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Dielectric Elastomer Sensors

Na Ni and Ling Zhang

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Abstract

Dielectric elastomers (DEs) represent a class of electroactive polymers (EAPs) that exhibit a significant electromechanical effect, which has made them very attractive over the last several decades for use as soft actuators, sensors and generators. Based on the principle of a plane-parallel capacitor, dielectric elastomer sensors consist of a flexible and stretchable dielectric polymer sandwiched between two compliant electrodes. With the development of elastic polymers and stretchable conductors, flexible and sensitive dielectric elastomer tactile sensors, similar to human skin, have been used for measuring mechanical deformations, such as pressure, strain, shear and torsion. For high sensitivity and fast response, air gaps and microstructural dielectric layers are employed in pressure sensors or multiaxial force sensors. Multimodal dielectric elastomer sensors have been reported that can detect mechanical deformation but can also sense temperature, humidity, as well as chemical and biological stimulation in human-activity monitoring and personal healthcare. Hence, dielectric elastomer sensors have great potential for applications in soft robotics, wearable devices, medical diagnostic and structural health monitoring, because of their large deformation, low cost, ease of fabrication and ease of integration into monitored structures.

Keywords: dielectric elastomers, soft capacitance sensors, electronic skin, flexible mechanical sensors, robot sensors, tactile sensors

1. Introduction

In recent years, the soft sensing systems have attracted considerable attention because of their potential applications in assistive soft robots, healthcare and entertainment [1]. In contrast to traditional rigid sensors, their advantageous compliant properties enable the soft sensors to safely monitor soft movements or interactions with humans. Many of these devices can be used to measure strain, pressure, force, light, humidity and temperature similar to the human

skin, which have advantageous properties such as flexibility, stretchability, highly sensitivity and technological compatibility with a large area [2, 3].

Various transduction methods for fabricating flexible sensors have been developed [4], including piezoresistivity, capacitance, piezoelectricity, optics and wireless antennas. Current applications require highly sensitive, flexible, stretchable and low-cost devices, where capacitive-based sensors exhibit better potential for use, because of their high strain sensitivity, static force measurement and low power consumption [5]. These capacitive tactile sensors measure the magnitude of mechanical forces or strain by converting mechanical solicitations into an electrical signal. Dielectric elastomer (DE) sensors are one type of the capacitive-based sensors, which are flexible, soft and stretchable for measuring deformations, forces and pressures.

The dielectric elastomers (DEs) are a type of field-activated polymers that belong to the family of electroactive polymers (EAPs) [6]. The typical structure of a dielectric elastomer (DE) is a dielectric material sandwiched between two electrodes, which can produce a large strain response and high electromechanical efficiency from an electric field. Based on the electromechanical effect, DEs can be used as soft actuators, sensors and generators.

Recently, several reviews have been published in the literature, which have detailed the properties and chemistry of dielectric elastomers [6, 7]. However, these reviews focused primarily on the development of dielectric elastomer actuators and generators. A detailed overview of the recent progress in dielectric elastomer sensors has not been reported, so this current review focuses on the recent research in dielectric elastomer sensors. In the first section, several sensing principles of dielectric elastomer sensors are introduced. In the second and third section, the materials of the dielectric and compliant electrodes are described. In the fourth section, a detailed overview is given of the recent progress regarding applications of dielectric elastomers in electronic skin, structural health monitoring, tissue elasticity measurements, self-sensing actuators and robotic technologies. Wearable dielectric elastomer sensor systems are also reviewed based on multiple physical sensors. Conclusions and future developments in practical applications of dielectric elastomer sensors are discussed in the final section.

2. Principle of dielectric elastomer sensors

The capacitance of a parallel plate capacitor can be written as:

$$C = \epsilon_0 \epsilon_r \frac{A}{d} \quad (1)$$

where C is the capacitance, $\epsilon_0 = 8.854 \times 10^{-12} \text{ F/m}$ is the permittivity of the vacuum, ϵ_r is the relative permittivity, A is the electrode area and d is the dielectric distance [8]. A capacitive sensor can be designed to provide elastic deformation by sandwiching an elastomer film between two compliant conductive electrodes to form a dielectric elastomer sensor. The deformation of the dielectric elastomer produces a change in capacitance of the sensor. A simple sensing method is shown in **Figure 1**. When the sensor is subjected to external tension or

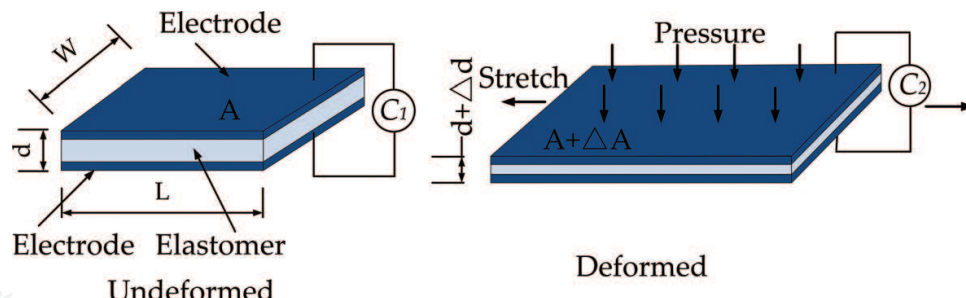


Figure 1. Simple measurement principle of a dielectric elastomer sensor.

compression, the surface of the sensor film expands, while the displacement between the two electrodes decreases, which causes an increase in capacitance.

According to the model of an ideal dielectric elastomer, assuming that the volume and permittivity remain constant, when a dielectric elastomer sensor is stretched in its plane, the change in capacitance can be derived as follows:

$$L_{stretch} = \lambda_1 L \quad (2)$$

$$W_{stretch} = \lambda_2 W \quad (3)$$

$$d_{stretch} = \lambda_3 d = \frac{1}{\lambda_1 \lambda_2} d \quad (4)$$

where λ_1 , λ_2 , λ_3 are multiples of L , w , d , which are the initial dimensions of the dielectric elastomer as shown in **Figure 1** [9]. Combining the above equations with the Eq. (1), the capacitance C of the dielectric elastomer can be written as:

$$C = C_0 (\lambda_1 \lambda_2)^2 \quad (5)$$

where C_0 is the initial capacitance. When a uniaxial stretch is applied, the length of dielectric elastomer is λ times its initial length and the width and the thickness become $\frac{1}{\sqrt{\lambda}}$ times their initial values, and the capacitance value of the deformed dielectric elastomer is then:

$$C = C_0 \lambda \quad (6)$$

Hence, the capacitance change ΔC can be expressed as:

$$\Delta C = C_0 \varepsilon \quad (7)$$

where ε is the strain along the stretched axis of the dielectric elastomer. Eq. (7) implies that the capacitance change is linear with the strain of dielectric elastomer sensor.

