

Review Article

Recent progress in flexible tactile sensor systems: from design to application

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Abstract

With the rapid development of artificial intelligence, human-machine interaction, and healthcare systems, flexible tactile sensors have huge market potentials and research needs, so that both fundamental research and application demonstrations are evolving rapidly to push the potential to reality. In this review, we briefly summarize the recent progress of the flexible tactile sensor system, including the common sensing mechanisms, the important performance evaluation parameters, the device design trend, and the main applications. Moreover, the device design trend towards flexible tactile sensor systems nowadays is discussed, including novel structures for outstanding performance, sensor arrays for large-area information acquisition, multi-mode information acquisition, and integration of tactile sensors with transistors. Various emerging applications enabled with these sensors are also exemplified in this review to show the potentials of the tactile sensors. Finally, we also discuss the technical demands and the future perspectives of flexible tactile sensor systems.

Keywords: Tactile sensor, flexible sensing, sensor system

1. INTRODUCTION

Tactile sensation is the basic perception ability of human skin, which is a kind of feeling produced by tactile receptors in response to external stimuli. There is a tactile cone in the deep layer of the skin, where the various tactile mechanoreceptors respond to the pressure exerted on the skin surface and generate a small current signal, which is immediately transported to the brain through the nerve fibers. The sense of touch is enabled by distinguishing the magnitude and the position of the signal [1]. The touch of the finger is the most sensitive as a result of the maximum contact density distributed on the finger's abdomen, providing one of the most direct resourceful means for the human to obtain interactive information from the environment. Humans can feel the temperature, humidity, material type, shape, surface texture, hardness, vibration, and other information of the target object through touch. However, the tactile sensation of human skin cannot quantitatively gain the specific sensing

parameters. Mimicking the functionality of the human skin, a tactile sensor is a sensing system that can detect pressure, strain, temperature, humidity, and other information about an object. The measured information is converted into electrical signals and analyzed by an external processing circuit to obtain a more accurate tactile detection capability than the human skin [2]. The tactile sensor needs to be flexible to adapt to objects with different surfaces morphologies, and shapes, as is an important difference between the tactile sensor and the traditional sensor.

In recent years, with the rapid development of flexible electronics and the rapid popularization of intelligent terminals, the flexible tactile sensing technology has been developed rapidly, and widely used in intelligent robots, human-machine interfaces, virtual and augmented reality, medical treatment, health monitoring, and other emerging applications (Fig. 1). Meanwhile, to satisfy the requirements of numerous emerging applications, flexibility, sensitivity, sensing range, response time, stability, and other performance parameters of flexible tactile sensors are also continuously improved [3-19]. Through the optimization of sensing material and device design, an ultra-thin sensor was realized without any sensory interference [20]. A multimode integrated tactile sensor system that can detect strain, temperature, and gas simultaneously was reported [21]. Wireless tactile sensors were enabled with the development of Bluetooth transmission and near field communication technology [22-24]. To extend the application fields, a sensor array was realized to decode the facial strains through machine learning [25], and a sweat sensor that can detect blood glucose, nicotine, and other health information was developed [26-28]. Thus, flexible tactile sensing has sufficient momentum of development and huge market potentials. Therefore, both fundamental research and application demonstration are evolving rapidly to push the potentials to reality.



Fig. 1. Diagram of application of flexible tactile sensor: Human-machine interfaces. The brain-computer interfaces. Reproduced with permission from Ref. [97]. Copyright© 2018. AAAS. Integrated contact lens sensor system. Reproduced with permission from Ref. [94]. Copyright© 2021. Elsevier. Constructed sensor sleeve. Reproduced with permission from Ref. [105]. Copyright © 2020. Springer Nature; Intelligent robots. Microrobots, reproduced with permission from Ref. [96]. Copyright© 2020. OAE Publishing Inc. Robot hand responding to “ok” gesture. Reproduced with permission from Ref. [57]. Copyright© 2021. Elsevier. Social robotics. Reproduced with permission from Ref. [97]. Copyright© 2018. AAAS; Health monitoring. Tactile sensor for speaking pressure monitoring. Reproduced with permission from Ref. [52]. Copyright© 2014. Springer Nature. A wireless sensor system for health monitoring in neonatal. Reproduced with permission from Ref. [23]. Copyright© 2021. Springer Nature. Flexible exoskeleton. Reproduced with permission from Ref. [100]. Copyright© 2021. AAAS; Medical treatment. A piezoelectric sensor for energy harvesting in the operation of heart pacemakers. Reproduced with permission from Ref. [54]. Copyright© 2014. PNAS. Eye astigmatism treatment system.

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In this review, we summarize the recent progress of the flexible tactile sensor systems. After a short introduction about the common sensing mechanisms, the important parameters to evaluate the sensor performance are summarized, with typical data reported for different mechanisms listed for comparison. The development trend of tactile sensor systems is covered in section 3. Starting from the performance optimization for a single tactile sensor emphasizing certain performance indicators, we further discuss the multimode tactile sensor aiming to obtain multiple sensing capabilities, and the integration of processing circuits with the tactile sensor systems. The outstanding properties of the tactile sensors cover ultra-high sensitivity, self-powered operation, wireless connection, self-repairing capability, degradable material system, good biocompatibility, and nontoxicity. These properties enable wide applications including virtual and augmented reality, intelligent robots, human-machine interfaces, medical treatments, and wearable health monitoring, which are discussed in section 4. Finally, we address the potential development trends and remaining challenges for the flexible tactile sensor systems in future research.

2. WORKING PRINCIPLES OF THE FLEXIBLE TACTILE SENSORS

2.1. Sensing mechanisms

Tactile sensors usually convert the tactile information into electrical signals. They can be classified as piezoresistive, piezoelectric, capacitive, inductive, electromagnetic, photoelectric, and triboelectric types depending on the transducing mechanisms. The most widely used four types of tactile sensors are piezoresistive, capacitive, piezoelectric, and triboelectric, which are briefly reviewed as follows. The basic mechanisms of these four types are briefly shown in Fig. 2.

