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# Recent progress of sensor devices and materials: Especially in the intelligent applications

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ABSTRACT

Sensor technology is now driving the development of intelligence in various fields. This review focuses on the mechanism, materials, performance, and intelligent applications of four representative kinds of sensors: resistive sensors, capacitive sensors, photodetectors, and triboelectric sensors. The intelligent applications of these kinds of sensors are reviewed emphatically, such as applied the sensors for internet of things, big data, artificial intelligence, and human-machine interaction. In addition, the review delves into the advantages, characteristics and challenges of each kind of sensors and relative materials, emphasizing their ability to interface diverse applications. This review also discusses how these sensors can be used to meet the needs of various application areas, thus facilitating the realization of smart functions. Insights into potential future challenges and development trends in the field of sensor devices and materials is offered. The objective is to provide researchers in related disciplines with comprehensive and in-depth references, thereby facilitating continuous innovations and broad applications of sensor technology in the artificial intelligence era.

## 1. Introduction

Recently, the internet of things (IoT) [1,2], big data [3,4], artificial intelligence (AI) [5,6], and human-machine interaction (HMI) [7,8] technologies are collectively and constantly reshaping human life. In the context of intelligent applications, the IoT depends on sensors to accurately collect environmental and device status information [9], facilitating a wide range of connections between things, or things with people. Similarly, big data relies on sensors to provide accurate and efficient data sources for processing massive and complex data sets. The sensors must possess characteristics such as flexibility and high sensitivity to adapt to the varied demands of different interaction modes [10]. AI relies on sensors to sense external changes and provide the foundation for intelligent decision-making [11]. Sensors, as an integral component of these technologies, play a pivotal role. Among the resistive sensors, capacitive sensors, photodetectors, and triboelectric sensors have become the focus of research due to their unique performance and wide application potential in intelligent applications.

Resistive sensors [12], which convert physical quantity changes into resistance value changes, are mostly simple in structure and low in cost. For example, strain sensor as one kind of resistive sensors, is based on the resistance strain effect and can directly drive related components, making them widely used in various industrial sectors. However, the resistive sensors are sometimes characterized by suboptimal accuracy and dynamic response because of the limitation of materials, which hinders their efficacy in rapidly measuring changes. To enhance the efficacy of these sensors in high-precision measurement applications, efforts such as advanced functional materials must be made to improve their accuracy and response speed. The capacitive sensor [13] boasts a number of advantages, including low input energy requirements, high sensitivity, and superior dynamic performance. They are capable of functioning in a variety of specialized environments and facilitating non-contact measurement processes. The broad range of its potential applications in diverse fields, including industry and agriculture, is a testament to its versatility. However, the low frequency output impedance of most of the capacitive sensors leads to weak load capacity, affecting their stability. The key problem them faces is determining how to reduce the output impedance and enhance stability. Photodetectors

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[14], on the other hand, function based on the photoelectric effect. They have been found extensive application in various fields, including national defense, life sciences, and rapid technological advancement. The emergence of novel photoelectric materials has collectively contributed to enhancing their performance. However, there is still room for improvement in the integration of high sensitivity detection and multi-band detection of photodetectors. Operating through the triboelectric effect, triboelectric sensors [15] are self-powered and can operate continuously for extended periods, providing them with distinct advantages in energy collection and specific environmental monitoring applications. However, there are two significant challenges that must be addressed to enhance their functionality and adaptability of triboelectric sensors. Firstly, the stability and accuracy of the output signal require further enhancement. Secondly, the sensors' ability to operate reliably in complex environments is yet to be optimized. To address these challenges, future research such as optimizing materials should prioritize the development of innovative signal quality and stability improvement techniques.

The above four kinds of sensors under consideration meet intelligent applications need to varying degrees through their own characteristics. Here, we have reviewed in-depth research on the connections of these four kinds of sensors mechanism, materials, performance, intelligent applications. The advantages and breakthroughs of each kind of sensors and sensor materials recently are also discussed. We expect this review will help promote the intelligent process of the sensor devices and sensor materials in various fields, solve problems in practical applications, open up more innovative application scenarios, and lay a solid foundation for future scientific and technological development.

## 2. Theories and materials of four kinds of sensors

Different types of sensors with different theories and materials can be highly adapted to complex scenarios and meet the requirements of test accuracy and dynamic characteristics. Based on the principle that the resistance characteristics of different materials change under external stimulation, the resistive sensor with a typical structure as shown in Fig. 1(a) converts the change of physical quantity into the change of resistance value to realize the perception. In different types of resistive sensors, material characteristics and construction methods have different effects on performance [16–18]. Recently, flexible resistive sensors are getting more and more attentions, which are combined with flexible polymer materials, improved the performance in many application scenarios [19,20].

Among the factors influencing the performance of resistive sensors, the properties of the material play a decisive role. **Pan et al.** [21] introduced a kind of pressure sensor made of microstructure conductive polymer polypyrrole (PPy). The high conductivity of the PPy makes the contact resistance change to be increased under pressure, realizing high sensitivity detection of pressure.

Capacitive sensors (Fig. 1(b)) work on the principle of capacitance change detection, and their performance is significantly affected by material and design factors [22–26]. In principle, the capacitance is measured by changing the polar distance type, area type and medium type based on the formula:

$$C = (\varepsilon\, \varepsilon_0\, A)\ /\ \delta \tag{1}$$

From the formula it can be seen that the change in the dielectric constant ($\varepsilon$), the dielectric loss angle ($\delta$) and the effective overlapping area (A) of the differential capacitor pair will result in a change in the capacitance C, $\varepsilon_0$ is the vacuum dielectric constant, which is a fundamental physical constant with a value of approximately $8.854 \times 10^{-12}$ F $m^{-1}$. The high permittivity of dielectric materials such as ceramics can improve the sensitivity of capacitive sensors to changes in physical quantities and perform well in precision measurement scenarios [27,28]. Metallic materials have good electrical conductivity, which can ensure fast response for electrodes of capacitive sensors [29,30]. Organic polymer materials are flexible and can make the sensor adapt to different surface shapes which have obvious advantages in the field of wearable devices [31–33]. Capacitive sensors are mostly made of traditional materials such as metal and silicon hindered their performances [34]. In recently, the advanced materials such as polymer derived ceramics (PDCs) [35] and polyimide [36] are gradually used in capacitive sensors. PDCs are ideal for capacitive sensors in high-temperature environments due to their excellent thermal stability and oxidation/corrosion resistance. Polyimide shows potential for high performance capacitive sensors due to its outstanding heat resistance