Another sensing method of the dielectric elastomer sensors can be found in the relative position change of two electrodes, which produces a capacitance change as shown in **Figure 2**. This sensing method is used for measuring shear forces.

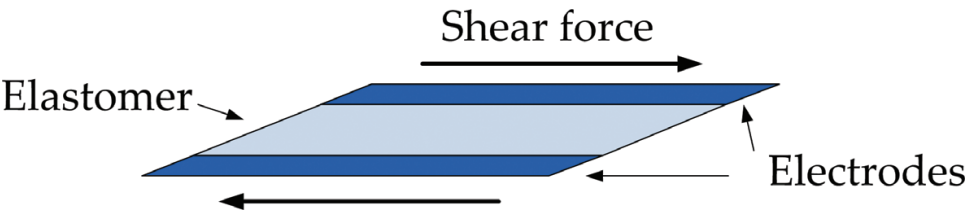


Figure 2. Measurement principle of a dielectric elastomer sensor when shear force is subjected.

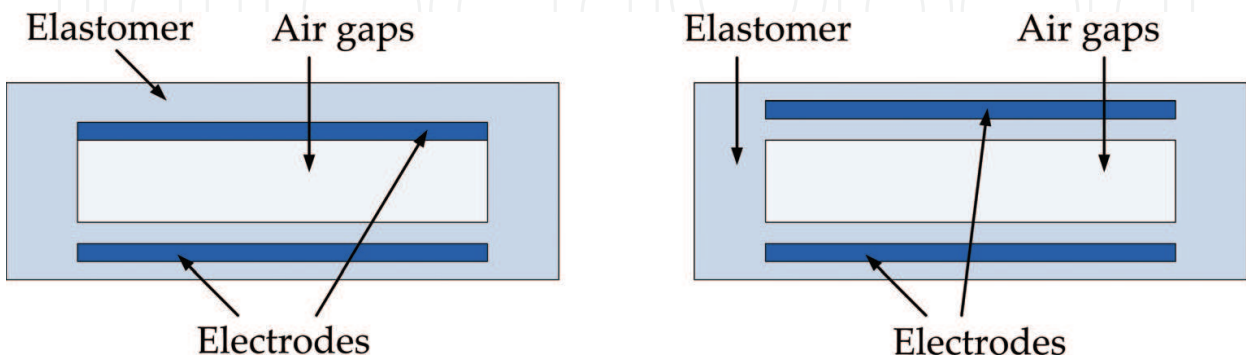


Figure 3. Prototype of a dielectric elastomer sensor with an air gap. Left: one elastic layer between two electrodes and right: two elastic layers between two electrodes.

To improve the sensitivity of dielectric elastomer sensors, **Figure 3** shows a complex sensing method that employs a multilayer dielectric including an air gap and dielectric films. By constructing the air gap, the device is able to sensitively detect multiaxis force and pressure [10, 11]. In addition, the micro/nanostructured dielectric layer can improve the sensitivity of dielectric elastomer sensors as well.

3. Materials of dielectric elastomer sensors

For the large deformation requirements of dielectric elastomer sensors, many classes of dielectric materials have been investigated, including acrylates, silicones, polyurethanes (PU), rubbers, latex rubbers, acrylonitrile butadiene rubbers, olefinic, polymer foams, fluorinated and styrenic copolymers [7]. Acrylates and silicon rubbers such as VHB, polydimethylsiloxane (PDMS) and Ecoflex have been widely used in fabricating flexible sensing devices due to their commercial availability and good performance [9, 12, 13]. The relative dielectric constant and modulus are important properties in the performance of dielectric elastomer sensors. The typical properties of a number of candidate polymers are listed in **Table 1** [7, 14–17].

A commercial acrylate adhesive film, VHB, produced by the 3M Company, is commercially available and exhibits large deformation and transparency. It can be stretched more than six times its initial length [9], and the strain is nearly linear with stress to as much as three times the initial length of the film [7]. VHB acrylates have a dielectric constant that is higher than silicon rubbers.

Elastomer material	Relative dielectric constant	Young's modulus
VHB 4910 (acrylate)	4.7	1–2 MPa
Ecoflex 0050 (platinum-catalyzed silicon)	2.65	83 kPa
Ecoflex 0050 (platinum-catalyzed silicon)	2.65	69 kPa
Ecoflex 0010 (platinum-catalyzed silicon)	2.65	55 kPa
Dow Corning, Sylgard 184 (polydimethylsiloxane silicon rubber)	2.75	1.84 MPa

Table 1. Properties of several dielectric elastomers [7, 14–17].

Silicones have also been studied for use as dielectric elastomers [18]. Many silicone materials are produced commercially, such as Dow Corning Sylgard184. The modulus of these materials typically ranges from 0.1 to 2 MPa and their dielectric constants are generally around 3 [7]. Their elongation at break is less than that of VHB adhesive film. Dow Corning Sylgard184 is a type of polydimethylsiloxane (PDMS) that is generally used for fabricating dielectric elastomer sensors as a dielectric [19] and a substrate [10]. The advantages of PDMS include variable mechanical properties, transparency and stability over a wide range of temperatures [20]. For bonding electric materials to its surface, defining potential adhesive and non-adhesive regions can be accomplished by exposure to UV irradiation [20]. Another commercial silicone material, Ecoflex rubbers are also widely used for flexible capacitance sensors [21]. Ecoflex rubbers are platinum-catalyzed silicones that are soft, strong and “stretchy” [22]. Compared to Ecoflex, PDMS is hard and brittle as shown in **Figure 4** [23].