2.1.1. Piezoresistive mechanism

The piezoresistive tactile sensor is built based on the strain-induced resistance variation, which can be easily detected by the resistance measurement system, as

shown in Fig. 2A. Generally, the resistance (R) of the piezoresistive tactile sensor is defined as $R=\rho L/A$, here ρ is the resistivity. L and A denote the length and area of the resistor, respectively. In response to the load applied by the contact operation, the change of the sensor resistance is of the following form:

$$dR = \frac{\rho}{A}dL - \frac{\rho L}{A^2}dA + \frac{L}{A}d\rho$$

The first two terms describe the resistance change due to the differential geometrical deformation effect, and the last term describes the resistance change due to the piezoresistive effect. For metallic conductors, the geometrical deformation effect usually dominates, while some semiconducting materials could exhibit a large piezoresistive effect, with which the order of magnitude for the signal is larger than that induced by the pure geometrical deformation. While the above equation can be used to explain the resistance change of a resistor formed by a single type of material, other factors also play an important effect for resistive tactile sensors, as the composition of the resistor includes both polymeric and inorganic nanomaterials. The change of the contact resistance between two conductive materials, and the change of conductive paths in conductive composites vary with the deformation of the flexible structures. For example, Zhang et al. embedded vertical aligned multi-walled carbon nanotube (CNT) arrays into the polydimethylsiloxane (PDMS) and bonded two CNT/PDMS films face to face to realize a tunable range piezoresistive tactile sensor by adjusting the thickness of the soft spacer between the two CNT/PDMS films. The resistance variation mainly results from increasing CNT contact area with applied pressure [29].

The piezoresistive tactile sensor has been widely studied and applied due to its simple structure design and readout mechanism. The piezoresistive tactile sensors have the advantages of simple structure, easy fabrication, low cost, high sensitivity [30, 31], and large measurement range, while there are also several drawbacks, such as obvious hysteresis effect, poor long-term stability, and requirement for external power supply, worthy of further investigating. The piezoresistive materials commonly used in

piezoresistive tactile sensors include monocrystalline silicon [32], Carbon nanotubes [29, 33-35], Carbon black [36], Graphene [37, 38], MoS₂ [39], and conductive polymers [40, 41].

2.1.2. Capacitive mechanism

The capacitive tactile sensor is based on the principle of capacitance change when the sensing structure responds to a mechanical stimulus, as shown in Fig. 2B. The capacitance (C) of the device can be calculated by using the parallel-plate capacitor model: $C = \epsilon_0 \epsilon_r A / s$, where ϵ_0 is the vacuum dielectric constant, ϵ_r is the relative dielectric constant of the material, A is the overlap area of upper and lower parallel plates, and s is the spacing between the upper and lower electrodes. Typical structures adopted in tactile sensors include the planar interdigital electrode/dielectric material and electrode/dielectric material/electrode sandwich structures. The differential capacitance of the sensing capacitor is given by:

$$dC = \frac{\epsilon_0 \epsilon_r}{s} dA - \frac{\epsilon_0 \epsilon_r A}{s^2} ds + \frac{\epsilon_0 A}{s} d\epsilon_r$$

Similarly, the first two terms describe the contribution by the geometrical deformation, and the last term describes the contribution by the material dielectric constant. As flexible dielectric materials usually exhibit a small Young's modulus, a large deformation can be induced by a gentle touch operation, resulting in a large differential capacitance.

Compared with the piezoresistive sensor, the sensitivity of the traditional capacitance sensor is relatively low, but it can be enhanced by using different micro- / nano-structures. As-fabricated nanostructured capacitor features air-gap between pillars sandwiched between the upper and lower electrodes, so that both the overlapped area and distance, as well as the effective dielectric constant are changed with applied pressure [42]. Beyond the traditional capacitive sensor, ionic sensor based on ion-interfacial sensing has been widely investigated in recent years because of its unique double electrode layer structure [44-46]. For instance, Guo et al. reported

an ionic sensor based on graded intrafillable architecture with a high sensitivity ($> 220 \text{ kPa}^{-1}$) in an ultra-broad sensing range (0.08 Pa-360 kPa) [45]. The advantages of capacitive tactile sensors include low energy consumption, independence of the operating temperature and good stability. However, its initial capacitance is very small so that it is very easy to be interfered with by the parasitic capacitance of the testing circuit, resulting in a poor signal-to-noise ratio. The dielectric materials commonly used in capacitance tactile sensors include air gap [42], TiO_2 [43], ionic conductor [44-46], Polyimide (PI) [47], elastomers [48, 49], and 3D fabrics [50, 51].

2.1.3. *Piezoelectric mechanism*

The piezoelectric tactile sensor is based on the piezoelectric effect, that is, generating electric displacement in response to the applied mechanical stimulus, as shown in Fig. 2C. Considering an application scenario that both normal and shear stress are applied to the piezoelectric tactile sensor, the differential electric displacement is given by $dD = -d_{31}T_1 - d_{32}T_2 + d_{33}T_3$, where d is the piezoelectric coefficients, and T is the applied stress, with the subscripts 1 and 2 describing the contribution from shear stress and 3 from the normal stress.

The piezoelectric tactile sensor has the advantages of high sensitivity, fast response time, and self-powered operation. As its operation does not have to involve the direct contact of the sensing object, it is widely used in the detection of acoustic vibration, sliding vibration, and other dynamic pressures. On the other hand, if an external force remains unchanged, the charge will be neutralized and cannot be measured statically. However, considering the unique energy collection characteristics of the piezoelectric materials, they have very important advantages in the development of fast dynamic response, low energy consumption, and self-powered flexible tactile sensors. The piezoelectric materials commonly used in piezoelectric sensors include lead zirconate titanate (PZT) [52-56], ZnO [57], BaTiO_3 [58], LiTaO_3 [59, 60], Group III-nitride (III-N) materials (AlN, GaN) [61-63], and intrinsic flexible polyvinylidene fluoride (PVDF) [64-66].

2.1.4. *Triboelectric mechanism*

The triboelectric effect is a common physical phenomenon in nature. When two substances with different electron binding energies contact with each other, one substance loses electrons to the other. This phenomenon is called the triboelectric effect [67]. The triboelectric tactile sensors are built based on the triboelectric effect. By contacting and then separating two materials with different binding energy in sequence, an electrical-potential difference is generated between the two materials. The resulting electric current flows through the external circuit, and converts mechanical energy into electrical energy, as shown in Fig. 2D. The research group of Wang Zhong-lin in the Georgia Institute of technology developed a triboelectric nanogenerator (TENG) using the triboelectric effect for the first time, which created a breakthrough way for energy collection technology [68]. As scientists continue to explore and study the triboelectric phenomenon, the triboelectric effect has been utilized for environmental energy harvesting [69].

