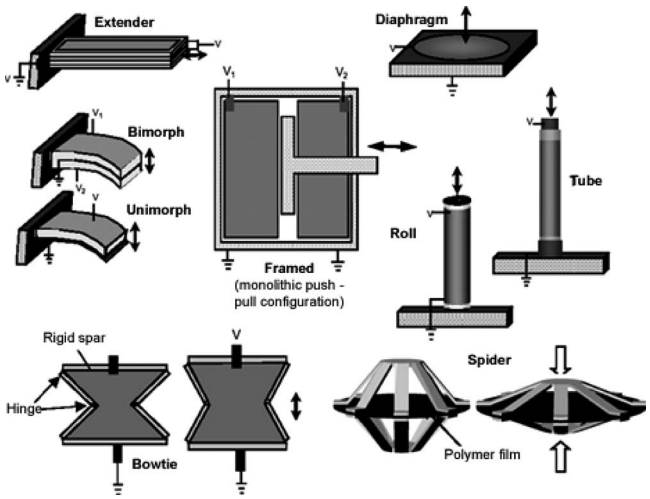

FIG. 7. Representative dielectric elastomer actuator configurations (see Ref. 23).

piezoelectric diaphragms could achieve the diaphragm motion possible with dielectric elastomers. Decreasing the thickness of the diaphragm film compromises parameters such as pumping pressure and packaging density.

Bow-tie actuators are linear actuators that have been used in robotic leg applications such as the self-contained hexapod robot.[25] Fabrication and deposition of electrodes is most easily carried out on single flat layers of film. However, a unique advantage of polymer actuators is their ability to be rolled to form linear roll actuators, thus squeezing a large single layer of film into a compact form. The main disadvantage of such an actuator is that only one direction of deformation is coupled to the load, so the energy coupling is not as effective as that of a bow-tie actuator. A more elaborate version of linear roll actuators developed by the SRI,[26] is the multifunctional elastomer roll (MER).[27] This configuration involves rolling a prestrained elastomer film, which has patterned electrodes around a central compression spring. Depending on the patterning of electrodes and the coordination and sequencing of their activation, 1-DOF (degree of freedom), 2-DOF, and 3-DOF MERs were fabricated. Figure 8 depicts the electrode pattern for a 2-DOF MER. These rolls are multifunctional because they combine axial extension, bending and position sensing. An actuator called ANTLA (antagonistically driven linear actuator) developed by Choi *et al.* also explores the concept of electrode patterning to achieve multiple degrees of freedom.[22]

Stacklike configurations derived from piezoelectric actuator approaches consist of several layers of dielectric elastomer, alternated by layers of electrode material, and the electrical shorting of two resulting series of electrodes. Such

FIG. 8. 2-DOF MER dielectric elastomer actuator. Patterned single film (left) and assembled device (right) (see Ref. 27).

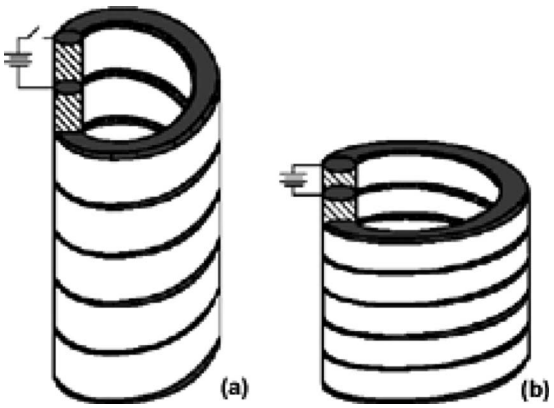

FIG. 9. Schematic drawing of the structure and actuation principle of the helical configuration. The actuator is represented in its rest condition (a) and under electrically activated axial contraction and radial expansion (b) (see Ref. 28).

configurations offer intrinsically linear contractile actuation, but the discontinuous nature of their structure makes fabrication techniques difficult. An alternative to this stacklike configuration saw the introduction of an electrically contractile monolithic actuator, realized by a helical dielectric elastomer actuator. This new configuration, designed by Carpi *et al.* at the University of Pisa comprises two helical compliant electrodes with an elastomeric insulator interposed between them, and achieved 5% contraction at a driving voltage of 14 V μm^{-1} at the prototype stage.[28] Helical actuators seen in Fig. 9 involve complex and time-consuming fabrication techniques.