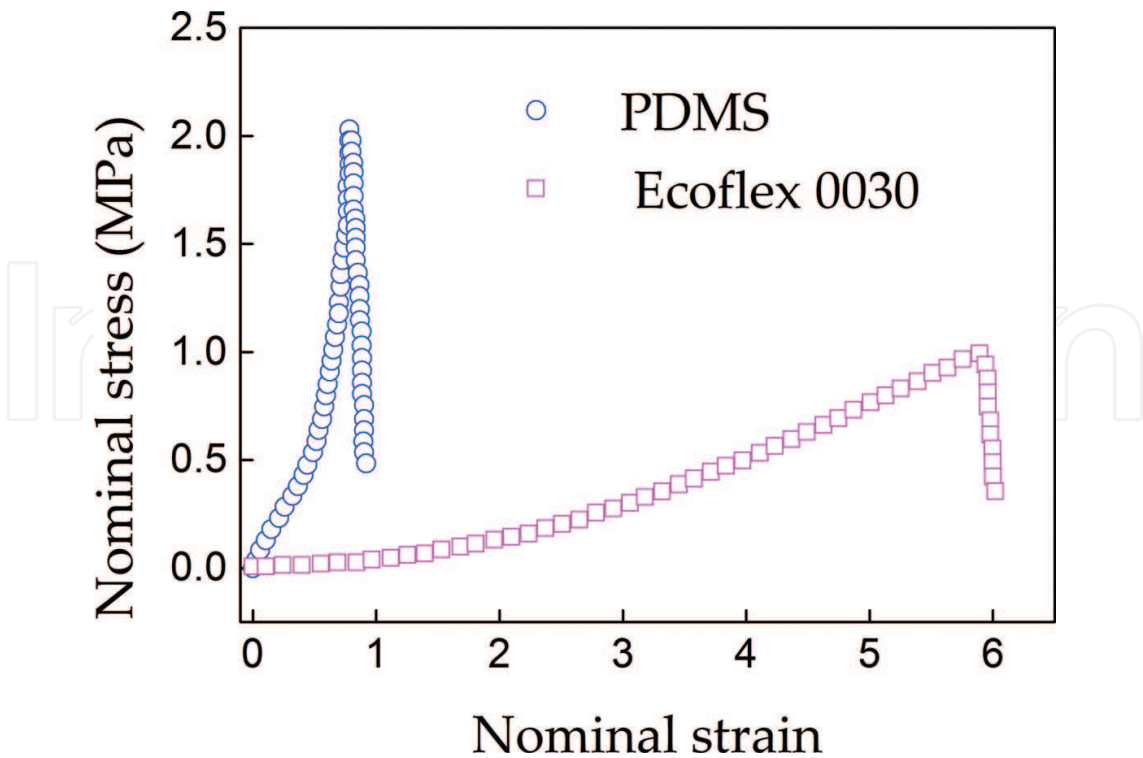


Figure 4. Uniaxial tensile test of Ecoflex 0030 and PDMS [23].

To improve the sensitivity of dielectric elastomer sensors, it is important to develop dielectric elastomers that have a relatively high dielectric constant. There are generally three routes for enhancing the dielectric constant of an elastomer, which include addition of high permittivity inorganic particles [24, 25], addition of conductive fillers [26] and chemical design [27]. Chemical design involves polymer chain modification. Titanium dioxide (TiO_2) [28] and barium titanate (BaTiO_3) [29] have reportedly served as high permittivity inorganic particles for improving the dielectric constants of elastomers. Conductive fillers enhance the dielectric constant of elastomers by increasing the effective electrode area or facilitating electronic polarization, such as carbon nanotubes (CNTs) [30, 31], metal particles [26] and conductive polymers [32].

4. Compliant and stretchable electrodes

Much like the dielectrics, good stretching ability and flexibility in the electrodes are necessary to enable the dielectric elastomer sensors to be used in soft robots, healthcare and entertainment. They must have the ability to exhibit large deformation (bend, fold, twist, compress, and stretch) while maintaining a high level of conductive performance, integration and reliability [33]. Of the work performed on stretchable and flexible electrodes, two main types of conductors, electrical conductors and ionic conductors, have been identified as the most desirable for modification of the electrodes based on their conductance.

4.1. Electrical conductors

Sensors employing electrical conductors (e.g., carbon grease, metal films and carbon nanotubes) as electrodes develop signals based on the movement of electrons in the material. The electronic conductors used as compliant electrodes in sensors mainly include carbon-based electrodes [11, 34], metallic thin films [35], composites of conducting materials and elastomers (or rubber fiber mats) [36], conducting films (indium-tin oxide (ITO)-coated poly (ethylene terephthalate (PET)) [37] and liquid conductors [38].

Carbon-based electrodes are widely used for dielectric elastomer sensors because they are compliant, easy to fabricate and exert a low impact on the stiffness of the dielectric [7]. Carbon-based electrodes are usually fabricated from carbon black, graphite [39], carbon nanotubes (CNTs) [34] and single-walled carbon nanotube (SWNT) [1, 40] as loose particles or mixed with the matrix to form a viscous media (carbon grease) [11] or mixed into an elastomer (conductive elastomer) [41]. Goulbourne's experiments showed that the performance of carbon grease was better than that of graphite power, graphite spray or silver grease [42]. Lipomi et al. [34] developed a skin-like pressure and strain sensor composed of carbon nanotubes (CNTs) as compliant electrodes. The advantage of these sensors was that they were transparent compared to the electrodes of sensors fabricated using other carbon-based electrodes such as carbon grease.

In other compliant electrodes composed of a single material (e.g., Au [43], Al [19] and Pt [44], AgNWs [45, 46]), metallic thin films are generally deposited on elastomers by sputtering and using an E-beam evaporator [7]. These electrodes are more suitable for use as pressure

sensors [19, 43] or normal and shear force sensors [44], compared to strain sensors [40]. This is because they are thin, highly conductive and can be patterned [7], but their hardness affects the stretching of the capacitance sheets.

Conductive elastomers (composites of conducting materials and an elastomer) offer the advantages of integration into the dielectric layer, robustness and durability. For example, Laflamme et al. [41, 47] reported on a soft, large surface area capacitor network employed in structural health monitoring that was composed of carbon black dispersed in poly-styrene-co-ethylene-co-butylene-co-styrene (SEBS) solution. Experimental testing demonstrated the improved robustness and stable capacitance of the device after it was cut or punched [47]. Cai et al. [36] designed an excellent, durable capacitance strain sensor based on CNTs-doped Dragon skin 30 (Smooth-on, Inc., USA) that could measure strains of up to 300% over thousands of cycles. An elastomeric capacitive sensor array was constructed with conductive PDMS (CNT-PDMS) using micro-contact printing techniques [10]. These devices were stable under various elastic deformations. In addition to these carbon-based electrodes, CNT fabrics were reported that employed a capacitor geometry grid as multimodal skin sensors [2]. In addition to CNTs, elastic conductors composed of silver nanowires (AgNWs) and elastomers have been used for improving mechanical robustness of sensors that can detect strains of up to 50% [48, 49].

Other electrodes used in capacitive sensors include conductive textiles composed of conductive particles and fabrics. A commercial, stretchable conductive textile, termed Electrolyca (Mindsets Ltd, UK), was composed of woven silver with nylon elastic fibers employed as electrodes in a flexible capacitance-sensing element integrated in a measured structure [4]. Another conductive textile, Zelt fabric (Mindsets Ltd, UK), made of soft copper-/tin-coated woven fabrics, was assembled into a dielectric film for use in soft tactile sensors [5]. Park et al. [50] fabricated stretchable, thin-film electrodes using silver nanoparticles and rubber fiber mats. The electrodes retained high conductivity at 140% strain and were compatible with various substrates and could be deployed over large areas.