The triboelectric tactile sensor has the advantages of simple structure, low cost, and lightweight, so it is an effective way of energy acquisition and dynamic information acquisition. Therefore, it is very suitable for building self-powered sensors to monitor and measure the surrounding information, such as speed, acceleration, and displacement. The materials commonly selected for triboelectric tactile sensors include polydimethylsiloxane (PDMS), polyvinyl alcohol (PVA) [70], Poly (3, 4-ethylene dioxythiophene) - poly- (styrene sulfonate) (PEDOT:PSS), Polyethylene terephthalate (PET) [71], polyacrylamide (PAM) [72], and graphene [73].

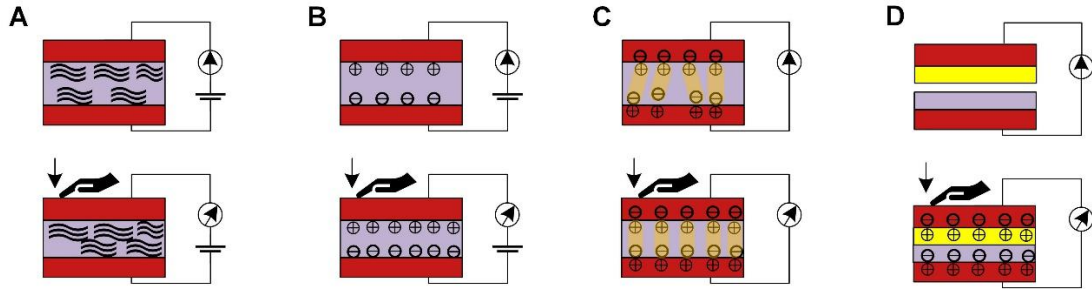


Fig. 2. Schematic illustrations of four sensing mechanisms: A. Piezoresistive; B. Capacitive; C. Piezoelectric; D. Triboelectric.

2.2. Performance evaluation parameters

One of the main advantages of a flexible tactile sensor over human skin is that it is a quantitative rather than a qualitative "feeling", as its electrical output signal corresponding to stimulation can be read out with an exact value. From this point of view, the performance of the flexible tactile sensor is evaluable and comparable. The main performance evaluation parameters of a flexible tactile sensor include sensitivity, sensing range, response time, repeatability, stability, and other indexes.

The sensitivity parameters and units for tactile sensors with different mechanisms are different. Generally, the sensitivity (S) can be defined as the ratio of the increment of the output signal (M) for the tactile sensors to the increment of the input pressure (P), described as $S = \partial M / \partial P$. The sensitivity may vary with the pressure, thus exhibiting a nonlinearity over the measured pressure range. For most tactile sensors, the sensitivity decreases with the increase of pressure. It is difficult to compare the sensitivity performance of tactile sensors with different mechanisms because the output physical quantities of them are different. To solve this problem, the relative change of the output signal, defined as $\Delta M / M_0$, can be introduced to define the sensitivity $S = \partial(\Delta M / M_0) / \partial P$, and the unit of the sensitivity is unified as Pa^{-1} . In some literature, the unit of sensitivity is $\text{V} \cdot \text{Pa}^{-1}$ or $\text{A} \cdot \text{Pa}^{-1}$ for certain, piezoelectric tactile sensors, corresponding to an output signal of voltage (V) or current (A), respectively. Besides, when the input stimulus is strain, the sensitivity is unitless and

is denoted as gauge factor (GF).

Sensing range refers to the pressure range that a tactile sensor can measure normally, and can be represented by the minimum and maximum pressure that the sensor can detect. High sensitivity tactile sensors often have a very low minimum sensing range, and the maximum sensing pressure is relatively small [74]. Meanwhile, the device that can sense a high external stimulus cannot sensitively respond to a small stimulus [75]. The tactile sensors with different response ranges can be applied in different situations. The pressure sensors with a large pressure detection range and low detection limit can be used for more tasks.

Response time describes how fast the tactile sensor changes its output signal in response to an external stimulus, which is also related to viscoelasticity and interface adhesion. There are some ways to calculate the response time. One is the time difference between the input time of external stimulus and the stable time of the response output, and the other is the time difference between the input time of input stimulus and the output response reach 90% or $(1-1/e)$ position. Besides, frequency response is also used to represent response speed. Periodic dynamic pressure can be applied to the tactile sensor to obtain the dynamic response and extract the time lag between the output response and input stimulus.

Repeatability refers to the coincidence degree of response curves between different cycles of measurement under the same measurement conditions. The stability of tactile sensors is evaluated by the drift of the response values after thousands or tens of thousands of cycles. The repeatability and stability are related to the irreversible deformation of the constituent materials in the process of material pressure deformation. Generally speaking, the less the irreversible deformation, the better the repeatability and stability.

In addition, flexibility is also a main evaluation parameter for the tactile sensors, and

it can be realized by adopting intrinsically stretchable materials and flexible structure designs. Nowadays, most of the flexible tactile sensors have achieved satisfactory flexibility [77, 84, 87]. Tactile sensors are expected to have high sensitivity to detect tiny pressure and hold a high sensitivity in a broad pressure range, simultaneously, which can be achieved by further exploring functional materials and proposing novel device design.

A perfect flexible tactile sensor that is impeccable in all sensing performance is certainly required, but most flexible tactile sensors cannot be perfect. We can design flexible tactile sensors with different performance highlights according to practical application requirements. Of course, the design of tactile sensors with more and more high-level performance indicators simultaneously will be an important research direction. Here, we list some typical tactile sensors with different sensing mechanisms and functional materials, and compare their sensing performance including sensitivity, sensing range, response time, and cycling numbers (Table 1).

Table 1. Summary for typical tactile sensors and comparison of their sensing performance.