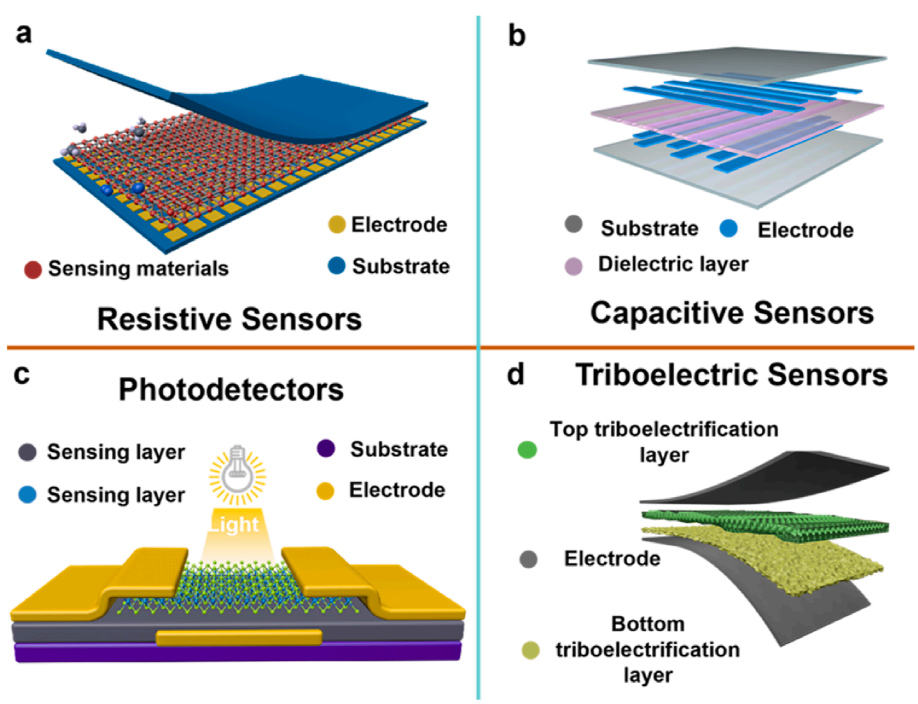


**Fig. 1.** Different structures of sensors. (a) Resistive sensor. (b) Capacitive sensor. (c) Photo detectors. (d) Triboelectric sensors.

and electrical insulation properties. Material properties have a critical impact on the performance of capacitive sensors. **Cheng et al.** [37] by doping surface-modified dielectric nanoparticles with graphene oxide sheets, which enabled the sensor to reach a sensitivity up to 1.41 $kPa^{-1}$ in the range of 0–40 kPa. **Peng et al.** [38] used polyethylene terephthalate (PET) film as the substrate, which was made of magnetron sputtered gold nanoparticles.

The photodetectors (Fig. 1(c)) convert the optical signal into electrical signal based on the photoelectric effect. Different materials such as semiconductors have different effects on sensor performance due to their respective characteristics [39–42]. Silicon as one kind of important photovoltaic materials is with high stability but limited response in certain bands [43–47]. Recently, the two dimensional (2D) Transition Metal Dichalcogenides (TMDs) are used in photodetectors because of the excellent photoelectric properties[48–53]. The heterojunction structures are also developing to meet various needs with advances in photodetectors [54–59]. TMD such as $MoSe_2$ and $WSe_2$, exhibit unique photoelectric properties that offer the possibility of constructing high-performance photodetectors. High-quality heterostructures of TMDs can be prepared by chemical vapor deposition (CVD) [60]. The crystal structure of as prepared TMD determines its electron and hole mobility, and defects will lead to charge complexation and reduce the detector performance. Furthermore, the high-quality interfaces and crystal structures in heterostructures help to improve the charge transfer efficiency and realize the high-efficiency photovoltaic conversion.

The principle of triboelectric sensor (Fig. 1(d)) is based on triboelectric and electrostatic induction [61–65], and different materials and structures have significant effects on its performance. Because of the various materials [66–69]and structures [70–73], the triboelectric sensors are developing to many kinds of hybrid devices. Early research on triboelectric materials mainly focused on the observation and basic application of triboelectric nanogenerators. In order to meet the needs of different applications, the research of high-performance triboelectric materials has been developed. For example, fluorene-based fluorinated polyarylene ether (DFAFW) [74] can adjust the molecular orbital energy level by changing the content of fluorene group to improve the triboelectric performance, in which DFAFW50 has an open-circuit voltage up to 70 V and a short-circuit current of 4.9 μA.

## 3. Advanced intelligent applications for four kinds of sensors

With the developing of big data, IoT and other technologies (Fig. 2), smart sensors have attracted attentions in our daily life. The IoT uses sensors and radio frequency identification to collect object information and achieve intelligent connection management. The sensors can cooperatively perceive parameters such as weather and air quality, monitor physical quantities, and identify user support equipment. Big data is a massive multivariate data collection and processing requirements in areas such as facial recognition [75,76]. Sensors are used to collect accurate information such as sounds or faces images. HMI is the exchange of information between humans and computers. AI relies on intelligent perception materials to perceive the environment for decision making and interaction. The selection of material composition systems and structures is closely related to the specific requirements of different applications. the connection between the capacitive sensors' materials and applications were employed as a case study to elucidate this relationship.

Firstly, for the IoT applications, capacitive sensors fabricated with advanced functional materials that with high sensitivity, stability, low power consumption. For example, the core-shell structure AgNWs@$TiO_2$ material is chosen to fabricate capacitive pressure sensor. Its $TiO_2$ buffer layer optimizes the interface polarization of AgNWs, achieving a balance among dielectric constant. This makes the sensor to meet accurately environmental changes sense and less energy consumption.