A conductive film has been reported, which was composed of indium-tin oxide (ITO)-coated poly (ethylene terephthalate) (PET) film and exhibited good performance when its bending radius was greater than 8 mm [51]. This ITO/PET film was suitable for use as a pressure sensor with microstructured elastomeric dielectric film [37, 51, 52].

In addition to the use of compliant electrical conductors, conductive liquids have also been employed based on liquid, metal-filled channels [38, 53, 54] or microliquid metal droplets [55]. This technical approach is beneficial to use in an array of soft tactile sensors.

4.2. Ionic conductors

There are instances when compliant electrodes must meet the stretch requirements of a sensor as well as the biocompatibility and transparency requirements [9]. Sensors employing ionic conductors can develop signals using these ions. Ionic conductors have been studied for use in applications that demand greater stretch and greater transparency than electronic conductors, such as polyacrylamide hydrogels [56–58] and ionogels composed of ionic liquid and polyacrylic acid [59]. Recent work has demonstrated that these materials can be used as the

electrodes of transparent sensors and actuators for artificial muscles, skin, axons and kines-
thetic sensing [60–64]. A transparent, capacitive sensor termed ionic skin was first developed
using a dielectric elastomer covered with ionic electrodes, which were composed of a poly-
acrylamide hydrogel with NaCl [9]. To solve the problem of water loss from the hydrogel,
high-retention hydrogel conductors [58] were applied in a highly stretchable and transparent
actuator [60]. This was then formed into a highly stretchable electroluminescence [65] and an
ionic cable that exhibited high-speed and long-distance signal transmission [66]. The high-
retention hydrogel conductors were very stretchable, with strains that exceeded 1000% as
shown in **Figure 5**. The hydrogel conductor was also very tough. We poked a knife at the
hydrogel conductor (**Figure 6a**). **Figure 6b** showed it remained intact after being poked [67].

For use in sensors, a good compliant electrode should exhibit low hysteresis of resistance
versus strain, a well-controlled surface resistance and limited degradation with load cycling [7].

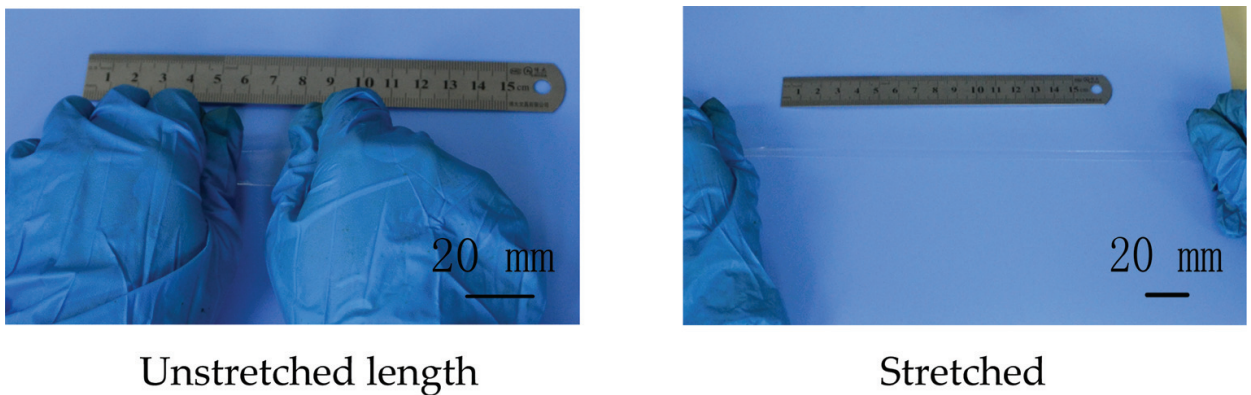


Figure 5. The hydrogel conductor from an original state to a stretched state.

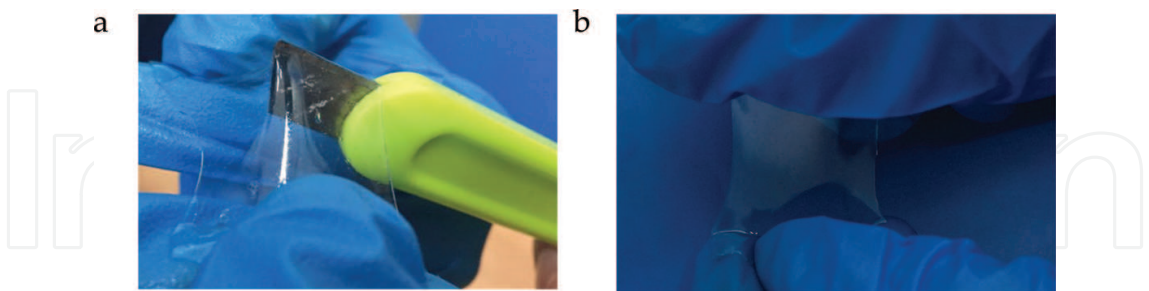


Figure 6. (a) Poking at the hydrogel conductor with a knife and (b) the ionic conductor remaining intact after being poked.

5. Applications of dielectric elastomer sensors

Compared to traditional rigid sensors (resistance strain gages, piezoelectric ceramics sensors, etc.), dielectric elastomer sensors exhibit advantages, including low cost, large deformation

(the strain even exceeds 100%) and fast response time, and are easily integrated into monitored structures [5, 50, 52]. They have been used extensively as physical sensors, such as pressure sensors [52], strain sensors [1, 36, 68], normal and shear force sensors [5, 34, 43, 53]. In addition, for simulating multifunctional human skin, multimodal sensors have been made for measuring pressure, temperature and humidity [2, 69]. These outstanding features make these sensors potentially useful in soft robots, human-machine interfaces, human-activity monitoring, personal healthcare and structural health monitoring (Figure 7).

