Review of dielectric elastomers for actuators, generators and sensors

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Abstract: Electroactive polymer (EAP) is a kind of smart material, which can change its shape under the stimulation of electric field. Dielectric elastomer (DE) is an important member of the EAP. DE has the characteristics of excellent performance, such as light weight, low noise, low cost, and so on, which guarantee its wide applications in the fields of actuators, generators, sensors. In this review, the principles of energy conversion, the research status and latest development of new technologies for DEs, and the performance characteristics of DEs are summarised. Simultaneously, it points out the development problems and feasible countermeasures. At last, the application prospects of DE are discussed, combined with the research direction of the international frontier.

1 Introduction

In 1775, the French scientist Nicolas-Phillipe Ledru observed the rise and fall of mercury within glass tubes upon electrification, an early investigation on electrically induced deformations of insulators [1]. Next year, in a letter the Italian scientist Alessandro Volt mentioned that the researcher Felice Fontana observed deformation of the Leyden jar during the charge and discharge experiment process, which opened up more than two centuries of exploration and research on electroactive materials. Since early studies on flexible dielectric materials are extremely few, and the responsive strain under the effect of electric field is very small, for a long time, ‘electro-strain’ was only considered as an ancillary phenomenon. Even in some application areas, it is necessary to avoid ‘electro-strain’.

In the 1990s, with the development of polymer materials, the emergence of electroactive polymers (EAPs) made industrial applications of the ‘electro-strain’ phenomenon possible. Since then, various types of EAP have sprung up like mushrooms. According to the different driving mechanisms, they can be divided into two types: ion-type EAP driven by ion-diffusion and electronic EAP driven by Coulomb force [2]. The representative materials of the ion-type EAPs include polymer gels, ionomer-metal composites, conductive polymers, and electroactive carbon-based materials [3–5] and the electronic EAPs include piezoelectric materials, electrostrictive materials, ferroelectric polymers, liquid crystal elastomers, and dielectric elastomers (DE) [6–9].

As a new type of EAP material, the DE can generate a large strain (about 50–380%) at a moderate stress level by applying an electric field. The DEs have a wide range of energy density ranging from 0.01 to 3 MJ/m3, which can generate a responsive deformation at the electric field strength range of 70–400 V/μm [10]. Among a large number of EAP materials, the DE is attracting more attention due to its excellent performance-low cost, simple manufacturing, light weight, and high electromechanical coupling efficiency (about 90%). Many researchers have attempted to design some valuable devices based on DEs, such as DE actuators (DEA) [11], DE generators (DEG) [12], DE sensors (DES) [13], and carried out relevant experimental researches [14–16]. The rapid development of a new generation of flexible electronic devices puts forward higher requirements on the working performance of DEs.

2 Energy conversion principles of DEs

2.1 Energy conversion principle of DEA

The ‘electro-strain’ of the EAP material is a result of the synergistic effect of the electrostrictive effect and the Maxwell stress [17–19]. The electrostrictive effect is caused by the electrical polarisation of dielectrics under the electric field and is related to the coupling relationship between polarisation and material strain, which is more apparent in piezoelectric crystals and ferroelectric materials. Maxwell stress is the stress caused by the free-charge Coulomb interaction of plates, which is the main cause of the ‘electro-strain’ of the amorphous polymer [15, 20]. Generally, DES are amorphous polymers, so the Maxwell stress effect is their main driving mechanism, which is also the difference between the DEs and other electrostrictive polymers [21].

As shown in Fig. 1a, the DE film is coated with compliant electrodes on the upper and lower surfaces. After the voltage is applied between the electrodes, the unlike charges distribute on both sides of the DE film, which is just like a charged capacitor. The plane-parallel capacitor model is used to illuminate the conversion between electrical energy and mechanical energy through DEs. Generally, the volume of DEs is incompressible, so the electrostatic force causes its shape change in the direction of thickness much more readily than volume. The compliant electrodes allow the DE films compress in thickness and stretch in area due to the attraction between unlike charges and the repelling force between like charges. Due to the combined effect of the two models, the DE actuators can convert energy more efficiently from electric energy into mechanical energy.

