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Advances in micro/nano-engineered flexible sensor arrays for intelligent human-machine interaction

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Abstract

Flexible pressure sensor arrays have emerged as a key enabling technology in the era of the Internet of Things and artificial intelligence, offering real-time, distributed, and multidimensional sensing capabilities. The micro/nano-engineered sensor arrays, composed of numerous integrated sensing units, show tremendous potential in human-machine interactions. However, meeting the increasing demands for high-resolution, high-performance area sensing presents critical challenges, including the fabrication of high-density arrays, mitigation of signal crosstalk, and the integrated optimization of sensing performance. This paper briefly summarizes and reviews the existing research strategies of flexible sensor arrays, from high-density sensor array manufacturing technology, anti-crosstalk design of multi-pixel units, performance control methods for sensing units, to intelligent human-machine interaction applications. Finally, a future outlook is proposed in light of the current state to promote the wider application of sensing arrays in human-machine interactions.

Keywords: Flexible sensor array, high density, anti-crosstalk, sensitivity, ultra-wide range

INTRODUCTION

With the continuous progress of science and technology, sensors, as the core carrier of information perception, are profoundly influencing human production and lifestyle in modern society[1]. They can collect a variety of physical parameters in real-time, such as pressure[2,3], temperature[4], humidity[5,6], sliding[7], gas[8,9], ion[10-12], *etc.*, and enable interconnectivity between humans and things, as well as between things, via the Internet[13]. This capability provides precise environmental perception and decision support for intelligent systems. Flexible sensors, characterized by bendability, stretchability, lightweight properties, and biocompatibility, have emerged as a breakthrough in sensing technology innovation and have garnered significant attention in fields such as intelligent electronics[14], robotic sensing[15], and medical health monitoring[16,17].

As an important branch of flexible sensing, flexible sensor arrays achieve multi-channel distributed information detection and sensing through the integration of multiple sensitive units. This feature gives flexible pressure sensor arrays a wider range of applications in human-computer interaction. Examples include smart skins in aerospace[18-20], smart sensing in medical and healthcare[21-23], and smart tactile gloves in human-machine interactions[24-26]. Despite significant progress in improving device performance through material optimization, structural design and manufacturing innovations, the preparation of high-density sensor arrays in a limited space remains a key issue as the number of sensor units and integration density increase. Secondly, signal crosstalk between adjacent channels of an array and mutual limitations between array performances are challenges that still need to be addressed [Figure 1].

In light of these challenges, this paper reviews existing research on sensor arrays following a challenge-strategy logical structure. The first section briefly outlines the recent progress of sensor arrays, including four types of work mechanisms, material components, structural design, and manufacturing methods. The second section identifies and discusses current challenges in sensor array research, such as high-density integration manufacturing challenges, crosstalk problems, and performance limitations. Based on existing literature, the paper summarizes strategies to address these challenges. The third section reviews the applications of flexible pressure sensor arrays in human-machine interaction including medical health, and intelligent equipment. Finally, the review concludes with a summary of future development directions for flexible sensor arrays.

RECENT ADVANCES OF FLEXIBLE SENSOR ARRAYS

Working mechanism and material components

Flexible sensors are capable of converting mechanical stimuli from the external environment into electrical signals[40,41]. Common sensing mechanisms primarily include four main forms: piezoelectric, piezoresistive, capacitive, and triboelectric.

The four primary sensing mechanisms exhibit distinct advantages depending on the application scenario. Piezoelectric and triboelectric sensors feature low power consumption and can operate in self-powered modes, particularly suitable for applications that involve dynamic mechanical stimuli, such as motion monitoring or touch detection[42]. In contrast, piezoresistive sensors are more appropriate for static or slowly varying signals, offering better signal stability and long-term durability[43]. The sensitivity and overall performance of each sensor mechanism are influenced by the materials and structural designs employed[44]. A comparative summary of their key characteristics is provided in Table 1.