5.1. Flexible and stretchable sensors as capacitive electronic skin

Recently, flexible and stretchable strain sensors have been developed that can be worn as electronic skin (e-skin) for soft robots, wearable devices and human motion monitoring in medicine, including diagnosis development, rehabilitation assistance and activity monitoring [3]. These flexible and stretchable capacitive strain sensors consisted of a dielectric polymer film sandwiched by two compliant electrical conductors. Cohen et al. [68] proposed a highly elastic strain sensor composed of dielectric elastomers sandwiched between CNT percolation electrodes. These sensors can be stretched to 100% of their original size over thousands of cycles with a 3% variability, which has resulted in the demonstration of useful applications in a robotics context for transduce joint angles. A highly stretchable and transparent capacitive strain sensor based on CNT elastic electrodes has been proposed [36]. The highly sensitive strain sensors can measure strains up to 300% with excellent durability, stability and fast response, which have potential applications in wearable smart electronics as demonstrated by experiments in glove and respiration monitoring. Yang et al. [1] made a recoverable motion sensor based on the surface-modified $\text{CaCu}_3\text{Ti}_4\text{O}_{12}$ (S-CCTO) nanoparticles involving a self-healing

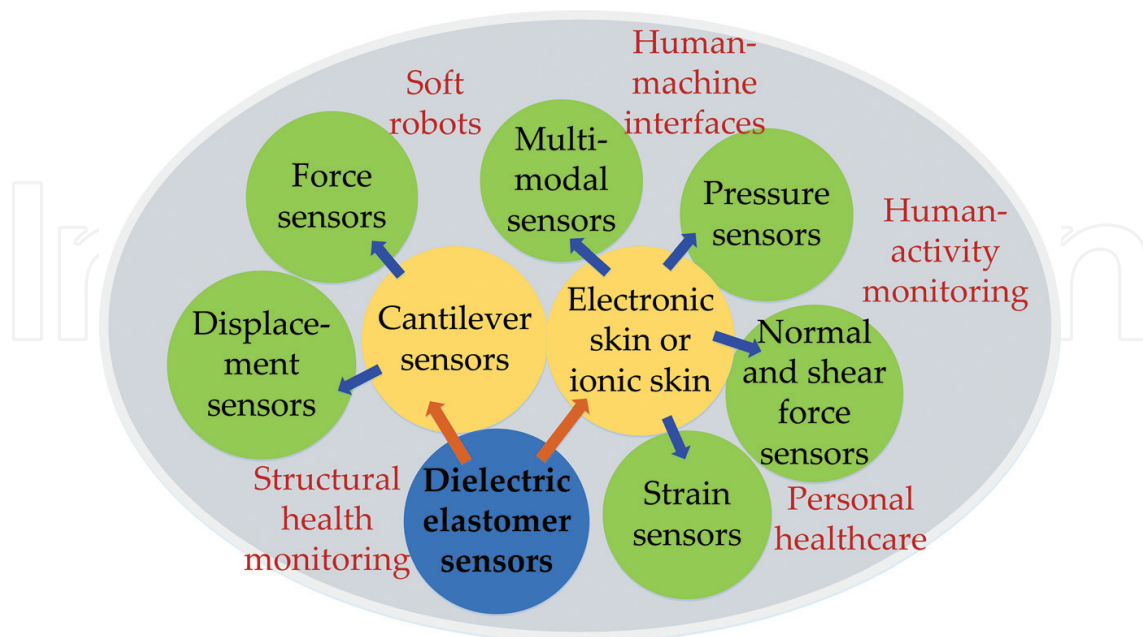


Figure 7. Applications of the dielectric elastomer sensors in soft robots, human-machine interfaces, human-activity monitoring, personal healthcare and structural health monitoring.

polymer matrix. The composites had a high dielectric permittivity of 93 at 100 Hz. These authors' work showed the benefits of the electrical and mechanical self-healing properties of their motion sensors.

Similar to the concept of human skin, the flexible and stretchable dielectric elastomer sensors can be used as soft strain gauges but can also be used for measurements of pressure and three-axis forces. Pressure sensors have been fabricated by sandwiching a soft dielectric between two sets of flexible electrodes, such as metal thin films [43], CNTs [34], AgNW-based [45], liquid electrodes [53]. Dielectric elastomer sensors were designed as skin-like tactile sensors, which could measure pressure produced by the human-body activity. These pressures included a low-pressure regime (<10 kPa) produced by intrabody pressure (intraocular pressure and intracranial pressure), a medium-pressure regime (<100 kPa) generated by wave, vibration or pulses (blood pressure, respiration, phonation, heart, radial artery, jugular venous) and a high-pressure regime (>100 kPa) produced in the foot [52, 68]. Extremely robust pressure sensors were fabricated using flexible polyurethane foams and Au thin films that could measure normal pressures from 1 to 100 kPa for applications as artificial skin and in wearable robotics [43]. Transparent and stretchable pressure and strain sensor arrays have been developed to detect pressures of up to 1 MPa using nanomaterial electrodes. Potential applications include prosthetic limbs, bandages, robotics and touch screens [34, 43]. Li et al. [53] proposed highly deformable tactile sensing arrays based on low modulus platinum-catalyzed silicone polymer (EcoFlex00-30) with embedded liquid metal microfluidic (eutectic gallium indium) arrays. The wearable tactile sensors could be stretched greater than 400% and could conform to curved objects or soft biological tissues.

However, the incompressibility and viscoelasticity of rubbers limit their sensitivity for use in pressure sensors [52]. By constructing an air gap and compressible dielectric layers between two electrodes, the performance of the pressure sensors can be improved [70]. Zhang et al. [21, 71] designed a compressive soft sensor with an air gap and theoretically demonstrated that the air gap could improve the sensitivity of the pressure sensors. These authors' results showed that when the thickness of the air gap was large, the detection range was large but the resolution was small.

Based on the structure containing an air gap, three-axial force sensors were designed using a 2D overlap with a larger top electrode on four bottom electrodes [5, 11]. In this structure, Zhang et al. [11] investigated the effect of the geometry (rectangle and circular sector) of the electrodes on the sensitivity, linearity, hysteresis and detection range of the device using simulations and experimentation. Their results showed that the rectangular strategy improved the performance of the sensor over that of a circular design (four circular sector bottom electrodes). Viry et al. [5] developed a highly compressible and sensitive capacitive three-axial force sensor that was fabricated with a top textile electrode and four bottom textile electrodes sandwiching a fluorosilicone film and an air gap. This device reportedly could detect pressures of up to 190 kPa (estimated up to 400 kPa) and minimal weights of less than 10 mg. Hence, the application of the sensor was extensive, including biomimetic touch, heartbeat monitoring and foot pressure-distribution monitoring.