Derivation of the electrostatic model is described by Peirine, Kornbluh, and Joseph [22]. The actuation pressure, p, is given by

\[ p = \varepsilon_0 \varepsilon_r E^2 = \varepsilon_0 \varepsilon_r (U/d)^2 \]  

(1)

where \( E \) is the electric field, \( U \) is the voltage, \( \varepsilon_0 \) is the permittivity of free space, \( \varepsilon_r \) is the dielectric constant, and \( d \) is the thickness of DE.

Then the thickness strain of DE film is given as

\[ s_t = -p/Y = -\varepsilon_0 \varepsilon_r E^2/Y \]  

(2)

where \( Y \) is the Young's modulus of DE.
increases with the increasing thickness of the DE film and the force. Secondly, the charge is injected into the DE film through the capacitor, an elastomer film sandwiched by flexible electrodes, which illustrates that the mechanical energy would be transferred into electric energy. During this process, the electrical energy is transformed into electric field force to finally convert the mechanical energy into electrical energy gain after the DE material relaxed, as shown in Fig. 1.

In generator mode, the input of mechanical energy (generally distance of like charges decreases with the decreasing of the thickness of the DE film and the distance of like charges decreases with the decreasing of the surface area of the DE film. Under the condition of constant charge, the voltage increase on the surface of the DE increases. This stage can also be understood as the process of elastic stress resisting the electric field force to finally convert the mechanical energy into electric energy. During this process, the electrical energy is collected and the DE film is restored to its original relaxed state. Repeating the process above can continuously generate power, which illustrates that the mechanical energy would be transformed into power energy.

As the typical equivalent circuit model of DEGs is the capacitor, an elastomer film sandwiched by flexible electrodes, the basic energy transformation principle of DEs is based on the electrical energy \(W\) stored in capacitors [22], given by

\[
W = \frac{1}{2}CU^2 = \frac{1}{2}\varepsilon_0\varepsilon_r Au^2/d
\]

where \(C\) is the capacitance, \(U\) is the voltage of the capacitor, \(\varepsilon_0\) is the vacuum permittivity, \(\varepsilon_r\) is the relative permittivity of materials, \(a\) and \(d\) are the area and thickness of the film, respectively.

Then the electricity generated by DE film can be expressed as

\[
\Delta W = W_2 - W_1 = \frac{1}{2}C_1U_1^2 - \frac{1}{2}C_2U_2^2
\]

where \(\Delta W\) is the garnered electrical energy, \(W_1\) and \(W_2\) are the electrical energy stored in the capacitor before and after relaxed of the stretched DE film, \(C_1\) and \(C_2\) are the capacitance at the two states above, \(U_1\) and \(U_2\) are the voltage of the capacitor before and after relaxed of the stretched DE film, respectively.

Considering the constant charges \(Q\) of the capacitor and the constant volume \(V\) of the DE film

\[
Q = CU = C_1U_1 = C_2U_2
\]

\[
V = Sd_1 = Sd_2
\]

Then

\[
\Delta W = \frac{1}{2}C_1U_1^2(d_1^2/d_2^2 - 1) = W(\lambda^2 - 1)
\]

where \(\lambda\) is the strain ratio of thickness, meaning the degree of membrane deformation. From (7), it is apparent that the garnered electrical energy is proportional to the electrical energy after charged and the square of thickness strain ratio.