In an attempt to overcome the fabrication complexity of the helical and stack actuator, the same group have developed a contractile folded dielectric elastomer actuator, which requires a simpler fabrication procedure, as depicted in Fig. 10.[29] Functionally equivalent to the stack actuator, the folded actuator is advantageously not discontinuous and can be assembled in one phase. At applied voltages of 10.75 V/μm, the folded actuator achieved axial strains of −10.5% and

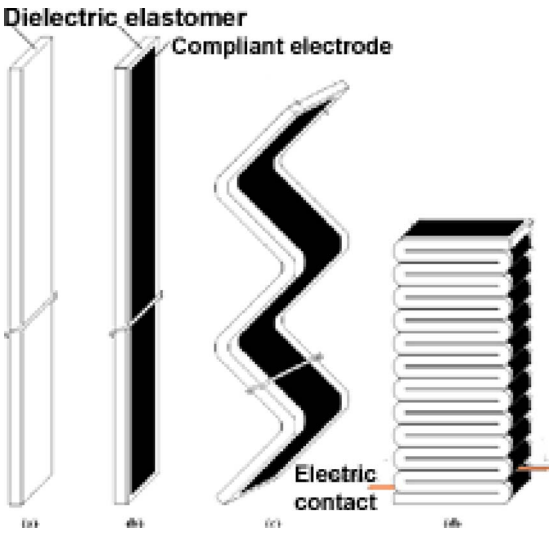

FIG. 10. (Color online) Steps to construct a folded dielectric elastomer actuator: (a) strip of elastomer, (b) strip with a couple of electrodes, (c) folding, and (d) assembled device (see Ref. 29).

axial stress of 3.75 kPa. A semiautomatic fabrication technique employing a custom laboratory-based folding machine is under development by this same group. These folded actuators are fabricated from a very soft commercial silicone (TC-5005 A/BC, BJB Enterprises Inc., U.S.A.), which has a number of advantages over the alternative acrylic material, as discussed in Sec. V C. The compliant electrodes used in the construction of this device are a silicone/carbon-black mixture. Suggested applications of such folded dielectric elastomers include hand splints for rehabilitation, lightweight flexible space structures, and a bidirectional tilter comprised of a couple of contractile folded actuators.

Unimorph and bimorph actuators are filmstrips, which are bending elements. A unimorph actuator consists of an active electrode, polymer film, and a ground electrode, forming a bilayer. Changing the polarity of the active electrode produces bending in the opposite direction. A bimorph actuator, however, is fabricated by stacking an active electrode, a polymer film, a ground electrode, a polymer film and a second active electrode constituting a trilayer. Appropriate application of voltage in a coordinated manner produces elongation in one film and contraction in the other resulting in a bending displacement. Unimorph and bimorph actuators have application potential in low force robotic grippers.

IV. APPLICATIONS OF DIELECTRIC ELASTOMER ACTUATORS

In a move to illustrate the potential of dielectric elastomer actuators, we take a look at some applications. Pelrine *et al.* at SRI configured four silicone bow-tie actuators (discussed in Sec. III D) to construct an insect-inspired flapping wing robot.[30] This mechanism was designed so that its optimum flapping frequency coincides with the resonance of its muscles, thus illustrating the importance of biological impedance matching. Further developments of this design could see applications in military exploration due to its potential to hover.