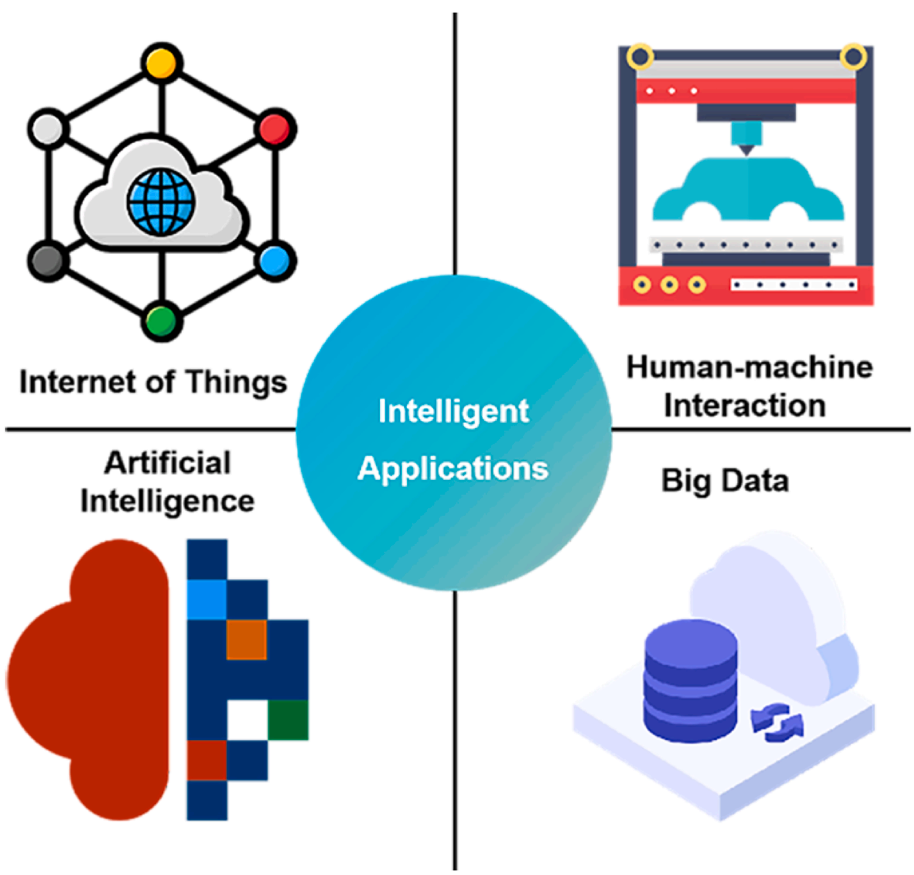


**Fig. 2.** Intelligent application diagram for sensors.

Secondly, in human-computer interaction application, the capacitive sensors need to have high sensitivity, fast response, and multi-modal sensing ability. The capacitive touch sensor composed of ultrathin PET, graphene-based electrodes, and an insulating dielectric layer to closely fit the deformable parts of the human body.

Thirdly, big data applications require the capacitive sensors to be high precision, high stability, strong data collection capabilities. The porous structure of the capacitive sensor electrode material and the spindle-knotted structure of the dielectric layer, along with the doping of 1-butyl-2, 3-dimethyl imidazolium chloride salt, improve the performance of the sensor.

Fourthly, AI places emphasis on sensors with bionic, high accuracy, intelligent processing ability. The ionic skin sensor based on a bio-inspired mineral hydrogel materials uses a polyethylene film as a dielectric layer between two hydrogel ionic conductive layers. The unique physical cross-linking properties of the hydrogel endow the sensor with excellent mechanical compliance and the ability to adhere to complex surfaces. This enables the sensor to provide accurate data for AI algorithms.

These material composition systems are related in that they all aim to improve the performance of sensors to better serve different intelligent application scenarios.

### 3.1. Advanced intelligent applications of resistive sensors

In Big Data, sensors play a key role in the data acquisition process, converting various information in the physical world into digital signals that form the basis for subsequent data processing and analysis. **Liu et al.** [77] proposed a fluorine-free $MoBT_x$ 2D transition metal borides (where $T_x$ represents O, OH, and Cl) humidity sensor (Fig. 3(a)) based on a multi-layer hydrophilic structure, providing abundant adsorption sites for water molecules, and functional end groups on its surface that enhance the interaction with water molecules. This structural advantage makes it excellent for humidity sensing. The $MoBT_x$ resistance in the humidity sensor could change with the change of ambient humidity. Because of the 2D materials, the power consumption of the device is only 2.2 μW. The sensitivity of the sensor is 1 % RH, indicating that it can accurately collect humidity data.

Due to the limitations of traditional rigid electronic devices, flexible wearable devices have emerged, but the traditional flexible sensors are mostly binary inputs, which limits the development of HMI systems. **Dai et al.** [78] developed a micro-ciliary structure on a PDMS film supported by a magnetic field, and a sensor with a hybrid microsheet/ciliary structure was constructed by secondary spin coating and magnetic field application. This structure can produce a significant and stable change in resistance when the sensor is bent bidirectionally. When the optimized sensor is bent at a small angle of $\pm 5°$, the internal bending resistance can change by $-18.4$ % and the external bending resistance can reach 26 %. Its characteristic advantages include flexibility, waterproofness, high stability, fast response, etc. These advantages enable it to effectively sense the bidirectional bending of human joints (Fig. 3(b)), enhanced HMI logic output and mouse system functions. It is expected to promote HMI in a more convenient, efficient and intelligent direction.

With the booming development of big data, the amount and types of data have exploded, posing serious challenges to computing systems. In the face of big data, traditional computing architectures suffer from problems such as data transmission bottlenecks, high energy consumption, and complex hardware design. **Zhang et al.** [79] proposed a chemoresistance-potential multicomponent sensor that utilizes the sensing electrode (SE) depositing on a solid electrolyte, such as $SnO_2$ nanofibers or $Ba_{0.5}Sr_{0.5}Co_{0.5}Fe_{0.2}O_{3-\delta}$ (BSCF) nanoparticles. This structure allows the use of various types of SE materials, avoiding the use of expensive Pt materials in sensors. It is very suitable for low cost IoT devices. The sensor shows high sensitivity for a variety of gases, such as the potential response sensitivity for 2-ethylhexanol up to 2.5 mV/ppm. This sensor with good stability has the potential to solve the problems of IOT devices, such as poor selectivity, high cost, insufficient stability.