Piezoelectric sensors work on the basis of the piezoelectric effect. When a piezoelectric material is subjected to a force and deforms, electrical charges are generated on its surface, allowing mechanical energy to be

Table 1. Comparison of flexible sensors based on different sensing mechanisms

Mechanism	Sensitivity	Work range	Response time	Power consumption
Piezoelectric	High sensitivity for dynamic signals	Wide pressure measurement and ultra-wide bandwidth sensing	Fast for dynamic signals	Self-powered
Piezoresistive	Good sensitivity for pressure measurement; enhanced by micro/nano structural design	Widen by multi-stage structural design and material modulation	Relatively slow, affected by material hysteresis	Increase during readout process[45]
Capacitance	Good sensitivity in detecting static and dynamic signals, affected by parasitic capacitance	Broad range in pressure measurement	Relatively fast for dynamic signal	Low power consumption
Triboelectric	Good sensitivity for dynamic signals, affected by environment (temperature, humidity)	Wide range for dynamic pressure, including contact-type pressure	Fast for dynamic signals	Self-powered

converted into electrical energy. These charges are collected via electrodes and subsequently converted into electrical signals, which can be used to detect and measure physical quantities such as pressure and vibration. Currently, a wide range of piezoelectric materials have been extensively utilized in various types of flexible sensor components, including inorganic nanomaterials (e.g., metal materials and nanofilms[46]), organic nanomaterials, polyvinylidene fluoride (PVDF)[47], and poly(vinylidenefluoride-co-trifluoroethylene) [P(VDF-TrFE)][48]. Huang *et al.* proposed a flexible piezoelectric sensor based on polydopamine-modified zinc oxide (PDA@ZnO)[49]. Ma *et al.* developed a PVDF-based flexible and multifunctional tactile sensor, as shown in Figure 2A[50]. Piezoresistive sensors mainly rely on the piezoresistive effect. When the sensitive layer material senses an external stimulus, its internal resistance changes, allowing the external stimulus to be detected by measuring the variation in resistance value. Commonly used materials in research include metal nanowires[51], carbon-based fillers (e.g., carbon nanotubes (CNTs)[52], reduced graphene oxide (GO)[53], MXene[54]), and conductive polymers such as poly(3,4-ethylenedioxythiophene):polystyrene sulfonate (PEDOT:PSS)[55] and polypyridine[56]. Wang *et al.* presented a novel design for tactile sensor array with a coplanar electrode layer and isolated sensing elements, which were made from polydimethylsiloxane (PDMS) doped with multi-walled CNTs (MWCNTs) for crosstalk suppression[57]. Yang *et al.* detailed a piezoresistive pressure sensor capable of high sensitivity, enabled by a fairly hard foam. The material was fabricated using high-internal-phase emulsion (HIPE) as a template to generate a highly porous material consisting of small pores packed between larger ones whose inner walls are lined with reduced GO[58], as shown in Figure 2B. The primary principle of capacitive flexible sensors involves converting received mechanical stimuli into capacitive signals. Sensors utilizing this mechanism typically consist of a pair of conductive electrodes and a dielectric layer. When subjected to external mechanical stimulation, the distance between the electrodes or the electrode area changes, affecting the output capacitance. Common capacitive sensor arrays employ air as dielectric layers such as sponge and porous structures (e.g., polyurethane (PU) sponge[59] and porous PDMS[60], as shown in Figure 2C) to achieve high sensitivity for pressure and touch perception. The working principle of triboelectric sensors is based on the coupling effect of triboelectricity and electrostatic induction. This mechanism enables the capture of small amounts of mechanical energy from various environments and converts it into electrical energy. It supports self-powered sensing, making it suitable for self-powered sensing and energy harvesting systems. In existing research, materials such as PDMS[61], hydrogels[62], indium tin oxide (ITO)[63], and polytetrafluoroethylene (PTFE)[64] are predominantly used in the fabrication of triboelectric sensors. Peng *et al.* fabricated a vertically aligned polymer microfibril array. In this work, bundles of high-density polyethylene (HDPE)

