Recent progresses on flexible tactile sensors

Yongbiao Wan, Yan Wang, Chuan Fei Guo*

Department of Materials Science & Engineering, Southern University of Science & Technology, Shenzhen, Guangdong 518055, China

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**Abstract**

With the popularity of intelligent terminals, flexible electronic products present a huge market prospect. Tactile sensors are a new type of electronic devices which provide the possibility for a machine to interact with the surroundings, being an emerging field after the rapid development of flexible electrodes—conformable tactile sensors or e-skins may enable the friendly interaction between a machine and human beings, or between machines. Flexible tactile sensors are possibly to combine advantages including flexibility, light weight, multiple functions, and low-cost, and have drawn extensive attention due to their wide application potential in wearable electronics and artificial intelligence. Here, we briefly review the state of the art of flexible tactile sensors, including the sensing mechanisms, signal transformations, common flexible sensing materials and their application in tactile sensing. Finally, we also provide perspectives on the challenges and the future of tactile sensors.

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1. Introduction

Tactile sense plays a critical role to the basic perceived ability in human skin. It is also one of the direct forms that most creatures acquire information from the outside world. In the first few weeks of birth, the baby’s eyes are too immature to clearly see mother’s face. However, the baby’s tactile sense is surprisingly sensitive to mother’s skin [1]. Even a large proportion of information is obtained by vision, the visual deviation is also directly dependent on the correction of tactile information [2]. The miraculous tactile sense has also long been accumulated into various social interactions, such as handshaking and hugging. In recent years, with the rapid development of flexible electronics, artificial intelligence (AI), robotic technologies, the demand for safe and friendly interaction between human beings and machines has become an important topic. A man-made tactile sensor, a device for detecting external stimuli, converts the stimuli into measurable or recordable signals. Most stimuli are produced by physical contact, and similar to human skins, a tactile sensor is expected to detect pressure, strain, temperature, and even humidity.

After years of extensive investigation, the developments in sensing materials, novel fabrication methods, and electrical sensing principles have contributed to significant progresses of flexible tactile sensors, and some flexible tactile sensors have demonstrated high sensitivity, high flexibility and even large stretchability, ultra-conformality, low cost, together with large-area fabrication [3–14]. In particular, a few flexible tactile sensors assembled with advanced sensing materials and high-performance electrodes exhibit high sensing capabilities beyond that of human skins [8,15]. These prominent features of tactile sensors enable successful applications in human-activity monitoring, personal healthcare, AI, etc. (Fig. 1) [5,9,11,16–31].

In this review we summarize the recent progresses of the flexible tactile sensors, covering the sensing mechanisms, functional materials, sensor design, and promising applications. We also address that some critical challenges, and perspectives on the development of tactile sensing devices in the last part of our review.

2. Fundamentals of flexible tactile sensors

2.1. Sensing mechanisms

The tactile sensing capabilities of the e-skin can be summed up as the measurements of pressure, strain, shear force, vibration, etc. In a tactile sensor, commonly used approaches for converting tactile information into electrical signals including piezoresistive, piezocapacitive, piezoelectric, and triboelectric types, as shown in Fig. 2. Here we briefly review the four types of sensing mechanisms below.
2.1.1. Piezoresistive tactile sensing

The principle of piezoresistive tactile sensors is based on piezoresistive effect, which occurs when the electrical resistance of a material of an interface changes in response to applied stimuli. Piezoresistive tactile sensors have been widely investigated owing to their simple device structure, low energy consumption, easy read-out mechanism, and broad range of detection. Fig. 2a shows the mechanism of piezoresistive sensors that convert mechanical signals to electrical signals. Generally, the resistance ($R$) of a conductor is described as $R = \rho L/A$, where $\rho$ is the resistivity, $L$ and $A$ denote the length and cross-sectional area of the conductor, respectively. In the case of strain sensors, the resistance change could be given by $\Delta R/R = (1 + 2\nu)e + \Delta \rho/\rho$, where $\nu$ and $e$ are Poisson’s ratio and strain, respectively. This resistance change is dependent on geometry and resistivity. In addition, the change in contact resistance ($R_c$) is another main source of the change of resistance. $R_c$ changes with applied force due to the change in geometry or contact area between the materials. The relationship between $R_c$ and applied force ($F$) could be given by $R_c \propto F^{-1/2}$, yielding a high sensitivity as well as a relatively large working ranges for


Fig. 2. Schematic illustrations of four typical transduction mechanisms: (a) piezoresistive, (b) piezocapacitive, (c) piezoelectric, (d) triboelectric.
piezoresistive sensors. Furthermore, piezoresistivity caused by a change in energy band structure has been observed in silicon [36], carbon nanotubes [37], and graphene [38], basically due to the fact that stress modifies band-gap and consequently the mobility of the charge carriers. Therefore a significant change in the resistivity is induced as a result of the variation of the mobility and density of the charge carriers [39].