Flexible piezoresistive sensors as one kind of resistive sensors are becoming more and more important for intelligent applications. **Chen et al.** [80] proposed the MXene/PDMS piezoresistive sensor based on the rose petal structure with a unique 3D layered array structure. This structure enables significant changes in the contact area by reducing the initial contact area and allowing continuous deformation, thus demonstrating superior sensing performance over a wide pressure range. The excellent performance of the MXene/PDMS piezoresistive sensor enable the sensors to more accurately perceive and feedback various pressure changes in AI applications, helping to improve the accuracy of decisions and judgments. The sensor is able to detect human physiological movements, distinguish between different sounds, and map pressure distributions in real time (Fig. 3(c)), especially through the machine learning module to achieve real-time tracking and highly accurate identification of handwriting processes.

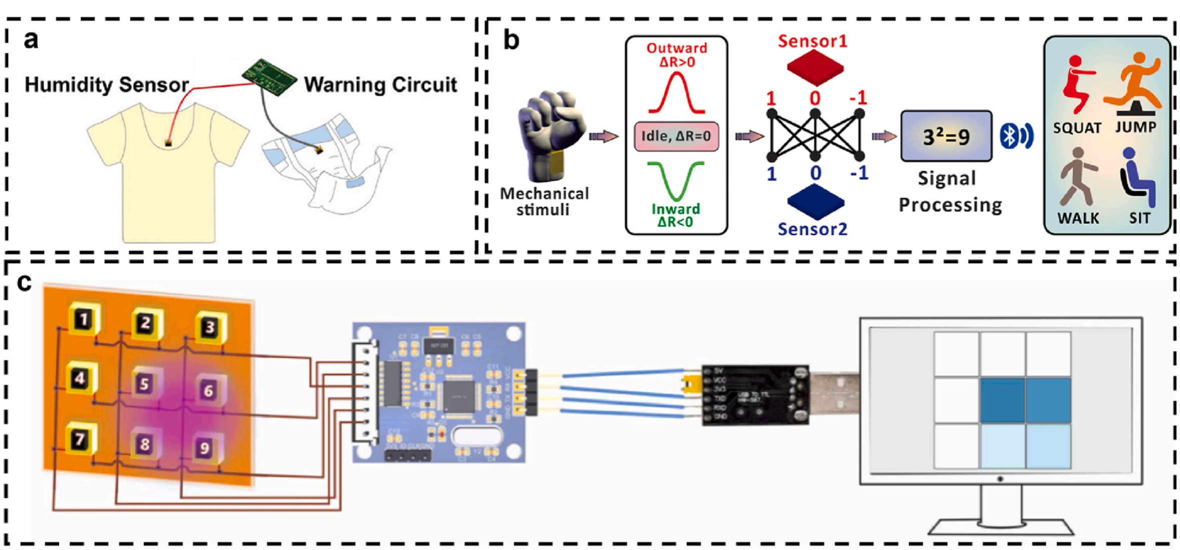


**Fig. 3.** Intelligent applications of resistive sensors. (a) Conceptual illustration of humidity sensors for early warning of sleepy babies' enuresis and back sweating. Copyright 2024 Wiley-VCH. (b) Used to control squatting, jumping, walking and sitting via two identical sensors. Copyright 2022 Elsevier. (c) Demonstration of 3 × 3 pressure sensors array assembled with MXene and polydimethylsiloxane structures of flexible piezoresistive sensor and diagram of circuit units to transform pressure signals into current changes. Copyright 2024 Royal Society of Chemistry.

Table 1 presents the performance comparison data of resistive sensors made from various materials such as MXene/PVA, $Ti_3C_2T_x$, $WSe_2$ nanosheets, MWCNTs, PEDOT:PSS, and ITP/Au. The data cover aspects like response time and detection range. Among them, the MXene/PVA sensor detection range is from 65.3 Pa to 294 kPa, and the response time is 70 ms. In contrast, the MWCNTs sensor has a detection range of 0–5 kPa, and a response time of 0.18 s. These data visually demonstrate the performance differences of resistive sensors made from different materials, which is helpful for researchers to select the most suitable sensor materials according to specific application scenarios, such as high-precision measurement and wide-range pressure detection.

Resistive sensors are widely used in various fields, but their future development faces challenges in both materials and sensors themselves. Balance the high sensitivity and wide operating range in flexible materials and other properties is complex, high cost, large-scale production difficulties. The future of resistive sensors addressing these challenges through multidisciplinary approaches. New materials with improved sensitivity, stability, and adaptability should be developed to enable multi-functional integration and reliable operation in diverse environments. Furthermore, the integration of resistive sensors with AI and IoT will be crucial for unlocking their full potential in applications such as smart healthcare, industrial automation, and environmental monitoring. Collaboration between materials scientists, engineers, and data scientists will be essential to overcome these hurdles and drive the next generation of resistive sensing technologies.

### 3.2. Advanced intelligent applications of capacitive sensors

The actual complex electromagnetic environment and object interference bring great challenges to the stability and reliability of IoT system. **Han et al.** [87] proposed a capacitive pressure sensor based on core-shell structure AgNWs@$TiO_2$. It has the characteristics of anti-electromagnetic interference. The $TiO_2$ buffer layer optimizing the AgNWs interface polarization, achieves an effective balance between dielectric constant, dielectric loss, and breakdown strength. This structural advantage provides potentials sensing technical support for accurate pressure data acquisition, stable system operation and multi-field expansion of IoT devices in complex electromagnetic environments.