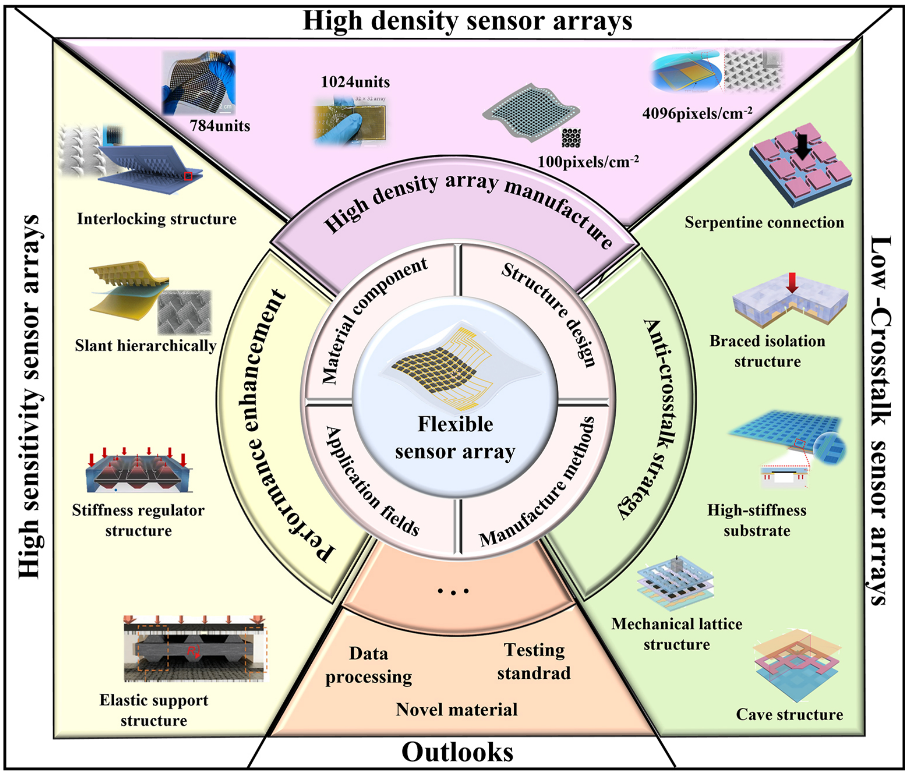

Figure 1. Overview of flexible sensor array: recent progress including material component, structure design, manufacture methods and applications; challenges and strategies in high-density, anti-crosstalk and performance enhancement. Sensor array with high density. Reproduced with permission[27]. Copyright 2023 AAAS. Reproduced with permission[28]. Copyright 2024 Wiley-VCH. Reproduced with permission[29]. Copyright 2024 Springer Nature. Reproduce with permission[30]. Copyright 2024 IEEE. Low-crosstalk sensor array. Reproduced with permission[31]. Copyright 2022 Wiley-VCH. Reproduced with permission[32]. Copyright 2024 Wiley-VCH. Reproduced with permission[33]. Copyright 2024 Wiley-VCH. Reproduced with permission[34]. Copyright 2024 Elsevier. Reproduced with permission[35]. Copyright 2023 Springer Nature. High sensitivity sensor array. Reproduced with permission[36]. Copyright 2024 Wiley-VCH. Reproduced with permission[37]. Copyright 2022 AAAS. Reproduced with permission[38]. Copyright 2023 Springer Nature. Reproduced with permission[39]. Copyright 2024 Wiley-VCH.

containing oriented microfibers that can be cut transversely into microchips were efficiently fabricated by extrusion molding techniques[65]. Such microchips were used as triboelectric layers for triboelectric sensors. A number of microelectronic devices have been successfully driven by 8×8 HMA (HDPE microarray) showing good output performance.