### 3 Structure-property relationship of dielectric elastomers

#### 3.1 Dielectric elastomers

During the few decades from the 1990s to the present, a number of materials were tested as DEs, including silicones, polyurethanes (PUs), acrylates, styrene-ethylene-butylène-styrene, fluoroelastomers, and nature rubber [12, 21, 24–34]. Among all of the materials, the silicones, PUs, and acrylates are identified to be particularly promising. Although their actuation performance is promising, it is not until more than 100% of actuated area strain of acrylic elastomers and silicone films is reported that the scientific community pays attention to this field [21, 35]. The key to this milestone is the pre-strain process on DEs. It is generally believed that the influence of pre-strain on the driving performance of DEs includes two points: firstly the pre-strain makes the DE film thinner in the thickness direction, large electric field strength can be obtained by applying only a low electric voltage; in addition, the molecular chains of the pre-strained DEs orient in a certain direction so as to limit the passage of carriers and improve the voltage resistance of the material [17, 36–39].

Silicones are a class of semi-inorganic polymers, namely polysiloxane which has a long chain with a basic unit of Si–O bonds and two hydrocarbon groups. The most widely used silicone rubber is polydimethylsiloxane (PDMS). According to the different cross-linkers, the PDMS can be divided into addition PDMS and condensation PDMS. Fig. 2 shows the preparation of condensation PDMS [40]. As the main chain of silicone rubber is made from Si–O bond with long bond length, the molecular chain is relatively flexible and has weak intermolecular forces, which makes silicone rubber has a series of excellent properties: a wide operating temperature range of −120 to 300°C, high conversion efficiency due to small viscosity loss, fast response rate, and long life span [20, 41, 42].

PU is a typical block copolymer, a complex chemical structure composed of diisocyanate, a variety of alcohols, as shown in Fig. 3 [42, 43]. Due to the large number of polar urethane groups, the dielectric constant of PU can reach about 7, which allows them to be actuated at low electric field. However, the presence of a large number of polar groups can also result in poor insulation characteristic and a low breakdown strength, simultaneously.
3.2 Improvement of dielectric elastomers

Elastomer material has its advantages, but there are also disadvantages that limit its practical application. Therefore, the improvement of the performance on elastomer materials is a research focus in this field. According to the energy conversion principle, the main parameters affecting the energy conversion performance include both experimental factors such as the charging voltage, and the thickness of the DE film, and inherent properties of the DE such as permittivity and elastic modulus [22]. Hence, from the perspective of improving the inherent properties of the material, increasing the dielectric constant and/or reducing the elastic modulus of the elastomer are effective methods to improve the electromechanical conversion performance. Generally, there are three approaches in present researches: elastomer composites, elastomer blends, and chemical modification of the elastomer backbone.

3.2.1 Silicone elastomers: Silicones are a kind of non-polar rubbers, compared with the other two types of DEs, so the dielectric constant of silicones is about 2–3, which is really small. Thus, silicone materials have lower energy density, require a large driving voltage to work, and have no advantage in breakdown strength. In recent years, in order to improve the dielectric properties of silicone rubber, a large number of related research efforts have focused on increasing the dielectric constant of silicones.

Adding the ceramic fillers with high dielectric constant to the matrix is a common and simple method to increase the dielectric constant of the elastomer. The common fillers include copper calcium titanate (CaCu$_3$Ti$_4$O$_{12}$) [46, 47], barium titanate (BaTiO$_3$) [26, 48–53], titanium dioxide (TiO$_2$) [33, 54–58], and so on. The addition of rigid particles with high dielectric constant leads to a significant increase in the dielectric constant of silicone rubber, while the modulus of silicone rubber also increases and the breakdown strength decreases simultaneously. Zhao et al. [56] have modified the silicone rubber by adding TiO$_2$ as high dielectric constant fillers and dimethyl silicone oil (DMSO) as plasticisers, and prepared high dielectric permittivity and low modulus silicone rubber composites. The swelling effect of DMSO makes the modulus of silicone rubber/TiO$_2$ composite significantly decrease from 820 to 95 kPa. Although the dielectric constant is also decreased, the modulus decrease is more significant. Thus, the ratio of the dielectric constant to the elastic modulus ($\varepsilon_r/Y$) of the silicone composite, commonly referred to as actuation coefficient ($\beta = \varepsilon_r/Y$) is increased.