Another mechanism leading to piezoresistance can be elaborated by quantum tunneling conduction which occurs in the case of conductive composites [40–43]. In general, conductive fillers (particle, wire, tube or flake) are embedded in an insulated polymer. The conductive fillers are placed close to each other but insulated by a thin polymeric layer, forming a tunneling barrier [40]. The quantum tunneling mechanism is achieved owing to the particular morphology of the conductive fillers, presenting sharp and nanostructured tips at the surface or very high aspect ratios of the particles. With the absence of any mechanical stimuli, the resistance value of the composite is extremely high, like an insulator. When compressed, stretched or twisted, however, the mechanical deformation induces a reduction of the polymer layer thickness among the conductive fillers, resulting in decrease of tunneling barrier. In that case, the conductive fillers form a tunneling pathway, and the probability of tunneling conduction increases, leading to a large reduction in resistance of the composite [43].

2.1.2. Piezocapacitive tactile sensing
Capacitance is the ability of a capacitor to store electrical charge. In general, a capacitor is in framework of two parallel plates that sandwich a dielectric (Fig. 2b). The capacitance (C) is given by $C = \varepsilon_0 A/d$, where $\varepsilon_0$ is the free space permittivity, $A$ is the area of the overlap of the two plates, and $d$ is the distance between the two plates [44]. In this equation, three of these variables ($\varepsilon_r$, $A$, and $d$) are sensitive to changes in strain and $\varepsilon_0$ is often a constant. The change in $\varepsilon_r$ can be used to detect forces by using specially designed materials, but this strategy has not yet been widely pursued. Changes in $d$ are typically utilized to measure normal forces [45], shear forces [46], and strain [47]. Capacitive devices for tactile sensing have demonstrated high sensitivity, compatibility with static force measurement, and low power consumption [44,48,49]. However, devices are susceptible to the interference from approaching objects that modify the fringe fields of the capacitor [50], and this effect may cause uncertain signals during measurement.

The sensitivity and responding speed of capacitive tactile sensors with elastomeric dielectrics is generally limited by the viscoelastic and incompressible nature of rubbers [45]. The performance of the tactile sensors can be improved by using a highly compressible dielectric. Consequently, air gap is commonly used for its high compressibility [46]. However, the formation of thin air gap requires patterning of the dielectric layer, and relatively large air gap leads to low capacitance and impaired sensitivities. By processing the dielectric into taper shapes, people are able to significantly diminish the adverse effect of the viscous properties of bulk elastomers, and the dielectric is possible to be made thinner. Small dielectric thickness that enables high capacitance has been utilized in highly sensitive tactile sensors [45].

2.1.3. Piezoelectric tactile sensing
Piezoelectricity is another commonly used transduction method for tactile sensing. The produced voltage in response to applied mechanical stresses is called piezoelectricity [51], which is derived from oriented, permanent dipoles in the material. Fig. 2c shows the occurrence of electric dipole moments. The deformation of oriented non-centrosymmetric crystal structures results in the separation of electric dipole moments and a piezoelectric voltage on the two sides [52]. For instance, in wurtzite-structured ZnO, the tetrahedrally coordinated Zn$^{2+}$ and O$^{2-}$ are stacked layer-by-layer along the c-axis. The charge centers of anions and cations coincide with each other in their undisturbed state. However, the structure is deformed when applied an external force. In that case, the charge centers of the anions and cations are separated and form electric dipoles, leading to the formation of a piezopotential. Consequently, the free electrons are driven to flow through the external circuit to screen piezopotential and achieve new balanced state [53].

Generally, piezoelectric coefficient ($d_{33}$) is a physical quantity that evaluates the energy conversion efficiency of the piezoelectric material. Typically, piezoelectric inorganics possess a high $d_{33}$ but a low flexibility, whereas piezoelectric polymers exhibit a high flexibility. To develop flexible piezoelectric tactile sensors with a high $d_{33}$, numerous efforts have been attempted, such as the use of piezoelectric polymers or inorganics/polymer composite [54,55], and the construction of piezoelectric inorganics on flexible substrates [23]. Owing to the high sensitivity and fast response time, piezoelectric sensors have been widely used in the detection of dynamic pressures such as vibrations of sound and slip [44]. Considering the inherent energy harvesting property, it could be assumed that the piezoelectric materials are a class of promising candidates for developing low power-consumption or self-powered tactile sensors.

2.1.4. Triboelectric tactile sensing
The triboelectric effect is a common phenomenon in our daily life. It appears when contacting materials are under friction caused by normal touch, shear friction from sliding motion, or torsions. However, the mechanism behind triboelectric effect is still being studied. It is generally believed that electrical charges are induced on the surface when two different materials are rubbed with each other. The amount of electrical charge generated depends on the difference in triboelectric polarities between the two contacting materials [56]. Fig. 2d shows the general principle of triboelectric sensors that convert mechanical energy into electrical energy. In an original state, the two materials have a small gap. When applied an external pressure, the two materials with different triboelectric polarities come into contact with each other, and the triboelectric effect induces opposite charges on both sides of surfaces [57]. After the strain is released, the two surfaces with opposite charges are automatically separated, and compensating charges are generated at each side of the top. Owing to the air layer between the materials, the charge on the two surfaces cannot be completely neutralized, forming a potential difference. This mechanism enables the triboelectric devices to generate electrical signals in response to various mechanical stimuli and thus can be used as self-powered tactile sensors.