Single-mechanism sensor arrays can no longer meet complex requirements due to technological advances and the increasing complexity of practical application scenarios. Consequently, sensor arrays incorporating integrated multimodal sensors and coupled multimodal sensors have emerged[66-69]. The essence of integrated multimodality lies in achieving the measurement and perception of multidimensional physical quantities through the integration of independent sensing units. A pressure-temperature sensor array represents a typical example of an integrated multimodal device. As illustrated in Figure 2E, An *et al.* developed a transparent and flexible capacitive fingerprint sensor array using composite materials such as silver nanofibers (AgNFs)-silver nanowires (AgNW), capable of simultaneously detecting tactile pressure for mobile smart devices and finger skin temperature[70]. A hybrid nanostructure network comprising ultra-long metal nanofibers and thinner nanowires was formed into transparent, flexible electrodes for a multifunctional sensor array. Coupled multimodal sensors are a type of sensor capable of detecting multiple physical parameters simultaneously. By leveraging the characteristics of multifunctional composite

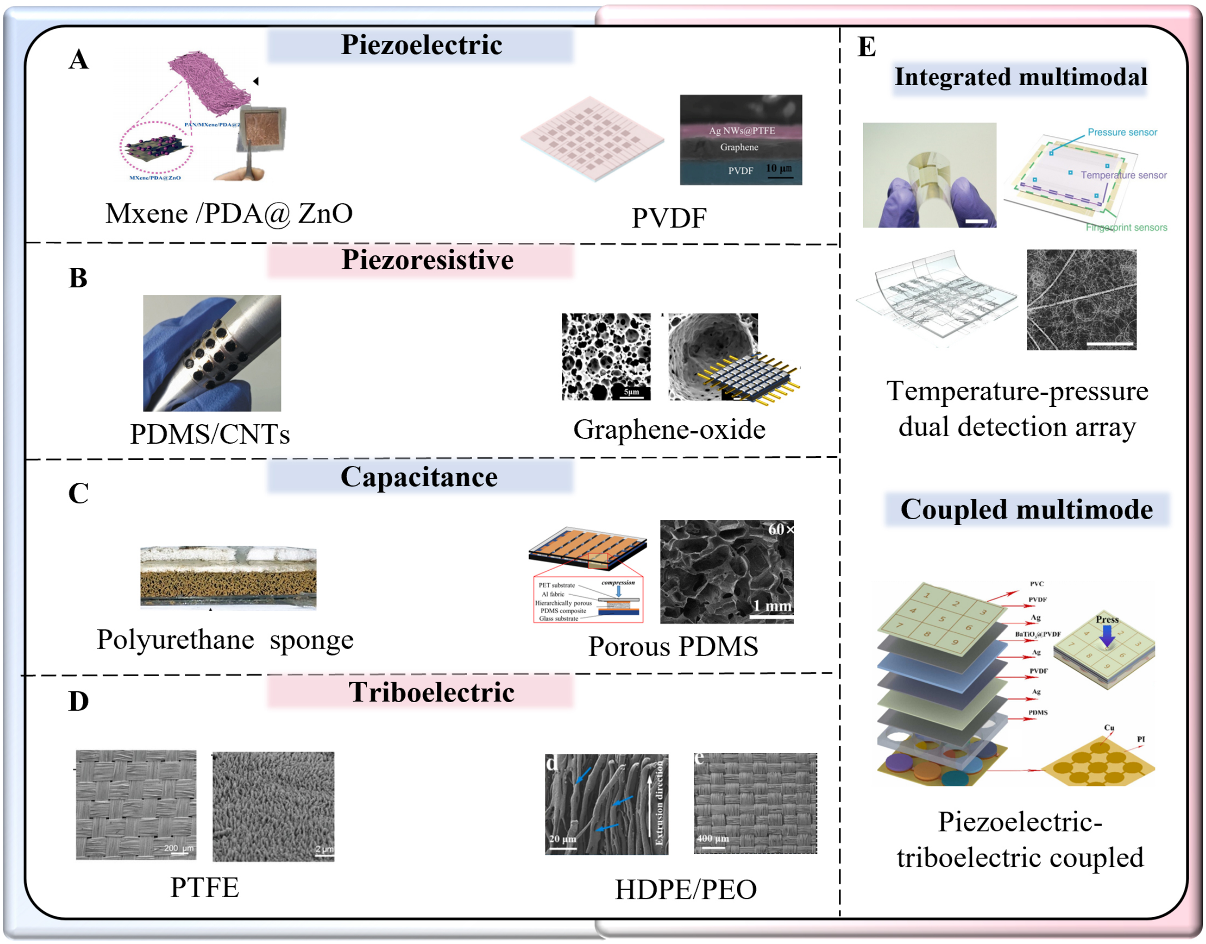

Figure 2. Sensor arrays with different work mechanisms and material components. (A) PDA@ZnO-based piezoelectric sensor array. Reproduced with permission[49]. Copyright 2024 Elsevier. PVDF-based piezoelectric sensor array. Reproduced with permission[50]. Copyright 2019 Elsevier; (B) CNTs/PDMS-based piezoresistive sensor array[57]. Reproduced with permission. Copyright 2016 Springer Nature. Graphene-oxide-based piezoresistive sensor array. Reproduced with permission[58]. Copyright 2019 ACS Publications; (C) Polyurethane sponge-based capacitance sensor array. Reproduced with permission[59]. Copyright 2025 OAE Publishing. Porous PDMS-based capacitance sensor array. Reproduced with permission[60]. Copyright 2021 Elsevier; (D) PTFE-based triboelectric sensor array. Reproduced with permission[64]. Copyright 2020 Wiley-VCH. HDPE/PEO-based array. Reproduced with permission[65]. Copyright 2024 Elsevier; (E) AgNFs-AgNWs-based integrated multimodal sensor array. Reproduced with permission[70]. Copyright 2018 Springer Nature. $BaTiO_3$/PVDF-based coupled multimode sensor array. Reproduced with permission[71]. Copyright 2025 Elsevier. PDA@ZnO: Polydopamine-modified zinc oxide; PVDF: polyvinylidene fluoride; CNTs: carbon nanotubes; PDMS: polydimethylsiloxane; AgNFs: silver nanofibers; AgNWs: silver nanowires; PTFE: polytetrafluoroethylene; HDPE: high-density polyethylene; PEO: polyoxyrthylene; PVC: polyvinyl chloride; PI: polyimide.

materials, these sensors couple multiple sensing mechanisms together to enable comprehensive perception of different physical quantities. Liu *et al.* fabricated a sensor array based on piezoelectric-triboelectric coupling using $BaTiO_3$/PVDF as a composite material, enhancing keystroke signal characteristics for recognizing dynamic keystroke patterns and effectively improving the security level of human-computer interaction systems[71].