Sensor mechanism	Functional materials	Sensitivity	Sensing range	Response time	Cycling numbers	reference
Piezo-resistive	MWCNTs/LIG	2.41kPa^{-1}	1.2-400Pa	2ms	2000	35
	CNTs/PDMS	12.1kPa^{-1}	600Pa	3.1ms	4000	34
		0.68kPa^{-1}	1kPa			
	CNT	50kPa^{-1}	300Pa-6.5 kPa	24ms	10000	29
	Carbon black	5.54kPa^{-1}	0.01-800k Pa	20ms	10000	36
	polymer	$7.7\text{-}41.9\text{ kPa}^{-1}$	<100Pa	47ms	8000	41
		$<0.4\text{ kPa}^{-1}$	>1kPa			

	MoS ₂	0.011kPa ⁻¹	1-120kPa	180ms	10000	39
Capacitive	PDMS/air gap	10 ⁷ kPa ⁻¹	1.5kPa	0.03ms	10000	42
	TiO ₂	4.4kPa ⁻¹	< 0.8Pa	< 16ms	50000	43
	PVDF/IL	1.194kPa ⁻¹	0-0.5kPa	40ms	5000	44
		0.109kPa ⁻¹	0.5-120kPa			
			a			
	3D networks	0.31 kPa ⁻¹	0.05-3.8kPa	-	5000	51
		0.03 kPa ⁻¹	3.8-6.3 kPa			
	Ionic conductor	54.31 kPa ⁻¹	<0.5 kPa	29ms	5400	47
	PVA/H ₃ PO ₄	> 220kPa ⁻¹	0.08Pa-360kPa	9ms	5000	45
Piezo-electric	PZT	~5μA·kPa ⁻¹	10Pa	~0.1ms	-	52
	PZT	0.018V·kPa ⁻¹	1-30kPa	60ms	5000	53
	PVDF/ZnO	0.33V·kPa ⁻¹	9N	16ms	5000	57
	PDA@BTO/ PVDF	9.3V·kPa ⁻¹	33kPa	61ms	1000	58
	BTO/PVDF	3.95V·N ⁻¹	3N	-	7400	65
	PVDF/SnO ₂ NS @SiO ₂	0.99V·kPa ⁻¹	10-30kPa	1ms	-	64
Tribo-electric	PDMS/PVA	-	>100%	70ms	12000	70
	NFs		(strain)			
	PDMS/ PET	0.06kPa ⁻¹	150kPa	70ms	10000	71
	PAM/PEDOT:P	1.58	2850%	200ms	1200	72
	SS		(strain)			

PEN/Graphene	1.63kPa^{-1}	0.1-6kPa	< 3ms	10000	73
	0.04kPa^{-1}	6-100kPa			

3. DEVICE DESIGN TOWARDS FLEXIBLE TACTILE SENSOR SYSTEM

In the previous section, we have introduced some typical tactile sensors with outstanding sensing performance such as ultra-high sensitivity up to 10^7 kPa^{-1} (Fig. 3A), a fast response time of 0.03ms (Fig. 3B) [42], broad sensing range of 10Pa-800 kPa (Fig. 3C) [36], and good stable performance after 50000 cycles of measurement (Fig. 3D) [43]. In other more specific applications, the corresponding performance parameter needs to be considered, including low detect limit (1.2 Pa) for response to tiny pressure [76], large stretchability (workable strain range of up to 187%) for application in flexible electronics [77], biodegradable [78], anisotropic [79], recyclable [80], and self-powered [81]. Based on the performance constraints, the design of tactile sensors involves the choice of working principle, the device structure design including the functional material, flexible substrate and electrode materials, as well as the fabrication technology. It may also entail further integration of information acquisition, processing technology, and multi-physical quantity fusion [82, 83].

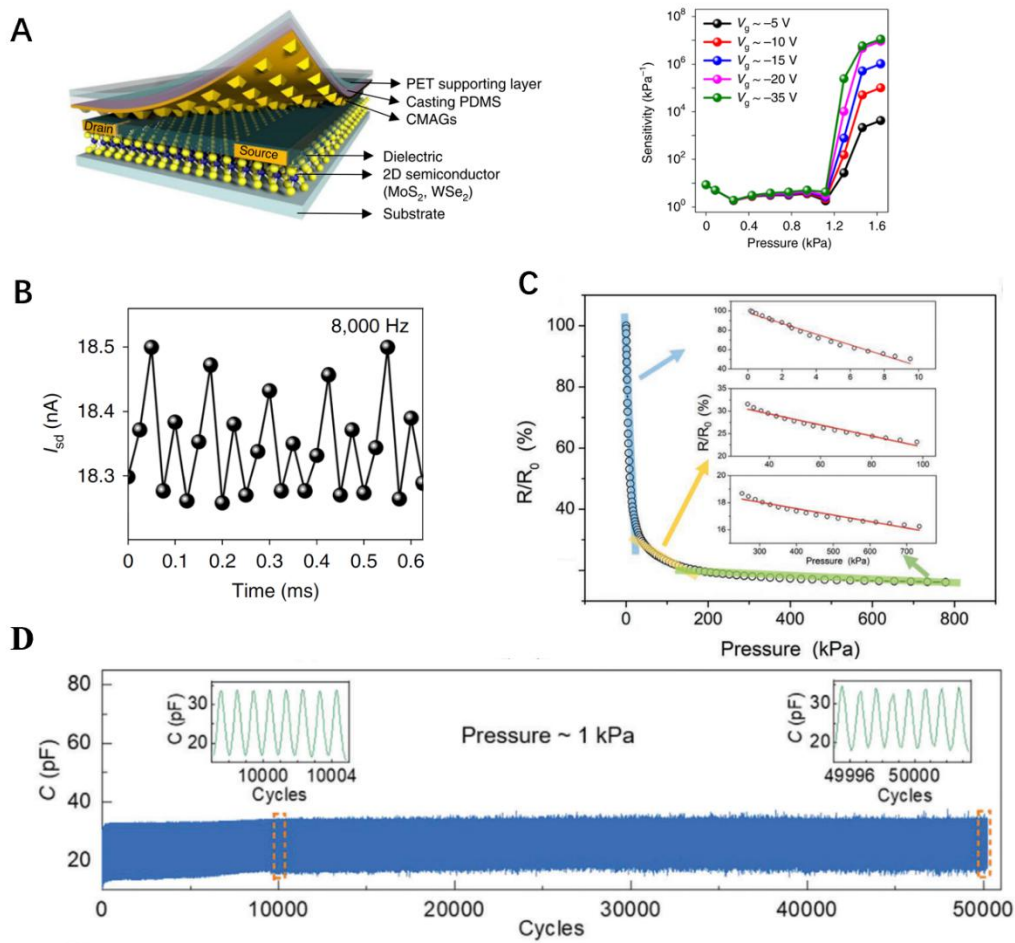


Fig. 3. Typical tactile sensors with outstanding sensing performance. A. Schematic of the tactile sensor based on air gaps and MoS₂ transistor and corresponding sensitivity up to 10⁷ kPa⁻¹; B. Highlighting the rapid response time, ~0.03125ms. A-B, reproduced with permission from Ref. [42]. Copyright© 2020. Springer Nature; C. Broad sensing range (10 Pa-800 kPa). Reproduced with permission from Ref. [36]. Copyright© 2018. John Wiley and Sons; D. Stable performance after 50000 cycles of measurement. Reproduced with permission from Ref. [43]. Copyright© 2020. John Wiley and Sons.