2.2. Key parameters of flexible tactile sensors
To ensure practical applications of the tactile sensor, we need to evaluate key parameters including sensitivity, limit of detection (LOD), response time, stability and repeatability.

Sensitivity is a parameter that reflects the measuring effect and accuracy of the sensor. In general, the tactile sensitivity is defined as $S = \frac{\partial X}{\partial P}$, where $S$ is the sensitivity, $X$ is the quantitative output signals, and $P$ is the imposed stimuli. When $P$ is the applied pressure, the unit of sensitivity is kPa$^{-1}$. Whereas in the case that $P$ generated by external force is strain, the unit of sensitivity is dimensionless, thus the sensitivity is also called gauge factor (GF).

LOD, another key parameter, denotes the area of measurement containing the minimum and maximum value of the external
stimuli. The typical pressure in human body produced by daily activities is distributed in low-pressure regimes (<10 kPa, e.g., gentle touch) and medium-pressure regimes (10-100 kPa, enabling object manipulation) [45]. High LOD of tactile sensors is critical for sensitive detection, as well as accurate and safe manipulation of objects.

Response time is defined as the time consumption of a tactile sensor from the beginning of applying stimuli to generating a stable signal output. The dynamic response can be described for the response and recovery time, typically expressed as the time required rise to the maximum value or recovery to the initial state. Many tactile sensors operated in instant-response displays or real-time healthcare monitoring systems require fast response (rising edge < 100 ms). In addition to the above parameters, the applied voltage, which is related to power consumption of the device, should also sometimes be considered.Reducing the operating voltage and energy consumption is a stupendous challenge for the sustainable maintenance of tactile sensors [58].

Thus, we compare some typical flexible tactile sensors in terms of sensing mechanism, key materials, and the key parameters, including sensitivity, LOD, response/recovery time, and cyclic stability (Table 1).

3. Materials in tactile sensors

Traditional inorganic electronic materials are may not meet the requirement of high mechanical compliance due to their rigid feature. Compared with the common rigid sensor, advances in flexible or even stretchable materials may allow for the fabrication of flexible tactile sensors. Therefore, it is essential to explore strategies to design flexible electronic materials. Materials with the combination of high mechanical compliance, favorable electrical properties, and the ability of large-area processing are urgently desired to make high-performance flexible tactile sensors. In the following, we summarized some functional materials including substrate materials, active materials, and flexible electrodes.

3.1. Substrate materials

The substrate, although does not contribute directly to the sensing function, may determine the flexibility of tactile sensors. For traditional tactile sensors, silicon, ceramics, and glass have been utilized as substrate [76–78]. However, these materials are brittle, limiting the practical applications of tactile sensors. In order to meet the requirements with flexibility in real-world applications, materials that are highly flexible or stretchable, and corrosion resistant are needed for substrates.

Polydimethylsiloxane (PDMS) is a well-studied and promising substrate for flexible electronics on account of simple process, large stretchability, high transparency, and chemical inertness [5,79,80]. Typically, a PDMS membrane exhibits a transmittance higher than 95% and stretchability over 100%. The cross-linked molecular chain of PDMS makes it recoverable after tension, torsion or compression. PDMS is also non-toxic, this allows for bio-applications on human skin or being implanted in body. Moreover, unlike many soft substrates, the high transparency of PDMS makes it an ideal substrate for photoelectronic devices. And interestingly, PDMS can mix with other electronic materials, offering the opportunity to fabricate PDMS-based composites for high-performance flexible tactile sensors [81].

Polyimide (PI) has been extensively used as substrate in flexible electronics owing to its excellent thermal stability, mechanical properties, and insulating feature [82]. A recent research has demonstrated that PI has a glass-transition temperature between 360 °C and 410 °C [83]. The high thermal stability of PI allows for fabricating devices that can work at high temperatures. In addition, PI film exhibits good bendability making it a preferred substrate material for flexible electronic sensing devices [6]. However, unlike PDMS, PI is not highly transparent, and cannot recover under large strains, such that it cannot be used as a highly stretchable substrate.

Other commercially available polymers, such as polyethylene terephthalate, polyethylene, and polyurethane, can also be employed as substrate materials for flexible tactile sensors [60,84,85]. Besides the synthetic polymers, some ordinary materials have also been developed as substrates for flexible electronics. For instance, paper, as a renewable resource, possesses features including low price, light weight, and good flexibility, and has been used in flexible tactile sensor [63,86,87]. Silk fiber, as an abundant biomaterial, can meet the mechanical requirement to endure relatively large deformation [88]. Silk fibers also exhibit other useful properties such as biodegradability, biocompatibility, and solution-processability, thus is a promising and environmentally