Electrode arrangement and structure design

The structural design of a flexible pressure sensor array can be categorized into two primary aspects: coplanar electrode arrangement and sensitive layer microstructure optimization. Shi *et al.* fabricated a nano-silver symmetric electrode on the surface of polyethylene terephthalate (PET) film using spin-coating lithography[72], as shown in Figure 3A. This symmetrical electrode structure ensures uniform signal acquisition, minimizes noise interference, and enhances both sensitivity and stability, making it suitable for scenarios with uniformly distributed pressure. Wang *et al.* developed stretchable electronic devices interconnected by liquid metal and conductive nanocomposite materials[73]. The independent sensing units effectively eliminate crosstalk between individual units. Furthermore, Lin *et al.* adopted a cross-laminated electrode arrangement, organizing the sensing units into a cross-array configuration[74]. This approach improves spatial utilization, enables high-density sensing, and reduces interference between adjacent electrodes, rendering it ideal for large-area, high-precision tactile sensing applications. Other studies have incorporated microstructures into the compositional layers of sensors. Shi *et al.* proposed a machine tactile sensing system based on micropillars. The system can successfully measure three-dimensional (3D) force and temperature distribution simultaneously[75]. Park *et al.* developed a sensor array with a micro-dome interlocking structure[76]. The dome-shaped microstructure design enhances the linearity and sensitivity of signal output, improving the resolution of the tactile sensor. Wang *et al.* made a piezoresistive sensor array (PRSA) with a micro-pyramid-structured pressure-sensitive layer to boost sensitivity[77]. This design allows the top layer to better detect mechanical contacts, thus improving the sensor array's sensitivity. In recent years, many research works have innovatively designed arrays based on bionic structures, such as cilia-based e-skin and fingerprint microstructures[78], inspired by biological skin and neural networks. Yan *et al.* successfully fabricated a bioinspired cilia-based e-skin that enables the sensing and detection of surface morphology, Braille, and airflow velocity[79], as shown in Figure 3E. The bioinspired cilia exhibited a linear sensing range for static detection, with bending angles from 15° to 60°, and a frequency range of 1-25 Hz for dynamic sensing. These designs enhance the sensor's comprehensive perception of various external stimuli (e.g., pressure, strain), making them more suitable for intelligent health monitoring and human-computer interaction. The combination of these structural design strategies enables flexible sensor arrays to meet diverse needs, including high precision and stretchability, and propels the development of intelligent sensing technology.