Although the addition of rigid particle fillers can remarkably improve the dielectric constant of silicone rubber, the breakdown strength of the composite decreases due to the poor compatibility of the rigid particles with the matrix resulting in many defects. Therefore, organic conductive polymers acting as high dielectric constant fillers have been used to increase the dielectric constant of the silicone elastomers. Molberg et al. [59] wrapped the conductive polyaniline (PANI) into the insulating polymer and then added them to the PDMS matrix as a high dielectric constant filler. The dielectric constant of PDMS composites with 31.7 vol% PANI is about three times higher than that of pure PDMS. The breakdown strength of the composite was maintained at a level of 50 kV/mm equivalent to that of the pure PDMS due to the protection of the insulating layer. The addition of PANI significantly increased the elongation at break of the composites, due to enhanced fracture toughness, allowing them to bear a large pre-strain in applications.

By physically blending fillers with silicone rubber, the dielectric constant has been improved, while the application of the silicone rubber composite is limited by the poor compatibility of filler and matrix. Hence, researchers hope to improve the performance of silicone rubber by molecular modification. Kofod et al. [60] prepared vinyl-functional push–pull dipole (N-allyl-N-methyl-p-nitroaniline), which is a class of organic molecules with great polarity. As shown in Fig. 5, the vinyl-functionalised dipole react with vinyl-terminated PDMS chains by photo-curing method to produce silicone rubber with a high dielectric constant. The result of DSC measurements showed that the crystalline peak of silicone rubber did not obviously shift, so the introduction of organic dipoles does not affect the operating temperature range. Generally, the fillers with high dielectric constant can easily increase the dielectric constant of the matrix, while increase the modulus at the same time. However, in this work, the addition of organic dipoles increases the dielectric constant and simultaneously decreases the elastic modulus of the silicone rubber. Finally, the actuation coefficient of the silicone rubber is increased by six times than pure PDMS.

3.2.2 PU elastomers: Unlike traditionally chemically cross-linked elastomers, in addition to the chemical cross-linking of the soft segments between macromolecules, the PU also contains physical cross-links composed of large amounts of glassy crystalline regions. This complex network structure makes the Young’s modulus of PU very high, thus the PU cannot be drastically pre-stretched, which limits its further development. In recent years, scientists have done a lot of research and made some progress in order to solve these problems.

Wang et al. [61] used the copper phthalocyanine as filler, and prepared PU composites by chemical bonding method. The microstructure of the composites was observed by transmission electron microscopy, which proved that the copper phthalocyanine has a small scale in the matrix due to the chemical bonding method. When the dosage of the copper phthalocyanine is 8.78 vol%, the dielectric constant of the composite reaches as high as 391 at 100 Hz, the actuated strain of the composite at the field strength of 10 V/mm is 17.7\%, and the dielectric loss is 0.19, which is much better than the pure PU material.

Tian et al. [62] prepared thermoplastic PU (TPU)/polyethylene glycol (PEG) composites by solution blending method, as shown in Fig. 6. According to the results of Fourier transform infrared
spectrometer (FTIR) test, the addition of PEG oligomers destroyed the hydrogen bonds between the molecular chains of TPU, so that the polarity of the TPU molecular chain increased. The combined effect of the ionic conductivity of the PEG oligomer and the polarity of the TPU molecular chains increases the dielectric constant of the composites. Due to the plasticisation of PEG, the elastic modulus of the composites decreased simultaneously. The increase of dielectric constant and the decrease of the elastic modulus make the actuated strain of the composites increase by 7.5 times compared with the pure TPU at the electric field 3 kV/mm. While the ionic conductivity of PEG also makes the electrical insulation properties of the composites deteriorate, the breakdown strength significantly reduced with the addition of PEG. Renard et al. [63] did similar work using azobenzene, a strong polar oligomer as fillers to prepare azobenzene/TPU composites by the solution blending method. FTIR results showed that azobenzene molecules could interact with the hard segment of the PU molecular chains through the hydrogen bond. 3.2.3 Acrylate elastomers: Although the dielectric properties of acrylic materials are excellent, there are two main problems that limit their application. The first one is that only under the large pre-strain station, the acrylic materials present excellent dielectric properties, such as large deformation, high breakdown strength, and so on. However, the large pre-strain will bring many practical problems, such as stress relaxation, equipment complexity, and so on [28, 64–67]. The second one is that the viscoelastic property of acrylates results in the low electromechanical speed response, and the low electromechanical conversion efficiency [68]. In addition, compared with silicone rubber, acrylic materials have poor adaptability to the environment [18, 41, 69]. In order to solve the above problems, researchers have done a great deal of work as depicted below.