3.1. From single sensor to tactile sensor arrays

A single sensor has to be expanded to sensor arrays to gain more information and adapt to the requirements of a large detection area and spatial mapping of the measurand. The adoption of a sensor array not only enables a large-area sensor but also increases the service lifetime of the sensor. Even though one or more sensor units malfunction, the overall functionality of the sensor remains. Meanwhile, information

acquired from each independent single sensing unit in a sensor array can be combined for pressure mapping. For example, Ahn et al. reported an 8×8 transparent capacitive sensor array with 84.6% optical transmittance, as shown in Fig. 4A. The sensor array shows overall good sensing performance in <10 kPa pressure range and remains stable within 200 cycles of measurement [84]. Hu et al. developed a 4×4 pressure sensor array based on PDMS microstructure (Fig. 4B). The sensor array exhibits a high sensitivity of 14.268 kPa^{-1} , very low detectable pressure limit (1.5 Pa), a fast response time (<50 ms), excellent cycling stability (more than 10000 cycles at 0.15 kPa), and shows an excellent pressure mapping ability [85]. Cheng et al. reported a 5×5 pressure sensor array based on the PDMS/ultrathin gold nanowires/PDMS sandwiching assembly with high stability (>50000 cycles), and also demonstrated the current mapping ability under pressure, as shown in Fig. 4C [86]. Yu et al. reported a 4×4 tactile sensor array based on PZT arrays on PDMS substrate, as shown in Fig. 4D. The sensor array exhibits a high flexible ability under continuous stretching ($\sim 8\%$), bending (180° at a radius of 3mm), and twisting ($\sim 90^\circ$) [87]. The rapid development of tactile sensor array has laid a solid foundation for realizing a large area ‘E-skin’, mimicking the human skin’s tactile functions.

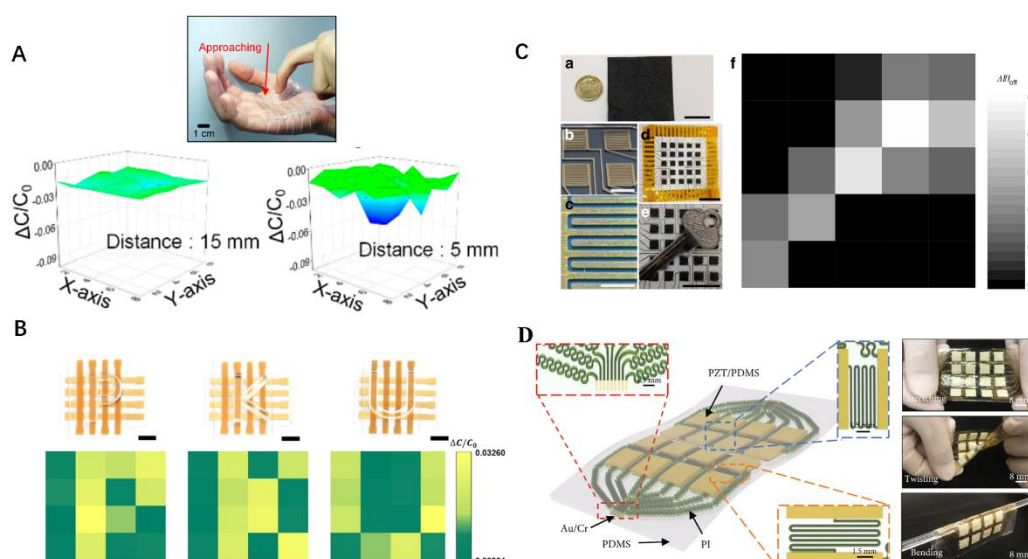


Fig. 4. Tactile sensor arrays. A. Image of 8×8 transparent capacitive sensor array on the palm and the capacitance changes when the finger approaches by 15 and 5 mm. Reproduced with permission from Ref. [84]. Copyright© 2017. American Chemical Society; B. Pressure mapping on

4×4 pressure sensor array by placing acrylic boards of “P”, “K”, and “U”. Reproduced with permission from Ref. [85]. Copyright© 2019. American Chemical Society; C. a-c. Images of a 5×5 tactile sensor array; d-f. The current mapping ability under the pressure of a key. Reproduced with permission from Ref. [86]. Copyright© 2014. Springer Nature; D. Images of a 4×4 tactile sensor array and a highly flexible ability. Reproduced with permission from Ref. [87]. Copyright© 2020. OAE Publishing Inc.

3.2. From single-mode sensor to multi-mode tactile sensor

Similar to the real skin, future flexible tactile sensors should be able to provide real-time feedback of various external stimuli and respond intelligently to the complex changes of the external environment. Besides simulating the basic physiological functions of human skin, such as realizing the sensing functions of pressure, strain, temperature, and humidity, other characteristics of the intelligent tactile sensor should be explored, including the detection of sound, light, heat, magnetic field and chemical information. In this situation, a single-mode sensor cannot fulfill all of the requirements, and researchers have developed dual-mode or even multi-mode sensors to realize various sensing functions. For example, Wu et al. reported a dual-mode sensor based on the interlocked piezoresistive and piezoelectric films, realizing the complementary performance of the two sensing mechanisms, and thus improving the sensitivity and broadening the sensing range [88], as shown in Fig. 5A. Lee et al. reported a transparent sensor combining piezoresistive and capacitive transduction mechanisms, which can distinguish touch and pressure [89], as shown in Fig. 5B. Besides the direct combination of two sensing mechanisms in a single device design, a single sensor can respond to a variety of stimuli by selecting specific functional materials. For example, Fu et al. reported a self-powered elastic conductor based on PEDOT:PSS natural rubber films, and realized both temperature- and tensile strain-sensing abilities [90], as shown in Fig. 5C. Bao et al. presented multimodal ion-electronic skin based on a deformable artificial ionic receptor, which can differentiate thermal and mechanical information without signal interference [91], as shown in Fig. 5D. Yu et al. used the blow-spinning method to prepare integrated

wearable electronics based on 3D-inorganic nanofiber IGZO networks, which can detect and differentiate multiple stimuli including test gas, strain, temperature, light, body movement, and respiratory functions [21], as shown in Fig. 5E.