Traditional technology has many difficulties in processing big data, such as limited feature extraction, small data transition, easy to be disturbed, which is difficult to meet the needs of accurate recognition. **Gao et al.** [88] proposed a capacitive-myoelectric dual-mode sensor, which combines a capacitive pressure sensor with a dry electrode in a 3D stacked structure. The porous structure of the capacitive sensor electrode and the spindle-knotted structure of the dielectric layer form a double-coupled microstructure, while 1-butyl-2, 3-dimethyl imidazolium chloride salt is doped to achieve an electric double layer effect. This structure greatly improves response sensitivity, stability and repeatability of the sensor. Excellent biocompatibility and bacteriostatic performance enable the sensor suitable for a variety environment. The fusion of capacitance and electromyography (EMG) provides richer data features for facial expression recognition, effectively improves the accuracy of facial expression recognition (up to 93.8 %) (Fig. 4(a)). It provides a reliability sensor technology for the accurate collection and analysis of facial expression big data, helps to build expression database, and promotes the further development of facial expression recognition technology.

Traditional HMI has many challenges, such as the rigid input limits the user's movement. **Kang et al.** [89] proposed an innovative capacitive touch sensor consisting of an upper and lower layer of ultrathin PET, a transparent electrode array based on three layers of graphene, an insulating dielectric layer, and a grounded single layer of graphene. This structure fully utilizing the advantages of graphene (mechanical flexibility and optical transparency), allows the sensor to fit closely to the deformable parts of the human body. At the same time, the thin structure helps to reduce mechanical failures and improve the reliability and durability of the device. These performance indicators provide high-precision touch input and non-contact perception for HMI, enabling users to interact with the device more naturally (Fig. 4(b)).

In AI systems, accurate perception of changes in the external environment is a key prerequisite for intelligent decision making and interaction. **Lei et al.** [90] proposed an ionic skin sensor based on a bio-inspired mineral hydrogel, which uses a polyethylene film as a dielectric layer sandwiched between two amorphous calcium carbonates/polyacrylic acid/sodium alginate hydrogel ionic conductive layers. This structure takes full advantage of the physical crosslinking properties and unique viscoelasticity of hydrogels, giving it excellent mechanical compliance and the ability to adhere closely to a variety of complex surface shapes (Fig. 4(c)). In terms of strain sensing, the capacitance-strain curve is reversible and in good agreement with the theoretical prediction in the range of 0 %–100 % tensile strain. In addition, the hydrogel used in the sensor has remarkable autonomous self-healing properties and can rapidly self-heal within 20 min at room temperature. This unique self-healing ability gives the sensor strong robustness in long-term use, and even if it suffers local damage. This kind of sensor provides a stable and reliable perception guarantee for AI in the complex, changing and possibly damaging actual application environment. Some of the performance comparisons of capacitive sensors with different materials are shown in Table 2. The capacitive sensors face many challenges in measurement accuracy and stability.

The future of capacitive sensors hinges on overcoming these challenges through innovative material science and engineering solutions. The development of new materials with enhanced dielectric properties, environmental stability, and mechanical flexibility is crucial. This may involve exploring hybrid materials or biological materials that offer unique combinations of properties.

### 3.3. Advanced intelligent applications of photodetectors

The IoT platform connects sensor nodes to accurately monitor environmental changes and provide a scientific basis for environmental protection decisions. Therefore, the development of highly sensitive multifunctional sensors is especially important. **Wang et al.** [95] developed a novel self-powered broadband photodetector based on a high performance mixed-dimensional $Sb_2O_3$/$PdTe_2$/Si heterojunction for the multiple detection of environmental pollutants (Fig. 5(a)). The combination of 1D $Sb_2O_3$ nanorods and 3D $PdTe_2$ improves the light absorption capacity, the large specific surface area of materials improves the light trapping and carrier transport efficiency. In addition, $PdTe_2$ reduces the lattice mismatch and improves the self-powering capacity of the sensor device. The detector performs well in the wavelength range of 255–980 nm. The device has the advantages of high sensitivity, fast response and strong stability at multiple wavelengths, high sensitivity to $NO_2$ and PM2.5. This work shows a broadband photoelectric detection and environmental pollutant monitoring by constructing a specific heterojunction structure sensor device, provides a low-power and high-precision sensor solution for IoT environmental monitoring.

In the era of big data, the speed of information acquisition, processing, and transmission has become particularly important, which places higher demands on photodetector. **Du et al.** [96] report a self-powered fiber-like UV photodetector based on a vertical ZnO/poly

**Table 1**
Performance comparison of resistive sensors with different materials.

| Materials | Response Time | Detection Range | Reference |
|---|---|---|---|
| MXene/PVA | 70 ms | 65.3 Pa- 294 kPa | [81] |
| $Ti_3C_2T_x$ | 130 ms | <15 kPa | [82] |
| $WSe_2$ nanosheets | 200 ms | 0.001–0.012 kPa | [83] |
| MWCNTs | 0.18 s | 0–5 kPa | [84] |
| PEDOT:PSS | \ | 0–50 kPa | [85] |
| ITP/Au | \ | 0–1700 kPa | [86] |