The micro/nanostructured dielectrics have been widely developed to improve the sensitivity and response and/or relaxation time of the pressure sensors [72]. Mannsfeld et al. [52] proposed a

type of organic thin film that consisted of a regularly structured dielectric layer with organic field-effect transistors (OFETs) for use as pressure sensors. The design of this device resulted in faster response and relaxation times ($<<1\text{s}$), and higher sensitivity (0.55 kPa^{-1}) than the unstructured film (0.02 kPa). Using a device with microstructured rubber dielectric layers, Schwartz et al. [37] further developed highly flexible transistor devices with high sensitivity (8.4 kPa^{-1}), high stability and low power consumption that were used as an electronic skin for human-machine interfaces [37]. Various microstructures have been studied for use as the dielectric layer for flexible capacitive pressure sensors, including pyramids [19], microhairs [73] and microspheres [74]. Tee et al. [19] found that the pyramidal structures with relative small sidewall angles were the optimum shapes for rendering improved sensitivity, compared to structures with relative large sidewall angles and square cross-sectional structures. In addition, when the structures were spaced further apart, the sensitivity increased. The authors also demonstrated that these pressure sensors could be used for blood pulse monitoring and next-generation force sensing track pads with high sensitivity, easy manufacturing and low cost [19]. The design of microhair structures for flexible pressure sensors can enhance the signal-to-noise ratio and enable signal detection of the deep-lying internal jugular venous pulses for healthcare monitoring [73]. Li et al. [74] proposed a pressure sensor composed of polystyrene microspheres (dielectric layer) and Au electrodes with a surface micropattern similar to lotus leaves. The devices facilitated measurements over a wide dynamic response range ($0\text{--}50\text{N}$) in addition to high sensitivity (0.815 kPa^{-1}) and a fast response time. This device was suitable for use over a wide pressure-measuring range for applications in wearable healthcare devices, patient rehabilitation and biomedical prostheses. In other devices, a dielectric layer of the pressure sensor respectively employed porous PDMS [51], porous silicone foam [75, 76] or graphene oxide (GO) foam [77]. In particular, Chen et al. [51] developed a microstructured elastomeric dielectric film with air voids (porous PDMS) integrated with ITO/PET electrodes, which was highly sensitive and fast, capable of measuring pressures from 1 to 250 kPa and durable under loads larger than 1 MPa. Experiments demonstrated that these advantages of this device readily let it for use as a smart insole and a wrist pulse monitoring sensor.

5.2. Ionic skin

Ionic conductors have attracted attention in capacitive tactile sensing applications, due to their high transparency and conductivity under large deformation [61–63]. Nie et al. [61] fabricated a capacitive pressure sensor utilizing an ionic gel matrix. This transparent film sensor had a high sensitivity (3.1 nF/kPa) because the electrical double layer produced an ultra-high unit-area capacitance. The sensor also exhibited excellent mechanical and thermal stability and a rapid response. The applicability of this sensor as a wearable device was successfully demonstrated so that it was later incorporated into the consumer electronic devices including a smart watch, augmented reality glasses and a custom fingertip-mounted tactile sensor. Sun et al. [9] developed a highly stretchable and transparent capacitive sensing sheet called ionic skin, which was composed of a dielectric and two ionic conductors. These sensors can detect strains over a wide range (from 1 to 500%) and pressures as low as 1 kPa. The working principle of the sensor was reported in detail in the literature [9]. A hybrid ionic-electronic circuit was formed by connecting the ionic conductors to electronic conductors for transmitting electrical signals. When a low voltage was applied between the two electrodes, electrochemical reactions did not

occur, and no electrons or ions crossed the interface between the electrode and the ionic conductor. This allowed electrical double layers to form at the interface, similar to a capacitor C_{EDL} , which was in series with a capacitor C_m formed by the ionic conductors and the dielectric (Figure 8). As a result, the capacitance C measured between the two electrodes can be written as $C = C_m / (2C_m / C_{EDL} + 1)$. The capacitance of the dielectric was much less than the electrical double layer since the separation (nanometer) of the charges in the electrode and in the ionic conductor was much less than the distance between the charges separated by the dielectric with a thickness. Consequently, the measured capacitance C was dominated by the capacitance of the dielectric C_m . According to this principle, a transparent capacitive sensing film was fabricated in our laboratory for structural health monitoring.

5.3. Flexible and large-surface dielectric elastomer sensors applied in structural health monitoring

Detecting and locating damage to bridges, roads, buildings and other structures is necessary to ensure a long lifespan of the national infrastructure. Detecting defects and providing warnings in time can prevent the collapse of structures. Soft film sensors employing functional materials have been proposed for monitoring the condition of structures. These sensors include resistance-based, piezoelectric, antenna, vacuum and capacitance-based strain sensors. Some of these technologies are unsuitable for use on a large scale, because their complex manufacturing processes make them too expensive.

In the recent developments in structural health monitoring, Laflamme et al. [78] first proposed a sensing technique for damage localization using a layer of commercial dielectric polymer (DEAP, Danfoss PolyPower) on the surface of a monitored structure with a same reference

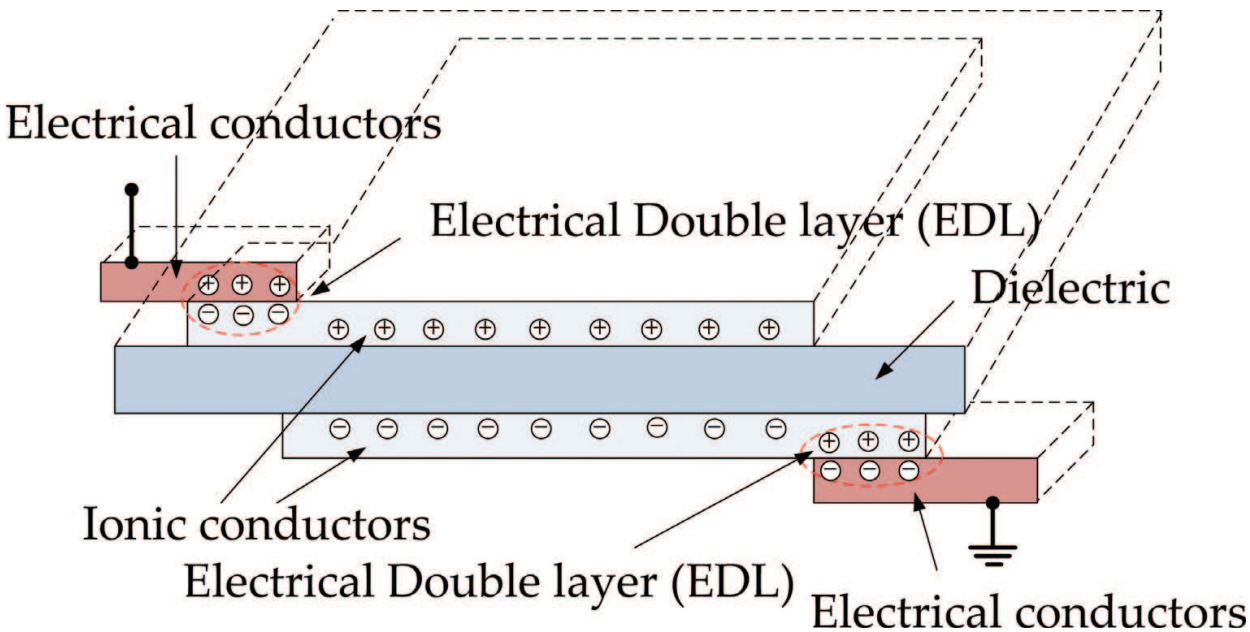


Figure 8. A schematic diagram of additional electric charges accumulated when a voltage is applied between the electrical conductors [9].