Fig. 6 Schematic representation of the microstructure of TPU/PEG blends [62]

Fig. 7 Schematic diagram of the fabrication process of an IPN DE film [71]

Ha et al. and Zhang et al. [70–72] modified 3M VHB acrylate elastomers by constructing an interpenetrating network (IPN) structure. The process of preparing IPN network structure is shown in Fig. 7. The VHB acrylate elastomers were firstly biaxially stretched and then soaked in 1,6-hexanediol diacrylate [70]. The 1,6-hexanediol diacrylate was cured by heat curing method to crosslink into a rigid second network. With the removal of external forces, the VHB network retains some pre-strain due to the support of the rigid second network. As the amount of 1,6-hexanediol diacrylate increases, the amount of retained pre-strain in VHB network increases. However, the over-dose of 1, 6-hexanediol diacrylate leads to a sharp increase in the modulus of the IPN-VHB elastomer during macro-deformation. When the content of 1,6-hexanediol diacrylate was 18.3 wt%, the preserved pre-strain of VHB 4910 network was 275% and the driving area strain of IPN-VHB 4910 film was as high as 233%, which is comparable to the 215% strain previously reported for VHB 4910 films with a 540% by 75% prestrain [21].

IPN structure has greatly improved the driving deformation of acrylate elastomer, while the temperature is still a major factor affecting its performance. When the temperature is close to or lower than the glass transition temperature of the acrylate elastomer, the molecular chains will be ‘frozen’. In response to this problem, Pei et al. [72] proposed an effective method by adding plasticisers to the IPN. They chose VHB 4910 acrylic elastomer and trimethylolpropane trimethacrylate (TMPTMA) monomer to prepare the IPN structure, using bis(2-ethylhexyl)phthalate (DOP) and dibutoxyethoxethyl formal (DBEF) as plasticisers. Due to the good compatibility of DBEF with the matrix and its own low viscosity, the driving performance of the modified IPN films is even more excellent than that of IPN films with DOP. The driving strain of the IPN film plasticised with 40 wt% DBEF be as high as 215% at −40°C and a voltage of 6.5 kV, whereas pure IPN film shows no deformation under the same condition. Therefore, the addition of DBEF broadens the operating temperature range of the IPN acrylic elastomer.

Hu et al. [73] prepared Al-acrylate nanocomposites by the bulk copolymerisation of acrylate-based modification of aluminium nanoparticles and acrylic monomers. The composite prepared from unmodified aluminium nanoparticles and acrylic monomer was used as a control sample. Scanning electron microscopy results showed that the modified aluminium nanoparticles could be uniformly dispersed in the acrylate matrix, while the aluminium nanoparticles had a serious agglomeration phenomenon in the control sample. The breakdown strength of Al-acrylate nanocomposites can reach as high as 140 kV/mm. Due to the addition of aluminium nanoparticles, the dielectric constant of composites increases obviously, and the highest value is up to 8.5. The high dielectric constant and high breakdown strength make the composite film have a large driving area strain of 56% and an expected high energy density, the theoretical value of 0.23 MJ/m. In Table 1, the properties of some DE materials discussed above are summarised.