An application of the rolled actuator (discussed in Sec. III D) aside from its application in the development of a mechatronic muscle, is as an inchworm robot. The inchworm robot consists of a rolled dielectric elastomer actuator with electrostatic clamps at each end enabling it to negotiate vertical as well as horizontal surfaces. This idea of an inchworm robot is being studied by a number of research groups.[31] The main benefit of this inchworm robotic application is the illustration of how a musclelike actuator can operate without the rigid support of a skeleton, just as worms do in nature. This mechanism could see applications in narrow tube inspections, space exploration, and with miniaturization of the technology, surgical procedures. Rolled actuators have also seen applications as robot legs. MERbot, for example, a robot developed by Pei *et al.* at SRI has six rolled actuator legs.[27]

Stretched film actuators consisting of a polymer film stretched over a rigid frame have potential as an optical switch, where an opaque electrode area interrupts a light beam when actuated. Dielectric elastomer diaphragm actuators also have a number of potential applications. Diaphragms can be employed to control surface roughness, for

FIG. 11. (Color online) Flat foam-backed EAP loudspeaker (right) compared to a conventional electromagnetic moving-coil loudspeaker (left). The EAP loudspeaker is approximately 15 cm on a side (see Ref. 33).

example, in aerodynamics and refreshable Braille displays as demonstrated by Choi *et al.*[32] One obvious application of diaphragm actuators is the pump, where there is direct energetic coupling to an external load. A prosthetic blood pump is an exciting potential application of such diaphragm actuators being investigated by Gloubourne *et al.*[24] The ability to actuate diaphragm configurations at a higher frequency than that of the fluid pumps to pump air in the case of acoustic actuators serving as loudspeakers was realized by Heydt *et al.*, an example of which is shown in Fig. 11.[33] Dielectric elastomer loudspeakers offer the advantage of being lightweight, scalability to small and large areas, and the ability to conform to both flat and nonflat surfaces. Speakers constructed to date are merely proof of concept devices and have not been tested rigorously or commercialized.

Aschwanden and Stemmer from the Nanotechnology group of the Swiss Federal Institute of Technology have demonstrated a low-cost, electrically tunable diffraction grating based on soft dielectric elastomers, namely VHB 9460, an acrylic by 3M.[34] Until now, the state of the art in tunable diffraction gratings for telecommunications and display device applications relied on standard hard piezoelectric materials. Planar expansion of dielectric elastomers is used to induce change in the period of these tunable elastomeric diffraction gratings. A 50 μm thick acrylic film is prestretched and mounted on a frame. Carbon black electrodes are patterned onto the acrylic using a polydimethylsiloxane stamp. A mixture of Elastosil and heptane is spin coated onto a master grating, which is then placed onto the prestretched acrylic, placed in a vacuum to remove air bubbles, and cured. The master grating is then mechanically peeled away from the Elastosil film, which remains bonded to the dielectric elastomer. As a final step, a reflection enhancing gold layer is evaporated onto the elastomeric diffraction grating. This tunable diffraction grating can achieve a continuous grating period change of 19.2% with applied voltages of 500 V, an improvement by a factor of 90 compared with conventional, analog tunable diffraction gratings based on hard materials. In addition this dielectric elastomer based device achieved a tunable angular range exceeding 100 mrad. This group also demonstrated that the tunable diffraction grating, combined with a collimated white light source, could be used for wavelength-adjustable luminous sources. Lowering the driving voltage of these devices would enable their integration into displays and potentially make possible the first technology to reproduce all perceivable colors.

Artificial Muscle Inc. (AMI) have made great progress in the commercialization of dielectric elastomer actuator technologies. The universal muscle actuator (UMA) was named "Actuator Technology Product of the Year" by Frost and Sullivan in 2006. As the world's first standard EAP actuator, the UMA utilizes a patented diaphragm cartridge configuration of AMI's patented EAP artificial muscle (EPAM) technology and provides an actuator platform, which can be utilized for a broad range of applications. The most recent product to emerge from AMI is a DLP-95 auto focus lens positioner. AMI's EPAM technology revolutionizes lens positioning for small form-factor lenses and offers a potentially more compact alternative to traditional voice-coil and stepper motor technologies for camera modules.