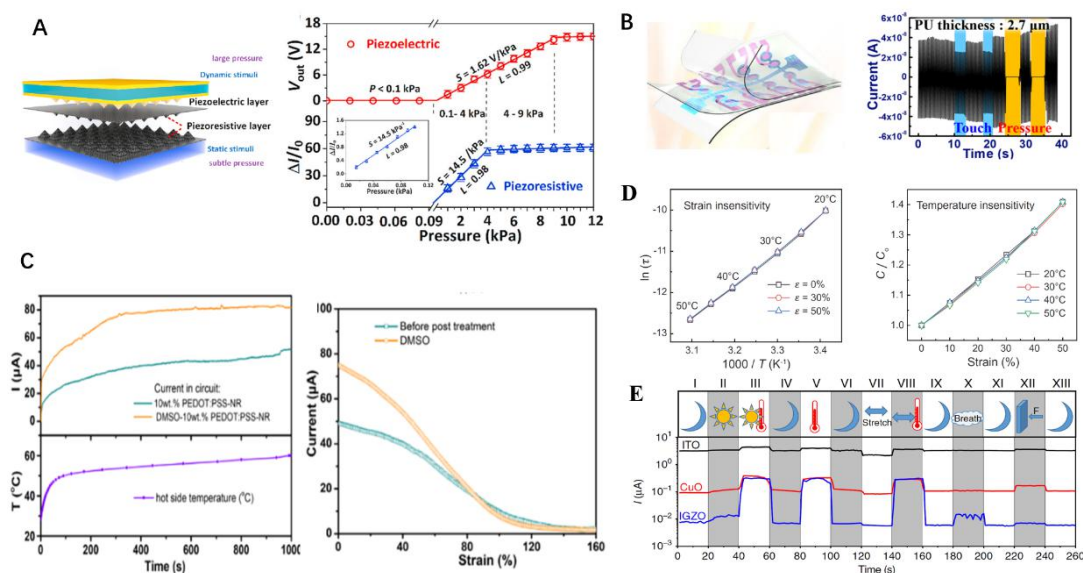


Fig. 5. Multi-mode tactile sensors. A. Schematic illustrations of the structure and sensitivity (sensing range 0-12 kPa) of a dual-mode sensor. Reproduced with permission from Ref. [88]. Copyright© 2020. Elsevier; B. Schematic diagram and current versus time of the transparent dual-mode sensor, which can distinguish touch and pressure. Reproduced with permission from Ref. [89]. Copyright© 2019. Springer Nature; C. The current response to temperature and strain stimulus respectively. Reproduced with permission from Ref. [90]. Copyright© 2021. American Chemical Society; D. Characteristics of multimodal sensor and its responses to heating and stretching without signal interference. Reproduced with permission from Ref. [91]. Copyright© 2020. The American Association for the Advancement of Science; E. Multiple stimulus responses including test strain, temperature, light, body movement, and respiratory functions. Reproduced with permission from Ref. [21]. Copyright© 2020. Springer Nature.

3.3. Tactile sensors integrated with transistors

The small output signal of a tactile sensor has to be filtered and amplified for information interpreting. However, many demonstrations usually connect the sensor with high-precision equipment so as to demonstrate the functionality of the sensor,

which is not practical in real-life applications. The interconnects required to connect the sensor with the processing circuit bring extra noises as well as increase the overall area. To alleviate this problem, researchers have explored novel device structures to directly integrate tactile sensors with transistors. For example, Duan et al. reported an ultra-high sensitive capacitive sensor based on the vertical integration of air-gap gates (capacitor sensor) with a two-dimensional semiconductor transistor, as shown in Fig. 3A. The integrated 2D transistor is used to amplify the output signal, resulting in an ultra-high sensitivity up to 10^7 kPa^{-1} , compared to 44 kPa^{-1} of the traditional air-gap pressure sensor [42]. Liu et al. reported a piezoelectric tactile sensor integrated with an organic field-effect transistor, as shown in Fig. 6A. External mechanical force is converted into a piezoelectric voltage to drive the transistor, and the piezoelectric voltage can be effectively amplified by the transistors to improve the sensitivity of the sensor. In addition, a 3×3 integrated sensor array was fabricated on PET substrate, showing a good stability and flexible performance, as shown in Fig. 6B. [92]. Rogers et al. reported an 8×8 PZT piezoelectric sensor arrays and the total signal output is horizontally integrated with a metal oxide semiconductor field-effect transistor, which transforms the output voltage signal into the drain current, as shown in Fig. 6C [52]. Dayeh et al. reported scalable tactile sensor arrays based on dual-gate piezoelectric zinc oxide thin-film transistors, which can detect compressive and shear stress, as shown in Fig. 6D. This ability has application value in achieving the slip and grip function of closed-loop robotics [93]. Zhao et al. reported an integrated contact lens sensor system, integrating temperature sensor, glucose sensor, and photodetector, and multiple MoS_2 transistors on the same platform, as shown in Fig. 6E, providing a possibility for realizing a multi-functional sensor system [94]. Triboelectric sensor as a promising self-powered sensor can also be integrated with transistors, showing the feasibility of novel self-powered sensor system [95]. For example, Zhang et al. reported a triboelectric sensor integrated with a stretchable organic transistor based on PDMS substrate for smart tactile interaction (Fig. 6F) [96].