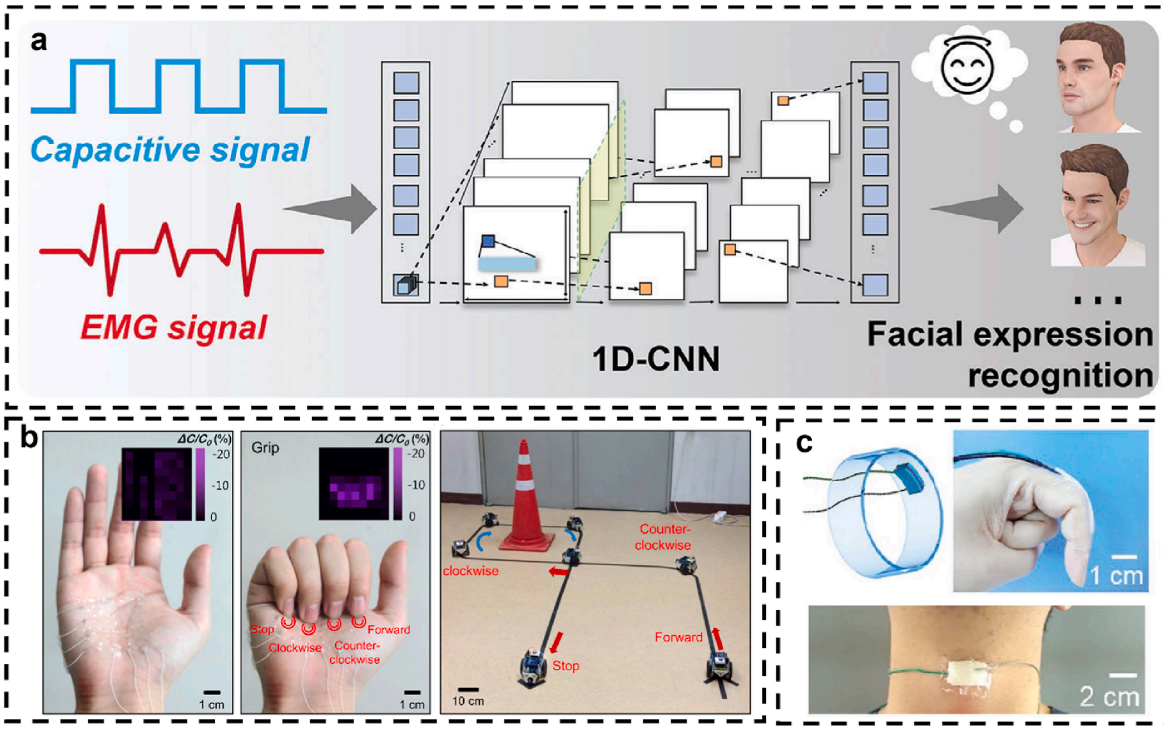


**Fig. 4.** Intelligent application of capacitive sensors. (a) Flexible sensor-based facial expression recognition system. Copyright 2024 Wiley-VCH. (b) Sensors mounted on the palm of the hand are used for remote control of toy cars. Copyright 2017 American Chemistry Society. (c) The ionic skin used as finger motion, throat motion, blood-pressure sensor, Copyright 2017 Wiley-VCH.

**Table 2**
Performance comparison of capacitive sensors with different materials.

| Materials | Response Time | Detection Range | Reference |
|---|---|---|---|
| PDMS/Cu | \ | 0–945 kPa | [91] |
| Ecoflex/CNT | \ | 10–150 kPa | [92] |
| PDMS/Ecoflex/AgNW | 70 ms | 0–80 kPa | [93] |
| PDMS/AgNPs/CNTs | <50 ms | 0–45 kPa | [94] |

(3-hexylthiophene) (P3HT) heterostructure, which is unique in achieving efficient carrier separation and fast transport through a series of coaxial p-n junctions and piezoelectric-photoelectric effect mechanisms. The device uses flexible tungsten wire as the inner electrode and conductive alginate fiber as the outer electrode. A dense array of 1D ZnO nanorods is grown by hydrothermal method and then dipped with P3HT to form a p-n junction. The innovative material and structural design of the device provide photodetector support for the application of big data related technology in multi-functional system integration.

Traditional HMI devices often have limitations in terms of flexibility, durability, and adaptability to complex environments. For example, wearable devices may degrade in performance due to mechanical deformation during long-term use. **An et al.** [97] developed a 2D material-reinforced flexible self-healing photodetector for large area photodetector. In terms of structure, 2D materials such as graphene, TMDs and black phosphorus (BP) are dispersed in self-healing polymers polymerized with imidazolyl norbornene. Thus, self-healing films are fabricated and transferred to the PCB substrate. The graphene self-healing photodetector has excellent optical response, with significant peak response at 550 and 800 nm wavelengths. By combining 2D materials and self-healing polymers, the photodetectors can solve the problems of irrecoverable performance and poor strain adaptability after mechanical damage, providing a more intelligent and natural way for HMI.

With the rapid development of AI technology, intelligent vision system has been key component of the information perception. **Wang et al.** [98] developed a cutting-edge photodetector based on a 2D intrinsic defect semiconductor $In_2S_3$. At the 359 nm wavelength, the photoelectric responsiveness of the photodetector is as high as 473.6 $AW^{-1}$. It can successfully simulate a variety of basic functions of biological synapses, such as paired pulse promotion high pass signal transmission, and efficient regulation of information transmission. The artificial convolutional neural network built on the basis of this kind of photodetector successfully realizes the recognition of letters (Fig. 5(b)). The use of 2D intrinsic defect semiconductor materials solves the problem that simultaneously photoelectric detection and neuromorphic vision. Its ability to simulate biological synaptic function and image recognition helps promote the efficient and accurate application of AI in tasks. **Liang et al.** [99] proposed ozone-treated $PdSe_2$ photodetector (Fig. 5(c)). The photodetector has the characteristics of controllable photoconductivity, the enhancement of negative photoconductivity and the tunability of positive photoconductivity gate. These advantages improve the efficiency of light sensing and optical communication of the photodetector. Oxygen doping significantly improves the catalytic activity of the $PdSe_2$ base surface, which opens up the possibility of developing simple but useful method to promotes the development of more efficient AI technology. Some of the performance comparisons of photodetectors with different materials are shown in Table 3. Existing materials of photodetectors still cannot meet the emerging demand for high-end applications. For example, it is difficult to prepare high-quality, large-area TMD materials for photodetectors material stability and compatibility are also key issues of photodetectors that need to be solved. In addition, cost issues of the high-quality semiconductors limit the wide application of new type photodetectors.

In the future, the photodetectors hinge on addressing challenges through innovative material science and engineering solutions. The development of new materials with enhanced stability, compatibility, and performance is crucial. This will pave the way for photodetectors to play a pivotal role in applications such as smart cities, wearable health monitoring, and environmental protection.