<table>
<thead>
<tr>
<th>Sensing mechanism</th>
<th>Key materials</th>
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<th>References</th>
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<tr>
<td>Piezoresistive</td>
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<td>[24]</td>
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<tr>
<td>Piezoresistive</td>
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<td>Piezoresistive</td>
<td>PPy</td>
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<td>8000</td>
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<tr>
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<td>10,000</td>
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<tr>
<td>Piezoresistive</td>
<td>Alumina ceramic</td>
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<td>100 kPa</td>
<td>–</td>
<td>–</td>
<td>[64]</td>
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<tr>
<td>Piezoresistive</td>
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<td>0.7 kPa</td>
<td>2.5 Pa</td>
<td>–</td>
<td>–</td>
<td>[65]</td>
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<tr>
<td>Piezoresistive</td>
<td>PDMS/Rubrene</td>
<td>0.55 kPa</td>
<td>3 Pa</td>
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<td>–</td>
<td>[45]</td>
</tr>
<tr>
<td>Piezoresistive</td>
<td>Ionic conductor</td>
<td>0.01 kPa</td>
<td>1% strain</td>
<td>–</td>
<td>1000</td>
<td>[66]</td>
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<tr>
<td>Piezoresistive</td>
<td>Fluororesilicone/air gap</td>
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<td>0.5 kPa</td>
<td>&lt;40 ms</td>
<td>–</td>
<td>[67]</td>
</tr>
<tr>
<td>Piezoelectric</td>
<td>PVDF-TiFe</td>
<td>0.41 V Pa</td>
<td>20 Pa</td>
<td>–</td>
<td>–</td>
<td>[68]</td>
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<tr>
<td>Piezoelectric</td>
<td>PVDF-TiFe</td>
<td>2.3 kPa</td>
<td>–</td>
<td>0.17 s</td>
<td>–</td>
<td>[69]</td>
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<tr>
<td>Piezoelectric</td>
<td>ZnO nanowires</td>
<td>2.1 μS kPa</td>
<td>–</td>
<td>0.15 s</td>
<td>1000</td>
<td>[70]</td>
</tr>
<tr>
<td>Piezoelectric</td>
<td>Polypropylene</td>
<td>0.001 kPa</td>
<td>2 Pa</td>
<td>–</td>
<td>–</td>
<td>[71]</td>
</tr>
<tr>
<td>Piezoelectric</td>
<td>Graphene</td>
<td>389</td>
<td>0.3% strain</td>
<td>–</td>
<td>3000</td>
<td>[72]</td>
</tr>
<tr>
<td>Trubolectric</td>
<td>PDMS/Ag nanowires</td>
<td>28 mV N⁻¹</td>
<td>40 N</td>
<td>0.4 s</td>
<td>–</td>
<td>[73]</td>
</tr>
<tr>
<td>Trubolectric</td>
<td>PDMS/ZnS</td>
<td>6 MPA⁻¹</td>
<td>0.6 kPa</td>
<td>8.7 ms</td>
<td>–</td>
<td>[74]</td>
</tr>
<tr>
<td>Trubolectric</td>
<td>PDMS/ITO</td>
<td>0.29 V kPa</td>
<td>0.4 kPa</td>
<td>0.1 s</td>
<td>–</td>
<td>[56]</td>
</tr>
<tr>
<td>Trubolectric</td>
<td>PDMS/PET</td>
<td>0.06 kPa</td>
<td>1 kPa</td>
<td>70 ms</td>
<td>10,000</td>
<td>[75]</td>
</tr>
</tbody>
</table>
friendly candidate for flexible tactile sensors [44,89].

3.2. Active materials

Active layer is an important component in flexible tactile sensors. The active materials with excellent mechanical and electrical properties are desired to meet the requirement of high-performance sensing device. Up to date, carbon nanotubes (CNTs), graphene, conductive polymers, metal and semiconductor nanowires have been used as the active materials for tactile sensors. The details of these materials are discussed below.

3.2.1. CNTs

CNT, as a carbon allotrope, is a one-dimensional cylindrical nanostructure with remarkable charge carrier mobility and robust mechanical properties, as well as high chemical stability [90]. Generally, CNTs with an appropriate chiral angle display high sensitivity owing to changes in the band structures when subjected to a mechanical deformation [91]. In addition, CNT also exhibits excellent mechanical strength and elasticity [92]. At present, there have been many preparation methods of CNTs that can realize large-scale and continuous preparation. On the basis of high throughput synthesis, there are simple solution methods including vacuum suction filtration [93], spin coating [94], spraying [95], and inkjet printing [96].

Several studies have been presented on CNTs based tactile sensors. Bao et al. reported a pressure sensor based on transparent, conducting spray-deposited films of single-walled carbon nanotubes (SWCNTs) [47]. By applying strain biaxially followed by releasing the strains, spring-like nanotubes would be produced as shown in Fig. 3a. The film accommodated strains of up to 150%, demonstrating a high conductivity of 2, 200 S cm$^{-2}$ in a stretched state, and was used as an electrode in arrays of stretchable piezo-capacitive strain sensor (Fig. 3b and c). More interestingly, Hata et al. developed a new type of stretchable CNTs strain sensor for the change in resistance versus strain for the strain sensor. Reproduced with permission from Ref.[22]. Copyright © 2011. Nature Publishing Group.