Manufacturing methods

With the development of information technology and new material science, innovations in manufacturing techniques have significantly contributed to the advancement of flexible sensor arrays. Common methods include coating, templating, laser processing, and nanoimprinting. Quan *et al.* fabricated a flexible capacitive micro-structured sensor with a sandwich structure, using spraying to deposit AgNWs on PDMS film[80]. Shuai *et al.* prepared a capacitive pressure sensor with elastic electrodes and microarray structures, using filtration and spin-coating to cover AgNWs on PVDF film as the dielectric layer[81]. Coating is widely used for preparing conductive layers of sensor arrays due to its ability to rapidly deposit conductive materials[82]. Gao *et al.* prepared a degradable chitosan (CS) polymer triboelectric layer using templating and plasticization, enhancing power generation and sensor performance[83]. Yang *et al.* used templating to prepare micro-pyramid dielectric layers with porous structures for high sensitivity[84]. Making templates is a commonly used method for preparing microstructures due to its simplicity and low cost. Laser direct writing (LDW) has emerged as a powerful patterning technology offering high precision, high throughput, mask-free operation and programmable flexibility[85]. These advantages enable the efficient manufacture of a wide range of advanced electronic devices such as wearable strain sensors, artificial necks, heterostructure transistors and flexible supercapacitors[86-88]. In addition, the high-precision capabilities of LDW have extended its applications to include the fabrication of flexible pressure sensor arrays, making it an indispensable tool for modern electronics manufacturing. Kim *et al.* used femtosecond laser technology to create patterned micro/nanostructures on PDMS, increasing contact areas between metal electrodes and polymer triboelectric layers and improving triboelectric nanogenerator (TENG) device power density[89]. Yan *et al.* developed a flexible high-resolution triboelectric sensing array (TSA) for self-powered real-time tactile sensing through LDW[90]. The process of fabrication is shown in Figure 4C. Nanoimprinting