V. TECHNOLOGICAL CHALLENGES

A. Compliant electrodes

Compliant electrodes are key to the development of EAP technology because they maintain uniform contact over the entire active region of the elastomer. The word compliant indicates the ability of a thin conducting electrode to deform with the elastomer without generating an opposing stress or losing conductivity. In simple terms, the electrode will stretch with the elastomer. A study carried out by Kofod outlines a number of approaches to compliant electrodes in the area of dielectric elastomers.[8] The approaches considered include carbon black, grease electrodes, rubber electrodes, dust electrodes, and glue electrodes. The main drawback of grease electrodes is that it is messy to handle. Rubber electrodes can be used, but their elastic modulus must be closely matched to the actuator material to prevent impeding of actuator performance. Dust electrodes are feasible when applied to adhesive films such as VHB 4910 from 3M. The conducting grease electrode proved most successful. There was no reported migration of electrode material with actuator strains below 50%. Only above 100% actuator strain was visible migration observed, where the grease aggregated in small cylinders perpendicular to the direction of actuator strain. An extensive study carried out by Carpi and De Rossi between two collaborating institutes in Pisa, Italy on an acrylic elastomer VHB 4910 by 3M, concluded that the electromechanical performance of dielectric elastomers is largely dependent on the electrode material and the prestress value (discussed in Sec. V B).[35] This paper investigated thickened electrolyte solution, graphite spray, carbon grease, and graphite powder electrodes. This study presents data from which one can select the most suitable electrode material and prestress in order to achieve optimum stress, strain, and efficiency for a given electric field. Thickened electrolyte solution electrodes proved best for most purposes for electric fields up to 20–25 V/μm, above which graphite spray electrodes were generally optimal. This study suggests that not only does the electomechanical performance depend on the electrode material, but that the suitability of electrode material is also dependant on the electric field range. In the earlier days of dielectric elastomer development, carbon grease was the electrode material of choice and is still used today in laboratories for proof of concept actuator configurations and

experiments. The messy nature of carbon grease and its uniformity problems have driven researchers to investigate more sophisticated alternatives.

An approach to compliant electrodes taken by Pei *et al.* at SRI International, in their development of multifunctional elastomer rolls, using a proprietary formula of compliant carbon paint has proved successful in a number of commercially available products.[27] A paper by Pelrine *et al.* reported the recent progress on the fabrication of highly compliant electrodes, which take the form of a zig-zag pattern of gold traces on silicone.[6] A common approach today in electrode design is carbon filled silicones, particularly in the case of silicone dielectric elastomer actuators, as seen in the work of Carpi *et al.* and his folded dielectric elastomer actuator as discussed in Sec. III D.[29] The most recent development in the design of compliant electrodes presented by Yuan *et al.* uses single wall carbon NTs.[36] This work was inspired by the need to reduce the gap between the strength of the intrinsic material and the strength of large area actuators by electrically isolating faults in the dielectric. When a defect develops in the actuator, the electrode in that area becomes nonconductive due to degradation of the carbon NTs in the region of the defect. The most exciting advantage of this electrode approach is the electrode's ability to self-clear thereby making dielectric elastomers more fault tolerant. With an applied voltage of 9.2 kV, the carbon grease on silicone actuator achieved 33.7% strain, and eventually the film catches fire with a breakdown field of 230 $V/\mu m$. In the case of the carbon NT on silicone actuator, a strain of 36% was achieved for a 10 kV applied voltage, and with a field of 255 $V/\mu m$ the film did not fail. In the case of the carbon NT on silicone actuator, clearing was happening at this field level as evident from observed pinholes and current spikes.