3.2.2. Graphene

Graphene, another carbon allotrope, has attracted tremendous attention since its first isolation by Geim and Novoselov in 2004. It exhibits several desired properties including excellent mechanical flexibility and stability, high intrinsic carrier mobility (200,000 cm$^2$ V$^{-1}$ s$^{-1}$), and is possibly used for large-scale fabrication at low cost [97]. The growing interest of graphene is driven not only by its unusual physical properties, but also by its potential to develop various sensors. Upon stretching, the structure of hexagonal honeycomb near the edge of the graphene film would be partially devastated, enabling a significant change in the electronic band structure and resistance of the film [98,99]. Based on the unique advantages, several studies have been carried out to explore the application of graphene for tactile sensors.

Zhu et al. synthesized graphene woven fabrics (GWF) with a CVD method using copper mesh instead of copper foil as the catalyst [27]. The GWF film was transferred onto a stretchable PDMS substrate and assembled to a flexible piezoresistive strain sensor, which possessed unique features including ultra-light, relatively good sensitivity, high reversibility, superior physical robustness, etc. (Fig. 4a, b). Significantly, the sensor could be employed in the detection of human motion, such as hand clenching, phonation, expression change, blink, breath, and pulse (Fig. 4c). In addition, Lee et al. used crumpled graphene and nanocellulose to develop a high-performance piezoresistive strain sensors, which exhibited a high stretchability of up to 100% and a high sensitivity (GF = 71) [26]. Tian et al. reported a flexible piezo-resistive tactile sensor based on a foam-like graphene fabricated by using a laser-scribing method as shown in Fig. 4d [100]. By

![Fig. 3.](image-url)

(a) SEM image of spring-like SWCNT film. Scale bar, 600 nm. (b) Photograph of stretchable capacitive strain sensors array. (c) Map of the estimated pressure profile over a two-dimensional area. Scale bar, 2 mm. Reproduced with permission from Ref. [47]. Copyright © 2011. Nature Publishing Group. (d, e) A strain sensor based on aligned arrays of SWCNT: (d) Schematic of Key steps in fabricating the SWCNT strain sensor. (b) Relative change in resistance versus strain for the strain sensor. Reproduced with permission from Ref. [22]. Copyright © 2011. Nature Publishing Group.
integrating two laser-scribed graphene films laid face to face, the structure could measure a wide pressure range. Particularly at low pressures (<50 kPa), the sensor demonstrated a high sensitivity of 0.96 kPa⁻¹ (Fig. 4e). Moreover, a 5 × 4 array of pressure sensors was also integrated in a chess board, achieving the electronically identifiable location of chess pieces (Fig. 4f).

3.2.3. Conductive polymers

Conductive elastomers have drawn extensive attention due to the fact that they present excellent mechanical properties and keep electrically conducting at strained states. Commonly used conductive polymers, such as intrinsically conductive polymers, conductive polymeric composite, and ionic conductors, have been developed for the production of flexible and stretchable tactile sensors.

Conductive polymer can be synthesized by using large-area solution-process. For instance, Bao et al. used polypyrrole (PPy) hydrogel with a morphology of hollow microspheres as the active element in a piezoresistive tactile sensor (Fig. 5a, b) [32]. Owing to the low elastic modulus of PPy spheres and the contact sensing...
mechanism, the sensor exhibited a high sensitivity of 133 kPa$^{-1}$ (Fig. 5c) and unprecedented LOD (less than 1 Pa) with a fast responding speed. Furthermore, conductive elastomer composite is a common choice as active materials for the production of resistive strain sensors owing to the high conductivity and high anisotropy [28,44,101,102]. Generally, filling conductive filler, such as CNTs, graphene, carbon black, metal nanowires, metal particles and conductive polymer into the elastomer is a good way to fabricate conductive polymeric composite [16,43,103–105]. Yao et al. used a polyurethane sponge as a flexible support filled with graphene in a flexible piezoresistive strain sensor (Fig. 5d) [60]. This structure displayed a high sensitivity (Fig. 5e) and cycling stability due to the instantaneous change in contacting area between the fiber networks under the applied force.

Ionic conductors, such as hydrogels and ionogels possess large stretchability and high transparency, which are promising candidates for flexible tactile sensor [106,107]. Generally, polymers that swell in brine are called hydrogels, and many of which are biocompatible. They can be softer than tissues and thus realize “mechanical invisibility” required by biometric sensors to monitor soft tissue [106]. In contrast to the traditional conductive materials, ionic conductors utilize ions instead of electrons as charge carriers, and respond to mechanical signals in the form of resistance or capacitance. Suo et al. reported a highly stretchable, transparent, and biocompatible ionic skin [66]. The sensor can detect the deformation with a wide range of strain up to 700% and exhibit an unsatisfactory LOD as low as 1 Pa.