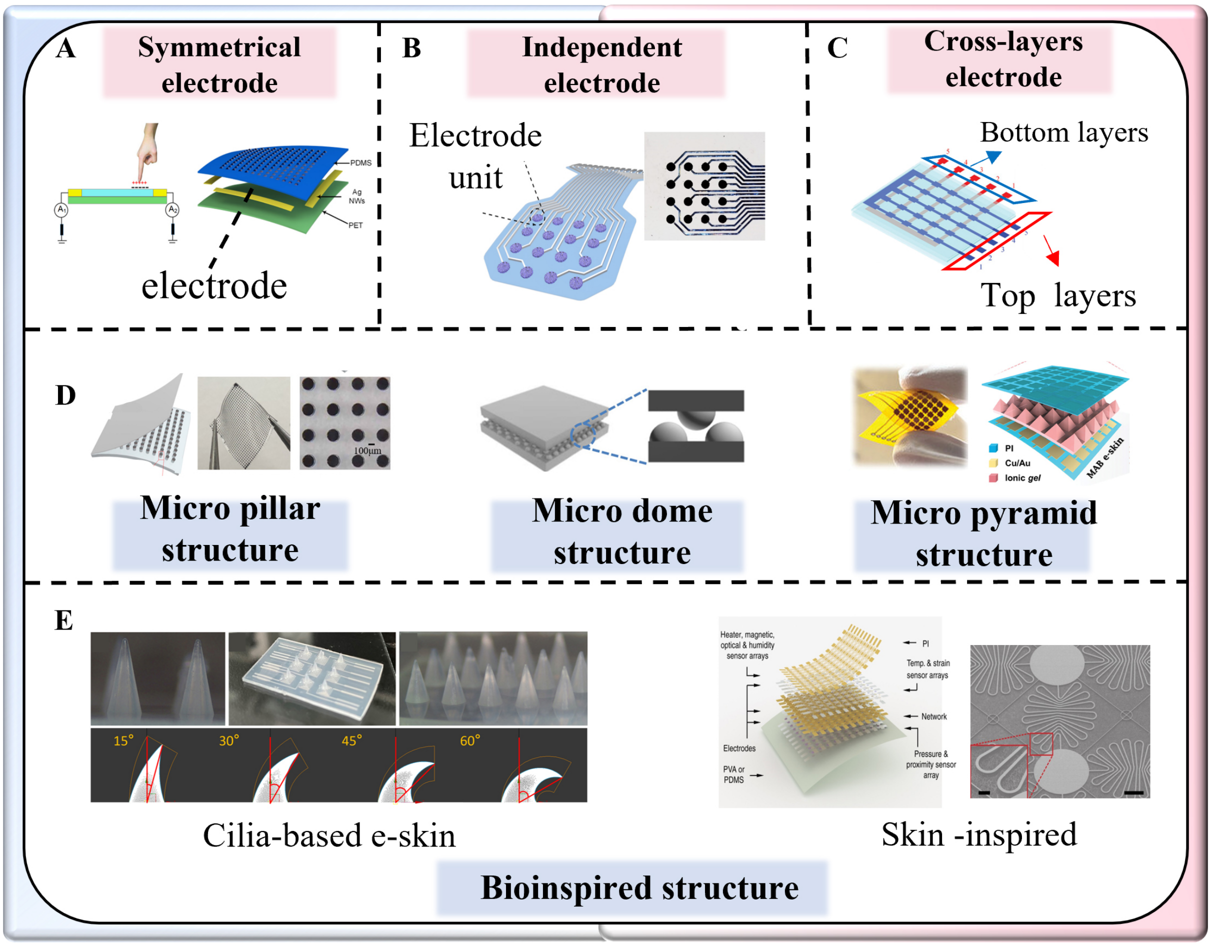

Figure 3. Sensor arrays with different structure designs. (A) Symmetrical electrode sensor array. Reproduced with permission[72]. Copyright 2016 ACS Publication; (B) Independent electrode flexible electronics. Reproduced with permission[73]. Copyright 2022 AAAS; (C) Cross-layer electrode sensor array. Reproduced with permission[74]. Copyright 2021 Wiley-VCH; (D) Regular microstructure sensor array: micro-dome structure; micropillars structure and micro-pyramid structure, Reproduced with permission[75-77]. Copyright 2020 Wiley-VCH. Copyright 2014 ACS Publications. Copyright 2024 Wiley-VCH; (E) Bioinspired structure sensor array: cilia-based e-skin and fingerprint microstructures, Reproduced with permission[78,79]. Copyright 2025 OAE Publishing. Copyright 2018 Springer Nature. PI: Polyimide; MAB e-skin: micropyramid array bimodal electronic skin; e-skin: electronic skin; PDMS: polydimethylsiloxane; PVA: polyvinyl alcohol.

lithography (NIL) is a nanopatterning technique that provides high efficiency, high resolution, and can be used over a large area[91]. The electrocapillary force allows NIL technology to be used to fabricate nanostructures with high aspect ratios or deformed geometries to meet the demand for flexible electronics with different functions.