4 Applications of DEs

4.1 Flexible actuators

DEs have large deformation and good flexibility, which allow them to be manufactured into flexible actuators, such as diamond drivers, cylindrical drivers, folding drivers, and tapered drivers [16, 31, 74–80], as shown in Fig. 8. Li et al. [81] created a bionic robot that can move quickly. The fabrication of the basic movement unit is inspired by the swimming stroke of the manta rays, which is by tapping the wide flippers up and down to achieve the water forward, and using the caudal fin to control direction. The basic structure and movement of the process is shown in Fig. 9. The DE material of the robot's actuation section is a bionic (3M VHB), and the DE materials of mechanical sections (fin limps and caudal fin) to achieve water-drawing, and the entire water-impermeable encapsulant are silicone rubber. The conductive ion gel is wrapped in the middle of the VHB as a flexible electrode, and the most innovative part is another flexible electrode: the surrounding water.

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Jun et al. [10] made a DEA for surface wettability control based on the electro-mechanical instability (EMI) phenomenon, which usually indicates that the DE material is inoperative. The wettability of material surface can be adjusted effectively by controlling the wrinkling degree of the material surface under the condition of EMI. In this work, VHB 4905 is selected as the main DE material, and flexible carbon black is used as the electrode. The fabrication process is shown in Fig. 10. The surface of the DE material wrinkled after pre-stretch relaxation. By adjusting the voltage value, the deformation level of the material can be controlled, thereby adjusting its wettability. This application can be used to produce materials with special surface hydrophobicity requirements.

### 4.2 Soft generators

As we know, the mechanical energy and the electrical energy can be converted to each other by DEs, so the DE can also be used to generate electricity. Soft generator based on the DE is also a research hotspot. In the past few years, DEGs have not only been achieved in laboratory, but also been tested in actual environment. Indeed, DEs have been demonstrated to harvest energy ranging from human walking, ocean waves, flowing water, and blowing wind [82–90].

Kaltseis et al. [91] have developed an experiment to monitor energy flows in DEGs and measure energy generation and efficiency of DEGs. A dielectric membrane of VHB 4910 in inflatable structure, coated with carbon grease as compliant electrodes shows an energy generated density of 102 mJ/g per cycle with electrical mechanical energy conversion efficiency of 7.5%. Jean-Mistral et al. [92] designed a generator located on the keen to harvest 0.1 mJ per cycle at 1 Hz from the human motion, enough to supply a low consumption system. Kornbluh et al. [93] prepared a buoy-type wave energy harvesting device. The schematic and physical figures are shown in Fig. 11. When the device floats on the sea, the disc-shaped DE units are actuated by the fluctuation of waves, and directly transform the wave energy into electric energy. In laboratory environment, the device can output 25 J of energy per unit cycle, while the unit mass is only 220 g and the energy density exceeds 0.1 J/g. While to avoid accidental failure in actual sea areas, the bias voltage is reduced to a more conservative level. The energy density is only half of the laboratory value, but the actual test results show that the energy capture efficiency reached 78%, which is considerable value for the application of power generation.

With the technological innovation of microprocessors, the power consumption of various types of portable electronic products has been relatively small, so it is entirely possible to supply power by human body energy. The human body energy has the characteristics of no cost, stability, and greenness. The Stanford Institute (SRI) of the United States developed a heel generator that, as shown in Fig. 12, has a multi-layered DE membrane at the heel that allows continuous power generation using the impact of a heel while walking [82]. The kind of shoes can output the energy of 0.8 J per step.