capacitance. The next step entailed fabricating soft elastomeric capacitors (SECs) that were inexpensive and useable on large surface areas [79]. The robust and static characterization of the sensors was demonstrated through testing [47]. Static characterization, dynamic monitoring, localization of fatigue cracks and the distribution of thin film sensor arrays on structures were studied using the referenced SECs [80–83]. The electrodes of these sensors were composed of SEBS containing carbon black particles, and the sensors were not transparent. The damaged parts of the subject structure are invisible when the sensors were placed on the surface.

We have developed a transparent, capacitive sensor that is inexpensive and can easily detect cracks in large-scale infrastructures [67]. The sensor was attached to a monitored surface by a bonding layer (**Figure 9**). The sensor consisted of a transparent dielectric elastomer sandwiched between two transparent and stretchable ionic electrodes. The transparent capacitive sensor could be used to monitor large areas of a structure to detect potential damage. The robustness of this sensor was demonstrated by tests (**Figure 10a** and **b**), particularly on the over-reinforced beam. Tests conducted on the over-reinforced concrete beam demonstrated that the sensor was capable of detecting small cracks (**Figure 10c** and **d**).

5.4. Cantilever sensors (force, torque and displacement) for robotic technologies

In the previously described applications of dielectric elastomer sensors, most of these sensors were in the shape of a flat sheet. This is not suitable for measuring other mechanical parameters such as concentrated force and displacement. The cantilever beam sensors are a class of force sensors that are used extensively for weight measurement, environmental monitoring, biological monitoring and gas detection. Most of these devices are rigid sensors that are unsuited for soft robotics applications. There have been few reports in the literature about soft displacement or force dielectric elastomer sensors based on the flexible beam. Lucarotti et al. [4] proposed a strategy to sense-bending angle and force in a soft body based on beam configuration, which was integrated with two capacitive sensing elements for distinguishing between convex and concave bending. In their analysis of the device, they imposed a bending and/or an external force to a soft beam. The results confirmed the superiority of this sensing strategy for use in soft robotics.

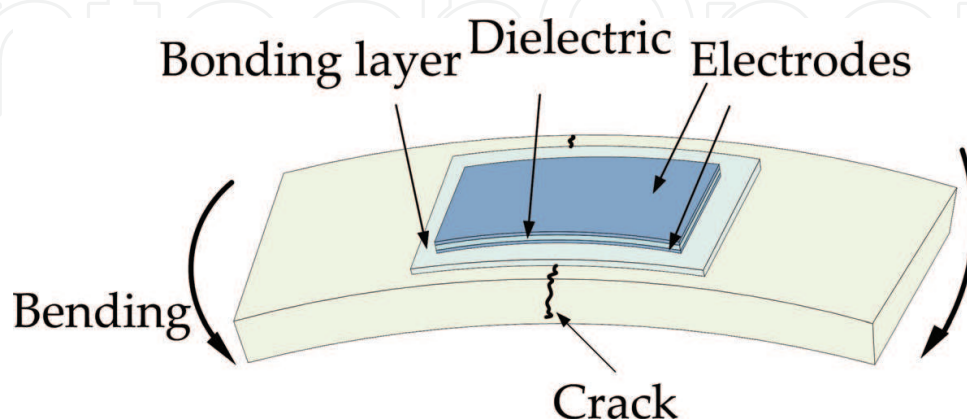


Figure 9. A schematic of a dielectric covered with ionic conductors deployed over the surface of a monitored structure by using a bonding layer [67].

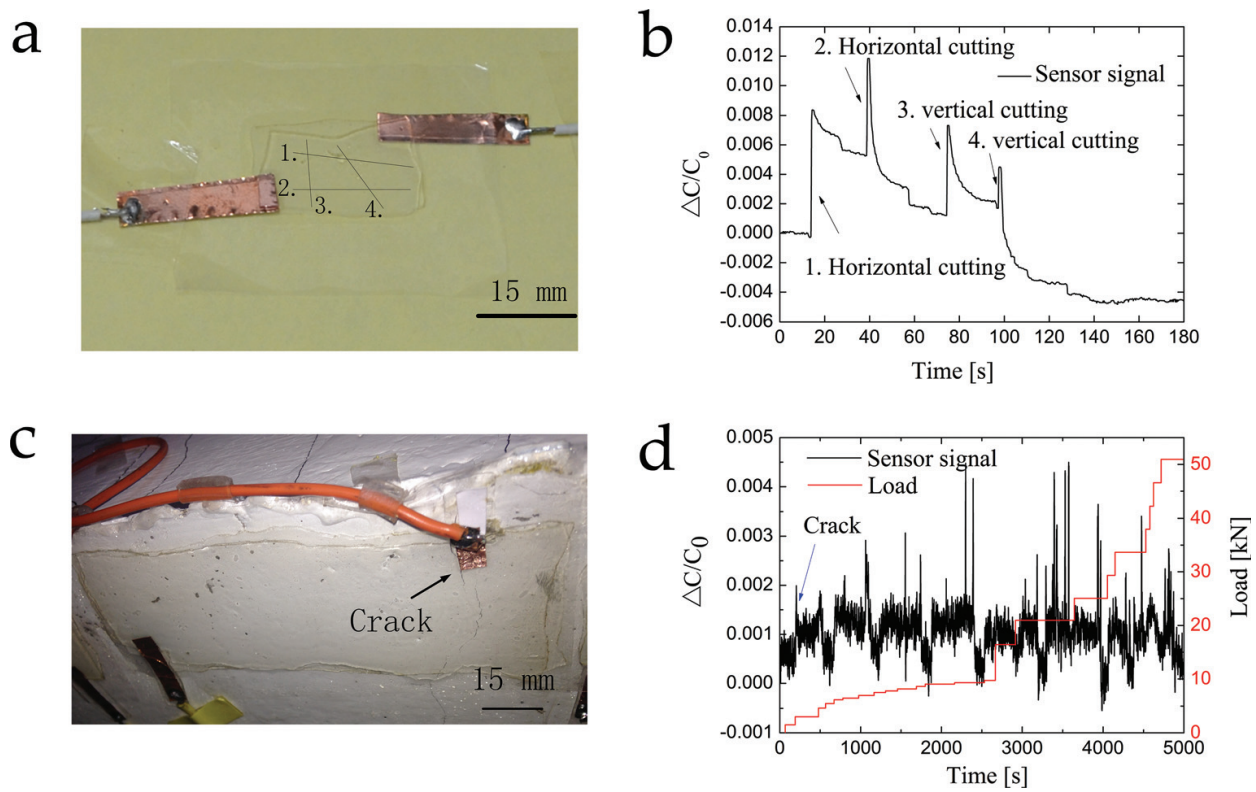


Figure 10. (a) An illustrative photo of four cuts on the transparent capacitive sensor, (b) relative change in capacitance when cuts were made, (c) a photograph of cracks formed under the sensor and d) relative change in capacitance of the sensor and load against time [67].