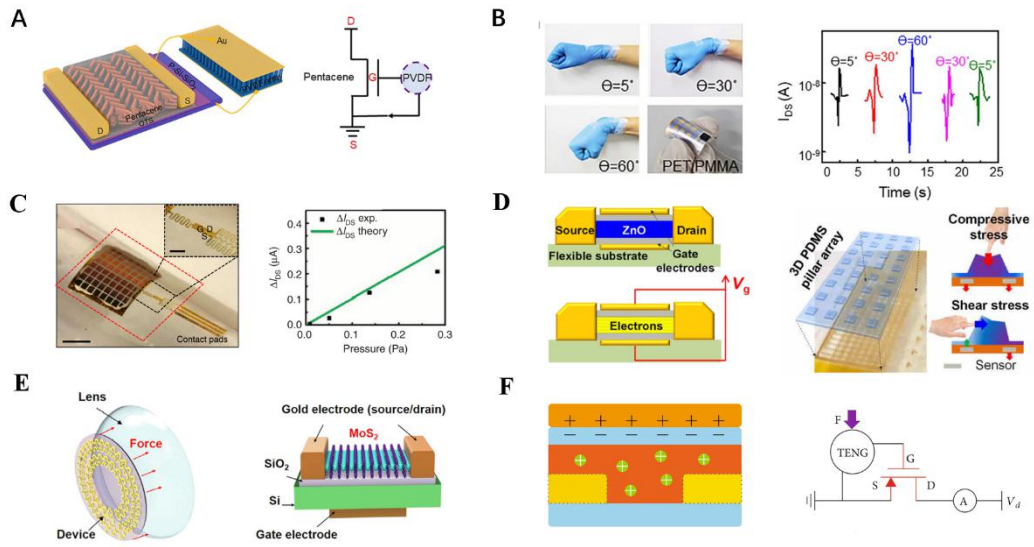


Fig. 6. Tactile sensors integrated with transistors. A. Schematic of the composition and mechanism of the tactile sensor integrated with a field-effect transistor; B. The image and results of the flexible performance measurement for the system in A. A-B, reproduced with permission from Ref. [92]. Copyright© 2020. Elsevier; C. Photograph and the drain current response to the pressure of the sensor array integrated with a field-effect transistor. Reproduced with permission from Ref. [52]. Copyright© 2014. Springer Nature; D. Schematic of the thin-film transistor and independent detection capability of compressive and shear stress using the three-dimensional PDMS pillar array. Reproduced with permission from Ref. [93]. Copyright© 2020. OAE Publishing Inc. E. Illustration of the sensor layer and 3D schematics of MoS₂ transistor. Reproduced with permission from Ref. [94]. Copyright© 2021. Elsevier; F. Working principle and equivalent circuit of tactile sensor integrated with a transistor. Reproduced with permission from Ref. [96]. Copyright© 2020. OAE Publishing Inc.

4. APPLICATIONS

With the rapid performance improvement of the tactile sensors and sensor arrays, various emerging application scenarios have been demonstrated in the field of artificial intelligence, human-machine interaction, virtual and augmented reality, as well as healthcare systems. For example, the tactile sensor system in a humanoid robot plays an important role in evaluating the overall performance of the robot [97]. Tactile sensor system is an indispensable part of artificial arms and knee joints,

flexible exoskeletons, intelligent prostheses, and medical robotics. Quantification of the pressure on the joint during moving extraordinarily relies upon the feedback signal from the tactile sensor system [98-100]. A flexible piezoelectric sensor array based on the inorganic AlN thin film has been attached to the skin, and the subtle facial strain is decoded taking advantage of the machine-learning algorithms and the mapped data from the sensor arrays [25]. Apart from the application in common robots, tactile sensor system also has great potential application value in micro-/nano-robots for a variety of deep-sea exploration and biomedical applications [101, 102]. In virtual and augmented reality field, tactile sensors are also widely used. For example, a tactile sensor system used for real-time detection of eyeball vergence in virtual reality can treat the astigmatism of eyes at home [103]. Using a skin-integrated wireless haptic interface, people can touch the far-away relatives (Fig. 7A). Those with disabled upper limbs can regain the sense of touch with the help of a flexible sensor system (Fig. 7B). People who play fighting games may feel the virtual pain from the game (Fig. 7C) [81]. In addition, a soft virtual reality glove integrating a pneumatic actuator with a piezoelectric tactile sensor can transmit the real stimulus to the users from virtual reality (Fig. 7D) [104].

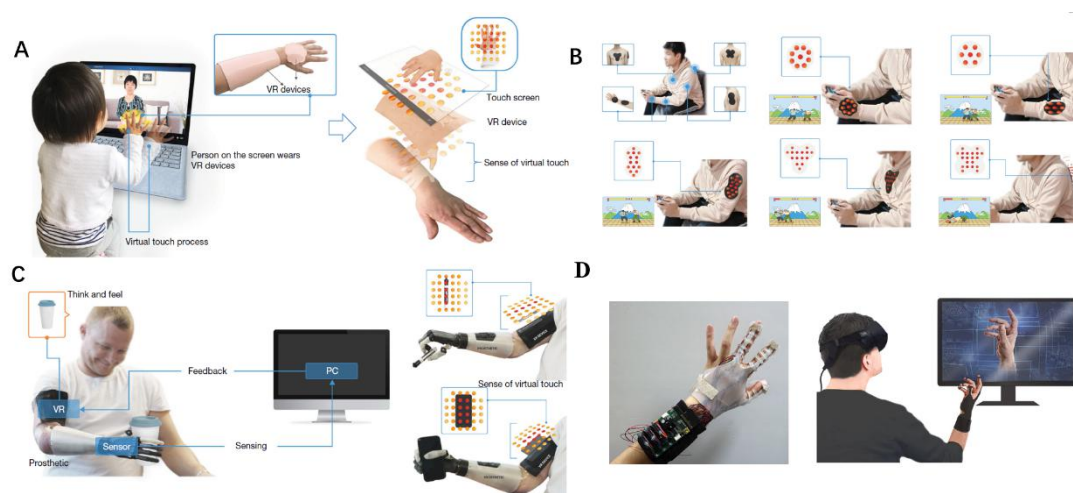


Fig. 7. Applications in virtual and augmented reality of tactile sensing system. A. The kid touches grandmother on the screen and the grandmother wearing the VR devices on arm can feel the touch; B. The man with disabled upper limbs has the sense of virtual touch with the help of the sensor system; C. The man playing fighting games feels the virtual pain from the game. A-C, reproduced

with permission from Ref. [81]. Copyright© 2019. Springer Nature; D. The actual appearance of the virtual reality glove and man wearing the virtual reality glove can feel the real stimulus from the virtual reality. Reproduced with permission from Ref. [104]. Copyright© 2019. Springer Nature.