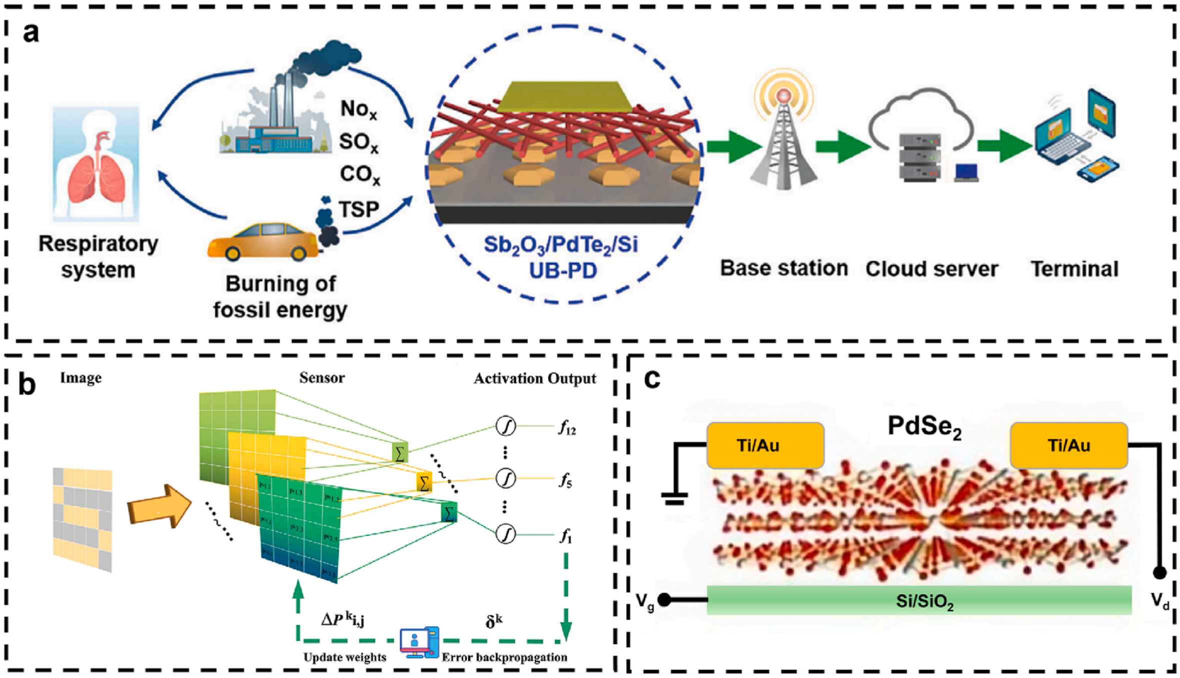


**Fig. 5.** Intelligent applications of photodetectors. (a) Schematic diagram of the broadband photodetectors depicting the detection of gases in the environment. (b) Scheme of the special pattern recognition platform based on photodetector. Copyright 2024 Wiley-VCH. (c) Schematic diagram of the oxygen incorporation in the photodetector materials. Copyright 2020 American Chemistry Society.

**Table 3**
Performance comparison of photodetectors with different materials.

| Material | Detect Wavelength | Response Time | Reference |
|---|---|---|---|
| $Sb_2O_3/PdTe_2/Si$ | 255–980 nm | 18.8 μs | [95] |
| $ZnO/P_3HT$ | 365–880 nm | <40 ms | [96] |
| Graphene/BP/self-healing polymer | 500–1450 nm | 0.91 s | [97] |
| $In_2S_3$ | 359 nm | 0.3 ms | [98] |

### *3.4. Advanced intelligent applications of triboelectric sensors*

The continuous generation and transmission of data by IoT devices poses serious challenges for data collection, processing, and security management. **Zhang et al.** [100] proposed the intelligent mouse sensor, which is based on the intrinsic contact separation characteristics of mouse button clicks. The copper film serves as the upper and lower electrodes while the fluorinated ethylene propylene (FEP) film serves as the lower triboelectric layer material, and the polyurethane film serves as a buffer layer to increase the contact area. The advantages of this structure take advantages of the inherent operation can work stably based on the triboelectric effects. Through the actual operation test of six volunteers, the sensor of the smart mouse can effectively collect the signal when the user clicks the mouse, achieving an identity recognition accuracy of up to 98.4 %. In the IoT environment, accurate identification can ensure secure access (Fig. 6(a)). The intelligent mouse promotes the development of the IOT system in a smarter and safer direction.

Traditional HMI methods can no longer meet the growing demands in some aspects, and the development of bionics has brought new ideas and methods for HMI. The integrated self-powered bionic transmission nerve sensor (Fig. 6(b)) proposed by **Zhang et al.** [101] was used in HMI. The single-electrode design is adopted in the structure, and the dielectric layer with gradient thickness and lattice structure on the surface have unique advantages. This structure enables transmission nerve to achieve good output performance. Its output current changes with the thickness of the dielectric layer, and the position of mechanical stimulation can be identified by analyzing the size of the output signal, which helps to more accurately capture user operation information in HMI.

In the field of environmental monitoring, the efficient acquisition, transmission, and processing of large amounts of environmental data has become a key challenge for accurate monitoring and intelligent decision making. The self-powered wireless environmental monitoring sensor based on a configurable rotary switch triboelectric nanogenerator (RS-TENG) proposed by **Liu et al.** [102] provides an innovative solution for environmental monitoring in a big data environment. The rotating design of RS-TENG enable it to adapt to a variety of natural environments, such as wind energy, water flow, with a high degree of flexibility and compatibility. The convolutional neural network is used to connect with triboelectric sensors. The sensors signals are classified and identified, while different signals are accurately distinguished to realize intelligent judgment and prediction of environmental state, providing an effective technical means for big data in the field of environmental monitoring. Some of the performance comparisons of triboelectric sensors with different materials are shown in Table 4. The development of triboelectric sensors faces many challenges, such as the tiny current signals.

The evolution of triboelectric sensors will depend on new materials with superior triboelectric properties, such as those with enhanced surface charge density and stability. Innovations in nanotechnology and surface engineering could achieve higher sensitivity and energy conversion efficiency. Addressing stability and durability concerns requires the development of wear resistant materials and protective coatings that can withstand harsh environmental conditions.