### 3.2.4. Metal materials

Metal materials, such as metal nanowires, nanoparticles, and thin film, possess high conductivity compared with other materials, and could be employed as an active layer for flexible tactile sensors. For instance, Hong et al. used silver nanowires embedded PDMS with a multiscale structure to fabricate a highly sensitive pressure sensor [108]. The sensor based on the piezocapacitive sensing mechanism showed a high sensitivity (>3.8 kPa$^{-1}$), a high bending stability and high cycling stability. Gold nanoparticles were also developed for flexible piezoresistive strain sensor by Qian et al. The sensor demonstrated a high sensitivity ($GF = 300$) under a 0.3% strain and an ultrafast response to the external acoustic vibration within a frequency range of $1–20,000$ Hz [109]. Furthermore, Zhang et al. integrated commercial abrasive papers with micro-cracked Au nanofilms to construct cuttable and self-waterproof crack-based piezoresistive bending strain sensors [63]. The sensor showed a high sensitivity ($GF = 75.8$) under applied strains in the range of 0–0.59%, ultrahigh stability and durability under over 18,000 loading-unloading cycles, and a fast response time of 20 ms. It is worth noting that metals in many cases play the role of both electrode and active layer, and we will discuss flexible electrodes in detail next.

### 3.3. Flexible electrodes

In flexible tactile sensors, electrode is required to mechanically match other materials. In fact, for some tactile sensors an electrode sometimes also plays as active elements. For many piezoresistive devices, the applied stimuli make the variation in contact sites between the electrodes, resulting in a resistance change and an effective current signal output. The ideal electrode for flexible tactile sensor should possess high mechanical flexibility, low strain fatigue, as well as high transparency in some cases.

Metal electrodes are now an extensively investigated group for flexible tactile sensors. A common form of metal electrodes is metal thin film (<100 nm). Typically, metal films does not damage under bending or folding. However, under stretching, metal films may form cracks. Graz et al. reported a stretchable electrode of gold thin film (50 nm) on PDMS substrate. Under stretching, the cracked gold film develops into an interconnected network, and the film could

![Fig. 6.](image-url)
be elongated reversibly within 20% strain without electrical failure after more than 250,000 stretching cycles [110]. To obtain better electrical property under a large strain (over 100%), some unique geometrical designs have been reported, such as bulking [111], serpentine structure [112], foaming [113], and metal encased in an elastomer [112], etc.

Another form of metal electrodes is metallic nanowire network, which can be silver, gold or copper because these metals have high conductivity. For example, Lee et al. developed a metal electrode with percolating ultralong silver nanowire network on elastic substrate, displaying a low sheet resistance (~9 Ω sq⁻¹) and could accommodate strains of over 460% [114]. More interestingly, Guo et al. reported a highly stretchable and transparent gold nanomesh electrodes by using a method which they call grain boundary lithography (Fig. 6a) [115]. The gold nanomesh consisted of serpentine and was transferred onto PDMS substrate. Upon stretching, the gold nanomesh undergoes two stages: at small strains, the deformation is elastic, and the stretchability comes from the out-of-plane deformation of the serpentine. Beyond the elastic regime, however, distributed slits forms and making the film a larger scale network, resulting in improved stretchability (Fig. 6b). The authors also found that by using a prestretched substrate and reducing the interface adhesion between the metal nanomesh and the substrate, the electrode can be stretched to 150% for 50,000 cycles without any fatigue (Fig. 6c) [116].

The composite of elastic polymers and conductors can also be applied as electrode materials. Zhang et al. prepared a high-performance pressure sensor based on aligned carbon nanotubes/graphene electrode, which showed high sensitivity and stability [14]. Lee et al. used the conductive elastomeric composite of polyurethane (PU)-poly(3,4-ethylenedioxythiophene) polystyrenesulfonate (PU-PEDOT:PSS) as the electrode material to develop flexible strain sensor, which is made of a novel sandwich-like stacked piezoresistive nanohybrid film of SWCNT and PU-PEDOT:PSS (Fig. 6d) [21]. The sensor showed a high stretchability of up to 100%, and a sensitivity (GF = 62). Such performance allows the sensor to detect small deformation induced by emotional expressions such as crying, laughing, as well as eye movement (Fig. 6e and f).

4. Device design towards practical tactile sensor

Wearable tactile sensors with high sensitivity, large stretchability, fast response time, and high stability require novel approaches in material design and structural engineering. High-quality materials, novel manufacture methods, and innovative device design considerations that can meet various requirements in practical applications should be provided. Herein, we discuss some strategies that may offer a direction for designing and fabricating high-performance tactile sensors.

4.1. Construction of device

The sensing performance of most piezoresistive tactile devices is usually determined by the mechanical properties of bulk materials. The relative large modulus and viscoelasticity lead to poor sensitivity and low responding speed [32]. A possible solution to this issue is to use micro/nanopatterned structure, which can contribute to significant change in contact resistance under external stimulus. Up to the present, many efforts have been extensively carried out to explore novel micro/nanopatterned materials. In particular, various design strategies based on bionic micro/nanostructures have been reported to enhance the tactile sensors’ mechanical compliance, sensitivity, selectivity, and response time. In bionic micro/nanostructures, the structural design of hierarchy [117], interlocking [24], crack [118], and whisker [119,120] have imitated the biological structures to acquire stress-direction-sensitive variation and easy deformation, resulting in high-sensitivity response to diverse stimuli, such as normal, shear, tensile, and vibration forces as well as multidirectional stresses.