Recently, tactile sensors have been widely used in medical treatment and health monitoring, collecting and testing the physiological indexes including blood pressure, glucose, pulse, temperature, respiratory rate, voice, electrocardiogram, electromyogram, and sleep status [28, 105-109]. For instance, an integrated wireless tactile sensor system was used for health monitoring in neonatal and already came into service in hospitals [23]. Pulse wave detection is a common application function of wearable sensors, and can be realized with a self-powered micro-structured piezoresistive tactile sensor (Fig. 8A) [110]. Similarly, the blood pressure monitoring is enabled with a conformal piezoelectric sensor (Fig. 8B) [111]. A piezoelectric sensor based on PZT ribbons was developed for energy harvesting from heartbeat and pulmonary respiration, which could offer sufficient power supply for the operation of heart pacemakers without an external battery [54]. Multifunctional electronic garments based on silica nanoparticle/PDMS layer showed waterproof, breathable, and antibacterial performance, and enabled the practical application in wearable electronics [112]. Infrared electronic skin for promotion of cutaneous wound healing was reported, as shown in Fig. 8C [113], bringing active therapeutic purpose and clinical value. By integrating sensors, Bluetooth, a cloud data infrastructure, automatic data processing platform and a user interface, a health monitoring system can detect the frequency and intensity of cough and its changes with the state of covid-19 disease progression. In the context of global covid-19 pandemic, this ability to continuously monitor key physiological parameters of the disease is very important [114].

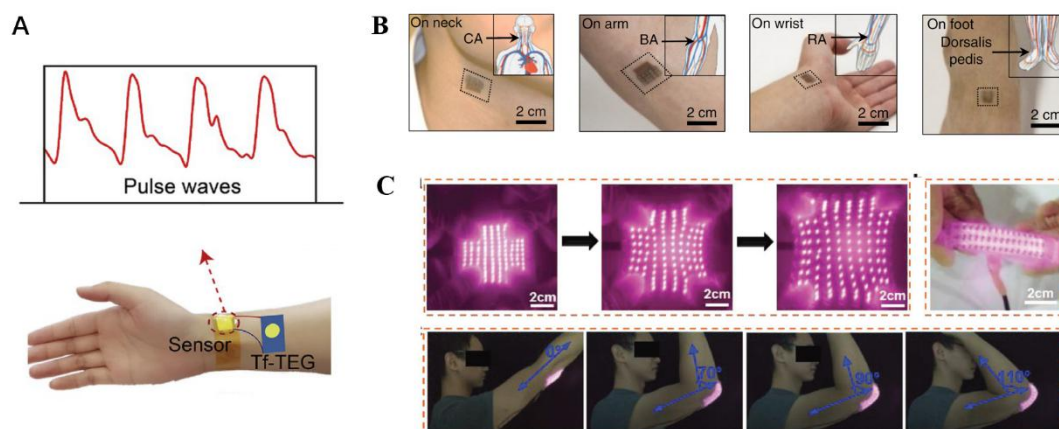


Fig. 8. Applications in medical treatment and health monitoring. A. Pulse waves detected by a self-powered sensor. Reproduced with permission from Ref. [110]. Copyright© 2020. Elsevier; B. Measurement of blood pressure in different parts of a body using a tactile sensor. Reproduced with permission from Ref. [111]. Copyright© 2018. Springer Nature; C. Infrared electronic skin with different elbow movement. Reproduced with permission from Ref. [113]. Copyright© 2019. John Wiley and Sons.

5. CONCLUSIONS AND PERSPECTIVES

In this review, we have briefly summarized the recent progress of flexible tactile sensor systems, including the sensing mechanisms, the common functional materials, the important parameters to evaluate the performance, the device design, and the main applications. In particular, the development trend of tactile sensor systems has been discussed. Besides the performance optimization for a single tactile sensor emphasizing certain performance indicators, the tactile sensor array for large-area pressure detection and the multimode tactile sensor aiming to obtain multiple sensing capabilities, and tactile sensors integrated with transistors will be the development trend of integrated tactile sensor systems to satisfy the requirements of various applications in virtual and augmented reality, intelligent robots, human-machine interfaces, medical treatment, and wearable health monitoring.

The device performance of the tactile sensor remains a key and challenge for realizing advanced tactile sensing system. Highly sensitive tactile sensors with a broad pressure

range is always a research focus. At the same time, reducing detection area, improving detecting accuracy, and distinguishing the stimulations of various forces coming from different directions are also challenging for advanced sensing systems. For the multi-mode tactile sensor, a critical problem is how to solve the crosstalk when more than two physical parameters are changing together, especially the changing of temperature, which can easily influence the other physical parameters. In the aspect of device design towards flexible tactile sensor system, realization of scalable sensor array is the foundation of large area tactile sensor system.

To satisfy the requirements of various applications in virtual and augmented reality, intelligent robots, human-machine interfaces, medical treatment, and wearable health monitoring, the future trend of the flexible tactile sensor system is summarized as follows. First, besides the basic requirement of flexibility and conformality, an ideal flexible tactile sensor is expected to exhibit a high sensitivity and multi-function integration to realize multi-dimensional synchronous sensing. Second, recent strategies toward low-power or even self-powered tactile sensors could overcome the energy constraints for longtime monitoring in wearable electronics. Third, various machine learning algorithms are adopted to interpret or enhance the information acquired from the tactile sensor array, so that the artificial intelligence auxiliary detection for human activity monitoring, medical service, human-machine interfaces, artificially intelligent robot, and other applications can be realized. Just like the real skin, future flexible tactile sensors are expected to provide real-time feedback of various external stimuli and respond intelligently to the complex changes of the external environment. In addition, besides simulating the basic physiological functions of human skin, such as the sensing functions of pressure, strain, temperature, and humidity, and getting the quantitative data, other characteristics of the intelligent tactile sensors should also be explored, including the detection of sound, light, magnetic field and chemical information. Moreover, emerging smart contact lenses based on integrated flexible tactile sensor systems are also expected for virtual and augmented reality applications. Therefore, the research on the flexible tactile sensors

and the integration systems is an important subject in scientific research and its practical applications in human activity monitoring, medical service, human-machine interfaces, and artificial intelligent robot will promote the development of human civilization.

DECLARATIONS

Authors' contributions

Jiefei Zhu: Writing - original draft. Changjian Zhou: Writing - review & editing. Min Zhang: Supervision, Writing - review & editing, Project administration.

Availability of data and materials

Not applicable.

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Conflicts of interest

All authors declared that there are no conflicts of interest.

Ethical approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

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