## 4. Conclusion and perspective

Sensor technology is critical to intelligent applications, and its materials and structure have a profound impact on performance. In terms of materials, resistive sensor materials are diverse, flexible polymers and other materials improve their performance, but the accuracy and dynamic response need to be improved; Capacitive sensor ceramic, metal, organic polymer and other materials play a role in different properties,

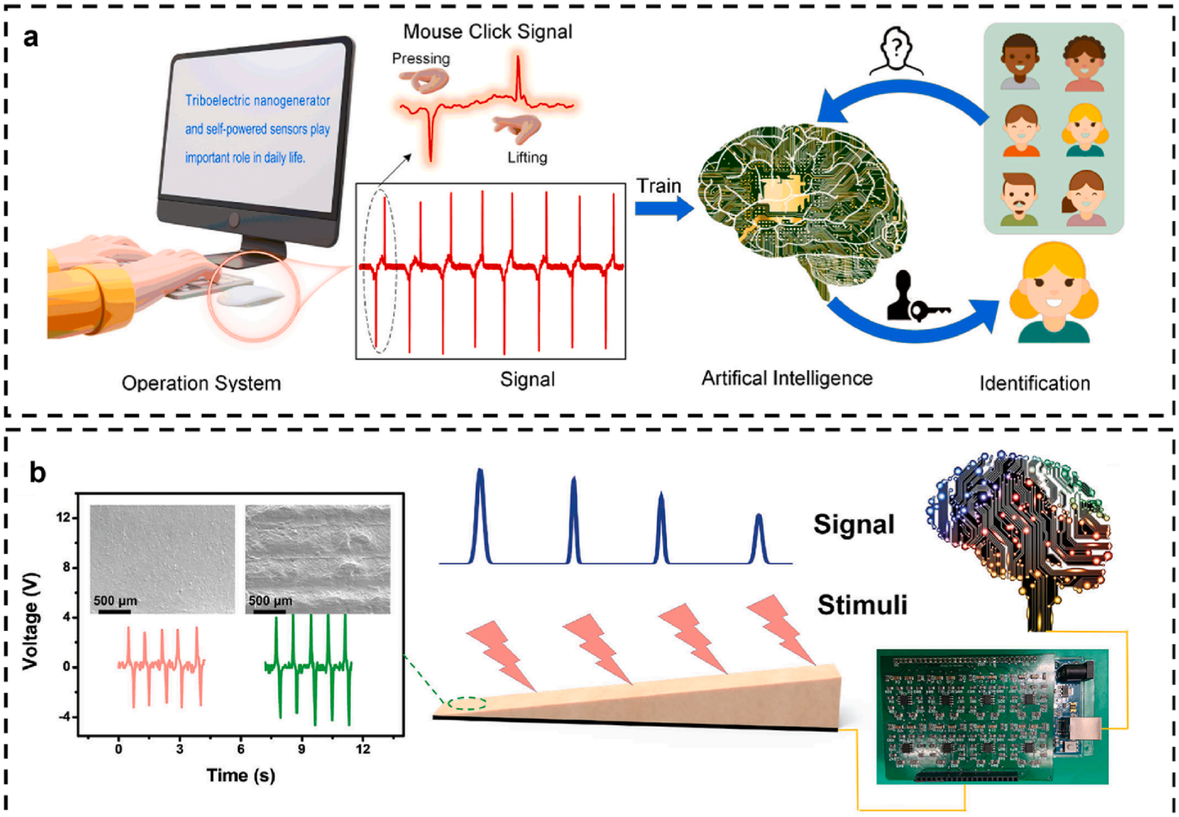


**Fig. 6.** Intelligent application of triboelectric sensors. (a) schematic diagram of the security verification system, which combines an intelligent mouse embedded with the triboelectric sensor and a machine learning method. Copyright 2024 Elsevier. (b) Schematic function of transmission nerve sensor. Copyright 2021 Wiley-VCH.

**Table 4**
Performance comparison of triboelectric sensors with different materials.

| Materials | Sensitivity | Accuracy | Detection Range | Reference |
|---|---|---|---|---|
| PDMS/LMPC | / | 94.4 % | 2–10 N | [103] |
| PET/ITO | 17.63 V $N^{-1}$ | 98.7 % | 0–4 N | [104] |
| PDMS/PTFE/PVAc | 0.218 V $N^{-1}$ | 99.12 % | 0–2 N | [105] |

but the output impedance problem needs to be solved; The silicon and TMD materials in photodetectors have their own characteristics, and their structures are constantly evolving. The materials and structure of triboelectric sensors are driving their evolution towards hybrid devices, and stability and reliability need to be optimized. In terms of structure, the resistive sensor is simple in structure, but its performance needs to be improved. The structure of capacitive sensor affects the measurement method, some of the structures have achieved performance improvement, but there are still shortcomings; photodetector structure innovation to achieve a variety of functions; triboelectric sensors vary in structure and have unique designs for different applications, but they also face optimization challenges. Today's devices have made remarkable progress in function integration, environmental adaptability, stability and reliability, and have solved some problems. In the future, sensor performance can be further improved by improving the material and structure. In terms of materials, the development of new materials such as nanomaterials, and surface modification improvements, nanomaterials with unique properties to enhance the performance of the sensor, improve the energy conversion efficiency, through surface modification to introduce specific functional groups or active sites to improve the sensitivity and selectivity of the sensor to the measured substance. In terms of structure, optimization design and multi-structure integration innovation are crucial, optimizing layout to reduce signal interference, improve response speed and accuracy, micro and nano processing technology to fabricate micro and nano structures, increase sensor-related performance, build composite structure sensors to achieve the integration of multiple sensor functions, and develop multi-function integration modules to achieve intelligence and miniaturization. These measures will improve sensor sensitivity, accuracy, stability and functional integration to meet demand. Promote the development of sensor technology to better support the intelligent process in various fields.

## CRediT authorship contribution statement

**Ming Wang:** Writing – original draft, Investigation. **Chunlei Zhang:** Writing – original draft, Project administration, Investigation. **Wenran Zhang:** Resources, Investigation. **Cheng Cheng:** Investigation. **Yuhao Hu:** Investigation, Data curation. **Xiangguo Li:** Supervision. **Qijie Liang:** Writing – review & editing. **Qian Zhang:** Writing – review & editing, Supervision, Conceptualization. **Yanglong Hou:** Writing – review & editing.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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