In human tactile system, the interlocking structure of the intermediate ridge at the epidermal-dermal interface (Fig. 7a) plays a key role in the effective transduction and amplification of the nearby mechanoreceptors [121]. It has been demonstrated that the capability of interlocked intermediate ridge is attributed to the stress concentration at the intermediate tip of the ridge [121]. Inspired by the interlocked epidermal—dermal layers, tactile-direction-sensitive tactile sensors with an interlocked microstructure have been investigated. Fig. 7b displays a resistive tactile sensor based on the composite of multi-walled carbon nanotubes and PDMS film with an interlocked microstructure [61]. Under applied forces, the two layers of interlocked microdome arrays can have a large change of contact area and thus the large variation of tunneling piezoresistance, resulting in a high sensitivity (Fig. 7c).

The unique microstructure of interlocked microdome arrays can also provide different levels of deformation in response to various mechanical stimuli including normal, shear, stretching, bending, and twisting forces.

As another approach based on bionic structure, cracking of materials have been demonstrated to effectively enhance the performance of tactile sensors. Kang et al. developed an ultrasonisensitve strain sensor inspired by the cracks on the slit organ of spider (Fig. 7d and e) [118]. The nanoscale cracks on the flexible substrate can readily be deformed in response the small applied forces, inducing a sensitive change of electrical resistance in response to the external stimuli including pressure and strain. The sensor is reversible, reproducible, durable and mechanically flexible and can also be employed in the detection of acoustic sounds and physiological signals (Fig. 7f).

Whisker structures can be found in mammals (Fig. 7g) and insects, functioning to monitor tiny stimuli such as airflow and surrounding obstacles [120,122]. By mimicking whisker structures, highly sensitive and bendable tactile sensors have been demonstrated. As shown in Fig. 7h, electronic whisker arrays composed of conducting polymer—CNT films and high-aspect-ratio elastic fibers coated with CNT/Ag nanoparticles provide the reliable sensing of the directionality and intensity of mechanical stimuli, which can detect gentle pressure induced by gas flow (Fig. 7i) [120].

4.2. Power consumption and manufacturing costs

Fabricating flexible tactile sensors with low-power consumption is essential for practical applications. Piezoelectric and triboelectric phenomena offer the opportunities to develop self-powered tactile sensor [123–126]. Significant progress has been witnessed to explore related functional materials as well as to fabricate self-powered tactile sensing devices. One interesting example is the triboelectric device based on micropatterned plastic films [126]. The self-powered pressure sensor can induce a voltage signal after an external stimulus and can successfully detect a water droplet or a falling feather with a low-end detection limit of ~13 mPa. Another example is a tactile sensor based on a piezoelectric change in the ZnO nanowire under small external forces. By integrating 700 lines of ZnO nanowires into an array, the device generates a peak voltage of 1.26 V at a low strain of 0.19% [127]. These outstanding properties, together with the power generation capability upon deformation allow a variety of potential applications in self-powered micromechanical components.

To realize the low manufacturing cost of the flexible tactile sensor, simple device structure and efficient fabricating crafts are
desired. Various simple-structured tactile sensors have been developed with cost-effective structures. As mentioned above, micropatterned surface can improve the performance of tactile sensors. However, traditional approach to acquire the microstructures is mainly realized by using lithographic processes, which are typically expensive, complicated, and time-consuming. To solve this issue, unconventional approaches for obtaining micropatterned substrates have been investigated. For examples, Wang et al. reported a high-performance pressure sensor by using a low-cost method [59], for which large-scale micropatterned PDMS film was molded from silk textile (Fig. 8a, b), and then a SWCNT film was coated on micropatterned PDMS as the active layer. By assembling two layers of patterned SWNTs/PDMS films (Fig. 8c), the structure demonstrated ultrahigh sensitivity, rapid response time, great stability and repeatability, and a limit of detection as low as 0.6 Pa. More interestingly, Li et al. reported a flexible piezocapacitive tactile sensor based on micropatterned PDMS molded from lotus leaf [13]. By integrating polystyrene, Au film, and micropatterned PDMS as shown in Fig. 8e, the tactile device presented stable and high sensing performance including high sensitivity ($S = 0.815 \text{ kPa}^{-1}$), wide dynamic response range (from 0 to 50 N), and fast response time (≈ 38 ms). Other microstructures molded from rose petal [128], mimosa leaf [62], and E. aureum leaf [14] have also been investigated for tactile sensing device.

### 4.3. From single functional device to multifunctional sensing

To imitate the complex characteristics of the human body sensing elements, man-made tactile sensors should not only respond to applied pressure, but also possess the capacity to distinguish various mechanical stimuli including torsion, shear, bending and stretching, which are usually produced during the interaction between human and surrounding circumstances. For instance, Suh et al. reported a flexible tactile sensor using electrode contacting mechanism, in which two interlocked arrays of high-aspect-ratio Pt coated polymeric nanofibers were supported on the thin PDMS layers [24]. The fabricated flexible sensors can sensitively respond to multiple mechanical stimuli including normal pressure, shear, and torsion (Fig. 9a). Via the hair-to-hair interlocked nanofibers, each small deformation produced by an applied stimulus is converted into a different electrical signal. Notably, each stimulus in the form of pressure, shear, or torsion results in a unique, recognizable waveform of the obtained signal. The successful detection of these three different mechanical modes indicates that these sensors could be potentially to be applied in AI.