B. Driving voltages

One of the major challenges in the development of dielectric elastomer actuators is the high electric field requirement. Driving voltages up to 150 $V/\mu m$ are required to actuate these elastomer films. This high electric field requirement is being addressed in a number of ways. A comprehensive study carried out by Zhang *et al.*, a group at the Swiss Federal Laboratories, investigated the effect of crosslinking, prestrain, and dielectric filler in silicone.[37] The silicone investigated was DC3481 from Suter-Kunststoffe (Jegenstorf, Switzerland). A number of hardeners from the same company were added to this silicone. It was found that the Young's modulus increased and the dielectric constant decreased with increasing hardener concentration. In general, it is observed that an increase in Young's modulus results in a decrease in actuation strain, while an increase in dielectric constant results in an increase in actuation strain. This study concluded that it is the ratio ε/Y, which is the important parameter in determining the strain response. The silicone, which had the highest dielectric constant but the lowest Young's modulus thus giving the highest ε/Y ratio, exhibited the highest strain response. Also different hardeners exhibited different strain responses, thus opening up an area for further research.

Dielectric fillers increase the dielectric constant so that the required field for a certain strain can be reduced. Again Zhang *et al.* reported an increase in dielectric constant from 3.27 for pure silicone to 5.85 for silicone with 20% copper-phthalocyanine oligomer (CPO).[37] This increase in dielectric constant translated to a field decrease from 32 $V/\mu m$ (hardened silicone without filler) to 25 $V/\mu m$ (hardened silicone blended with 20% CPO) for 10% strain. It was observed however that blending also causes a decrease in breakdown field and therefore limits the blended silicone strain response.

Prestraining elastomer films serves to thin the film and thus increase the breakdown field and also removes the boundary constraints of the inactive region. However it is generally agreed that high prestrain results in a lower actuator strain response. The reason prestraining results in a lower actuator strain response remains an issue for debate. A study conducted on silicones by Zhang *et al.* attributed the lower strain response to an increase in Young's modulus, considering the strain for a certain electric field.[37]

A study carried out by Choi *et al.* however, examined more specifically the effect of prestrain on the elastic modulus of acrylic elastomers from 3M.[38] By comparing a two-stage tensile test with a continuous tensile test, it was observed that there was no change in the elastic modulus due to prestrain regardless of the load, and it was suggested that this would indicate that prestrain does not contribute to the elastic modulus of the material. This observation is not in agreement with tests carried out by other groups such as Zhang *et al.* and Kornbluh *et al.*, discussed in the following paragraph.[37,39] In order to explain the decrease in actuation strain, Choi *et al.* looked to the dielectric constant. They presented results, which show a decrease in dielectric constant with increasing prestrain, and attribute this decrease to a corresponding decrease in actuator strain. Other groups observe this effect but consider it a nonsignificant contributing factor in the observed lower actuator performance with increased prestrain.[17] This observed effect requires further investigation, but is likely to be largely material dependent, with prestrain having a different effect on dielectric constant for silicones as opposed to acrylics, etc.

However high prestrain causes the material to become stiffer with an increase in Young's modulus resulting in a lower strain response, considering the strain for a certain electric field. This phenomenon was demonstrated by Zhang *et al.* for silicones[37] and by R. Kornbluh *et al.* for acrylics.[39] This observation contradicts observations presented by Choi *et al.*[39] Application of prestrain can be biaxial or uniaxial and this in itself affects the actuation performance. In the case of biaxial prestrain, the resultant actuation strain is equal in both directions. In the case of uniaxial prestrain however, this creates an anisotropic local elastic modulus and thus the actuator actuates primarily in the direction of less prestrain. Anisotropic prestrain is often combined with geometric constraints to produce actuation almost exclusively in one direc-

tion. The mechanism whereby breakdown field increases with prestrain is interesting but is not yet fully understood and thus requires further study.