We have proposed a dielectric elastomer cantilever beam sensor for measuring force or displacement [84]. A dielectric membrane sandwiched between compliant electrodes was pasted to the surface of a soft uniform strength cantilever beam by the bonding layer, which made the sensing device as shown in **Figure 11**. The concentrated force at the free end induced a change in the capacitance of the dielectric membrane. Therefore, the applied force could be determined from the change in the capacitance of the sensor. The beam of uniform strength was used to determine that the deformation of dielectric membrane was homogeneous. The results of the experiments showed the change in capacitance almost increased linearly with the increasing of the force from 0 N to 2 mN, which was applied to the end of the beam. As the results indicate, the dielectric elastomer cantilever beam force sensor appeared to work well. Because the force was linear with the deflection at the free end of the cantilever beam, the proposed device can be used as a displacement sensor.

5.5. Multimodality of dielectric elastomer sensors

The tactile sense of the human skin not only includes physical responses such as strain, pressure, shear and torsion but also temperature and humidity. To mimic the human skin, the electronic skin must be designed to sense multimodality consisting of physical, biological and chemical stimuli. The integration of flexible and stretchable multiple sensors into wearable platforms has been developed for applications in human-activity monitoring, human-machine interfaces and personal healthcare [2, 3, 69, 85]. To assess these parameters, multimodal

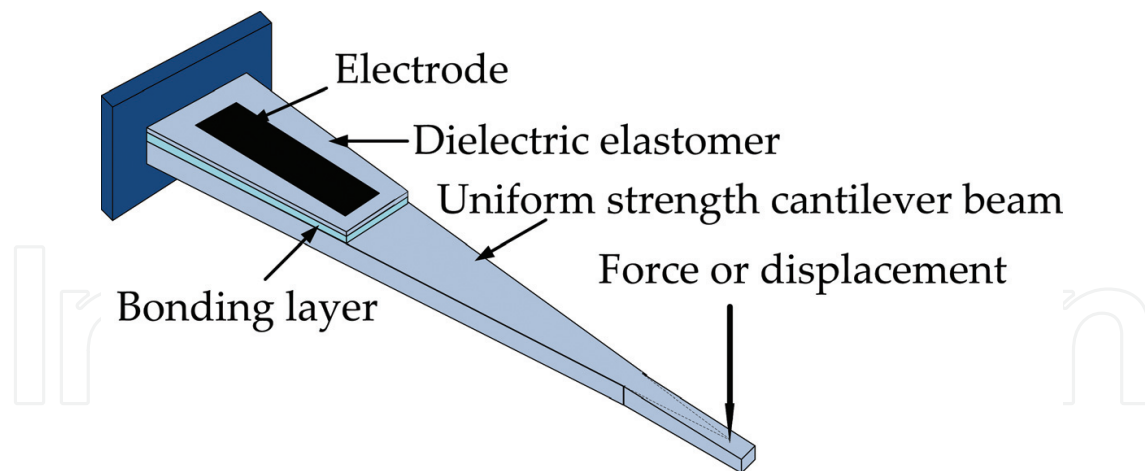


Figure 11. A sketch of the dielectric elastomer cantilever beam force sensor [84].

dielectric elastomer sensors have been tested. Kim et al. [2] described a highly sensitive and multimodal capacitive sensor composed of Ecoflex and carbon nanotube microyarns. The sensor was capable of measuring pressures as low as 0.4 Pa, temperature or humidity gradients and biological variables with different dipole moments in a single pixel. The measurements of mechanical deformation, humidity and biological variables were realized by the change in capacitance. The measurement of temperature was accomplished by determining a change in resistance. Ho et al. [69] developed a transparent and stretchable multimodal electronic skin sensor matrix. This sensor could measure pressure, thermal and humidity simultaneously using independent electrical signals. Graphene (chemical vapor deposition) electrodes sandwiched PDMS, which formed capacitive sensors for measuring pressure and strain. The graphene oxide (GO) and reduced graphene oxide (rGO) were used as impedance humidity sensor and resistive thermal sensor, respectively. The pressure, humidity and thermal sensors were integrated into a layer-by-layer geometry. In addition, excellent sensitivity of the sensors was demonstrated by monitoring moving hot air, breathing and finger touching.

In addition to the previously mentioned applications of dielectric elastomer sensors, other applications have also been developed. For example, a soft capacitive tactile sensor consisting of two sensing elements with different stiffness was reported for measuring tissue elasticity [86]. The results of tests using this device showed that the sensor could detect tissue elasticity from 0.1 to 0.5 MPa. Dielectric elastomer sensors have also been used as self-sensing actuators, such as pneumatic actuators [62], dielectric elastomer actuators [87], coaxial actuators [88] and McKibben actuators [39].

6. Conclusions and outlook

In this chapter, the primary sensing principles and materials used in flexible and stretchable dielectric elastomer sensors have been described along with the efforts to develop dielectric elastomer sensing devices for applications in soft robotics, structure health monitoring, electronic or ionic skin for human-activity and personal healthcare. In addition, developments in our own

laboratory on dielectric elastomers were presented, including cantilever force (displacement) sensors for soft robotics and transparent sensors used in structural health monitoring.

Highly sensitive, flexible and stretchable dielectric elastomer mechanical sensors have been developed for soft robots and personal healthcare; however, a tunable measurement range is needed for different positions on the human body or on robots. For practical applications of dielectric elastomer sensors, the performance of the sensors must be further improved to increase their durability and minimize drift and interference. The multiple dielectric elastomer sensors need be developed to improve their sensitivity in the measurement of temperature, humidity, chemical and biological stimuli. For future development, a sensor-integrated wearable platform with low-power consumption will be needed, which is equipped with a wearable power generator with high output efficiency as well as a power-storage device with large capacity [3].

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