### 4.3 Ductile sensors

The principle of the DES is when the external force (usually the amount to be detected) makes the DE deformation, and thereby changes its capacitance. By measuring the circuit and analysing the correspondence between the external force and the capacitance, the value of the external force can be calculated. In 2005, Carpi and De Rossi [94] predicted that DES will be widely used in the field of

### Table 1 Properties of some DE materials discussed in Section 3

| Polymer                  | Pre-strain, % | Young's modulus, MPa | Area strain, % | Energy density, MJ/m³ | Electric field, MV/m |
|-------------------------|--------------|----------------------|---------------|-----------------------|---------------------|
| HS3 [21]                | (68, 68)     | 0.1                  | 93            | 0.098                 | 110                 |
| HS3 [21]                | (280, 0)     | —                    | 117           | 0.16                  | 128                 |
| TiO₂-PDMS [56]          | —            | 0.8                  | 4             | —                     | 30                  |
| TiO₂-PDMS (plasticised) [56] | —       | 0.1                  | 13            | —                     | 30                  |
| PDMS [59]               | —            | 1                    | 4.8           | —                     | 50                  |
| PANI-PDMS [59]          | —            | 12                   | 0.85          | —                     | 50                  |
| TPU [62]                | —            | —                    | 0.07          | —                     | 3                   |
| TPU/PEG [62]            | —            | —                    | 5.2           | —                     | 3                   |
| PU-CuPc [61]            | —            | 29.6                 | 17.7          | 0.927                 | 10                  |
| PU/CuPc [61]            | —            | 21.7                 | 3.3           | 0.024                 | 10                  |
| VHB4910 [21]            | (300, 300)   | 3                    | 158           | 3.4                   | 412                 |
| VHB4910 [21]            | (540, 75)    | —                    | 215           | 1.36                  | 239                 |
| IPN-VHB4910 (1,6-Hexanediol diacrylate) [70] | — | — | — | — | 300 |
| IPN-VHB4910 (TMPTMA)/DBEF [72] | — | 1.5 | 215 | — | — |
| polyacrylates/Al [73]   | —            | 0.53                 | 56            | —                     | 140                 |

**Fig. 8** Representative DE actuator configurations [16]

**Fig. 9** Performance of the untethered fish [81]
biomedicine in the future, and large amount of work have been done in this area [95–100]. Fig. 13 shows the application of DES in the biomedical field, which can help amputees detect prosthetic pressure and improve prosthetic comfort [101]. At present, DES has been successfully commercialised. New Zealand Stretch Sense Company established in 2015 has developed sensors such as tensiometer, pressure sensors, and bending sensors in just 2 years, and can be customised according to customer requirements, while the current price of customisation is relatively high. With the development of DES technology and the progress of commercialisation, such products may be further reduced in cost and widely used in the future.

5 Summary and outlook

Based on the dielectric property and elasticity, the DE materials can realise the mutual conversion of mechanical energy and electrical energy, which makes the DE materials attract widespread attention and development. The research and development direction of DE materials mainly focus on three aspects: theoretical modelling, advanced material synthesis, and practical application.

Theoretically, it is necessary to establish accurate and complete mathematical or physical models to describe the electromechanical performance and stability of different types of DEs. The non-ideal model that considers actual conditions and environmental parameters needs to be studied. For the material preparation aspect, based on the current research results, some new composite materials should be fabricated; on the other hand, it is expected to find innovative materials. In addition, for the material preparation process, chemically grafting and structure design based on the molecular level are very promising. At the practical application level, many researches still remain at the laboratory level. Market-oriented applications need to ensure quality stability and minimise economic costs, which is an important factor in promoting the large-scale use of DEs. In addition, for practical applications, there are many key issues that need to be resolved, such as, the theoretical system, how to overcome high driving voltage, flexible electrode technology, biocompatibility, energy density enhancement, and so on.

DE materials have the advantages of high performance, light weight, low operation noise, and low cost. DE materials have broad development prospects in the three major areas of actuators, generators, and sensors, while they also face many challenges in the development process simultaneously. In this review, the principles, classifications, applications, and key issues of DEs are collated and summarised. The conquest of each key issue will represent a giant leap in the field of DEs. With the development of the manufacturing industry and the diversification of market demands, DEs will develop rapidly and have infinite possibilities.

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