C. Choice of elastomer material

To date, much of the research has been centered around two dielectric elastomer materials, acrylic (VHB 4910 from 3 M) and polydimethylsiloxane (CF 19–2186 from NuSil), which are showing great potential, particularly in relation to strain response. Other silicones being researched include Dow Cornig HS3 silicone,[6] and a very soft commercial silicone TC-5005 A/BC (BJB Enterprises Inc., USA).[29] 3M VHB 4910 is a pressure sensitive adhesive elastomeric film, which has been a candidate dielectric elastomer material for numerous research projects.[1,8,17,40] This material is available as a precast 1 mm thick adhesive on a liner. It is extremely compliant, stretching up to 36 times in area before breaking. This acrylic elastomer is made of a mixture of aliphatic acrylate, photocured during film processing. Its elasticity results from the combination of soft, branched aliphatic groups and the light cross-linking of the acrylic polymer chains.[4,17] The handling of this material is easier than that of silicone since, the film itself, as a double-sided adhesive tape provides gluing, such that electrodes are easy to apply and maintain good contact with the elastomer. While acrylic elastomer is a powerful material with regard to its strain response, silicone has a faster response time due to the higher viscoelastic losses in acrylic. Zhang *et al.* presented a new class of silicone elastomer which compared to acrylic elastomers. It has the advantage of a constant stiffness over a wide range of temperature and a lower viscosity resulting in a higher response speed of actuation.[37] This new silicone elastomer was produced by changing type and concentration of hardener and blending silicone with organic materials. A decrease in strain amplitude is observed with increase in operation frequency for acrylic elastomers. High actuator efficiency is a further advantage of silicone over acrylics arising from its lower viscosity. Actuator design using acrylic elastomer is potentially impractical due to their large variation in temperature. silicones however do not show this disadvantageous temperature dependence with elasticity remaining constant over a wide temperature range.

VI. FUTURE DEVELOPMENTS AND CONCLUSIONS

The further development of dielectric elastomers as a viable actuator technology requires much work, and to this end numerous exciting challenges lie ahead. First the development of improved elastomer EAPs is essential. Continued research into the effect of different hardener types and concentrations on actuator performance and also the incorporation of dielectric fillers could lead to the simultaneous enhancement of actuation force and the reduction of operating voltage, without losing too much of the mechanical deformation. Such improvements would serve to broaden application spectrum of these types of actuators. For example, significant reduction of operating voltage could enable applications in the biomedical field, and improved actuation forces could see the replacement of heavy motors with lighter elastomer actuators. More sophisticated compliant electrodes, which are highly elastic, have extremely low modulus and are conductive, which can be firmly attached to the dielectric elastomer, are required. From the modeling view point, much work is required to accurately model the behavior of dielectric elastomers by coupling both electrical and mechanical behavior to accelerate the development of new improved actuators. Suitable control parameters must be identified and control systems developed in order for dielectric elastomers to effectively replace existing actuator technologies.

EAPs and in particular dielectric elastomers were reviewed in this paper as exciting candidate materials for the development of a new age of actuator material. The principle of operation of these actuator materials was presented. The advantage of dielectric elastomers over conventional actuator technologies in a number of metrics, in addition to some of the unique characteristics, which they can offer, were discussed. Dielectric elastomers were examined at both the material and the actuator configuration level. Important material parameters, both mechanical and electrical, are highlighted and various approaches to optimize these properties for the development of superior actuators were addressed. Such approaches included the incorporation of dielectric fillers and prestraining of the material. From the discussion on compliant electrodes, it is concluded that the choice of electrode is both material and configuration dependent. Continued research into the development of more sophisticated compliant electrodes is essential in the further development of dielectric elastomer actuator technology as a whole. While there are a number of compliant electrode options which work quite well, further research into compliant electrode printing, for example, could be useful in the area of microactuator applications. A host of existing and potential applications were presented, and finally the challenges facing the dielectric elastomer actuator technology community in the future were discussed. In conclusion, dielectric elastomer actuators have been studied extensively under laboratory conditions where they have shown promising performance. However in practical applications, they have not yet achieved their full potential.

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