Apart from several modes of mechanical stimuli, tactile sensor for multiple physical stimuli, such as temperature, humidity, or even biological, chemical variables have also been developed. Temperature is one of the most common sensing parameter in nature and organism. Real-time detection of environmental or
Body temperature is of great significance in cardiovascular health, cognitive state, malignancy, pressure ulcers, and many other aspects of human physiology [129]. Humidity sensing can also provide clinically relevant information, such as blood, sweat and urine analyses, which could be employed in biomedical, nursing and geriatric care applications [130,131]. However, most of the existing tactile sensors have only one single function—the pressure measurement, and only quite a few tactile sensors exhibit multiple...
functions that can simultaneously detect the diverse external stimulus including force, temperature, humidity, etc. Several groups have developed tactile sensors that can differentiate and respond to mechanical stimulus, temperature, and humidity [130, 132–134]. By using a field-effect transistor integrated with multi-stimuli responsive materials as subcomponents of gate dielectrics (piezopyroelectric material) and channel (pyroelectric organic material), Park et al. fabricated a flexible bimodal sensor array that is able to detect pressure and temperature simultaneously (Fig. 9b–d) [134]. Takei et al. developed a highly sensitive multifunctional artificial electronic whiskers integrated with temperature and strain sensors by using printable nanocomposite inks [133]. Three-dimensional strain and temperature distribution could be mapped by using multifunctional electronic whisker arrays. Based on the electron tunneling effect in graphene quantum dots (GQDs), Berry et al. implemented a novel structure to detect humidity and pressure (Fig. 9e–g) [130]. The GQDs could selectively interface with polyelectrolyte microfiber, forming an electrically percolating-network. Under high humidity, the tunneling width in the GQDs network increases, thus resulting in a decrease in conductivity. The feature enables a good application in humidity sensing. These advances in bimodal tactile sensing technique make it possible for electronic devices to closely imitate the functions of their natural counterparts.

5. Conclusions and perspectives

In this article, we have briefly reviewed the work mechanisms of flexible tactile sensors and the efforts carried out to develop flexible sensing devices that have potential applications in human–activity monitoring, personal healthcare, artificial intelligent. The pursuits of new materials and novel preparation methods promote continuous progresses in improving sensor performance. In particular, some basic parameters of these sensors such as sensitivity, flexibility, and detection capability can even exceed those of the human skin. Moreover, multifunctional wearable tactile sensors that enable the simultaneous differentiation of complex stimuli information such as multi-component force, temperature, and humidity has been investigated intensively.

Despite the rapid progresses mentioned above, there is a big room of further improving the performance of flexible tactile sensors. In the preparation process, the present microfabrication methods represented by conventional lithographic techniques come at a price. Recently, some new methods inspired by nature have been developed to mimic the surface structures of some bio-surfaces, and such biomimetic surfaces are proven to be effective to be used as a part of high-performance tactile sensors. In addition, the printing manufacturing technology represented by 3D printing, is a promising technology in developing flexible electronics for its convenient and large-scale production [135, 136]. It is also urgent to explore new sensing mechanisms and multi-modal functions. Moreover, the battery miniaturization technology and small scale generators also need to be upgraded for low energy consumption and self-powered wearable tactile sensors.

To obtain combined features for practical applications, integrated tactile sensing system that incorporates multiple components is another research focus. In addition to the functions of mimicking human skin such as sensing of pressure, strain, temperature, and humidity, we should explore additional features of intelligent tactile sensors beyond the basic functions and physiognomy of human skin, probably including the detection of sound, light, heat, magnetic field, as well as chemical information. Hence, the highly integrated tactile sensing system is an important topic of both scientific research and real-world applications, indicating that flexible integrated circuits and other physical or chemical sensors should keep pace with the development of tactile sensor to meet the requirements of applications in robotics, human–machine interactions, health monitoring, and medical implant services.

Real-time and efficient tactile feedback is desired to achieve accurate and dynamic detection of external stimuli. For example, Fig. 10 shows an ideal artificial limb that is expected to transfer the signals of physical stimuli to real skin, and hereafter transfer to the brain, or directly transfer the tactile sensors to human brain via a brain-machine interface. In the future, an artificial hand with myoelectrical control might easily manipulate objects, while advanced tactile sensor and the feedback loop allows brain to receive tactile signals. Similar to the real skin that can provide real-time feedback of various external stimuli, future flexible tactile sensor will also intelligently respond to the complex variation in external circumstance. We expect that all these efforts will make flexible tactile sensors a glorious future.

Fig. 10. Schematic illustration of the tactile feedback system for an ideal artificial limb.
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