CHALLENGES AND STRATEGIES

As the demand for comprehensive information acquisition grows, sensor arrays are moving towards higher density to achieve more detailed and comprehensive external information detection. However, this trend also brings new challenges. High-density integration manufacturing is key to achieving high-density development. Increased density requires higher manufacturing precision, needing advanced equipment and techniques. Additionally, higher density leads to signal crosstalk between sensing channels, affecting detection accuracy. Effectively eliminating such interference is a crucial research topic. Finally, there are inherent trade-offs between the performance metrics of pressure sensing arrays, most notably sensitivity

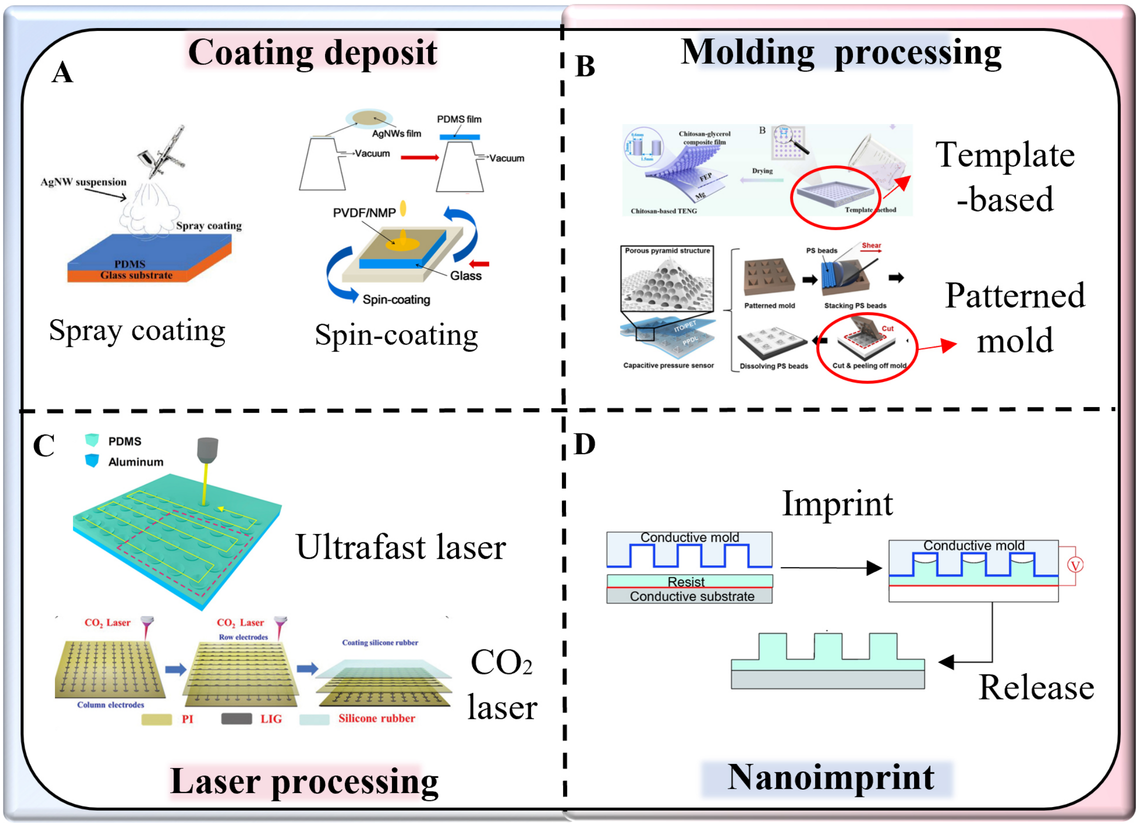

Figure 4. Sensor array with different manufacture methods. (A) Coating deposit: spray coating and spin coating. Reproduced with permission[80,81]. Copyright 2017 Elsevier. Copyright 2017 ACS Publications; (B) Template-based methods. Reproduced with permission[83,84]. Copyright 2023 Elsevier. Copyright 2017 ACS Publications; (C) Laser-based methods. Reproduced with permission[89,90]. Copyright 2017 Elsevier. Copyright 2021 Wiley-VCH; (D) Nanoimprint methods Reproduced with permission[91]. Copyright 2019 Springer Nature. AgNWs: Silver nanowire; PDMS: polydimethylsiloxane; PVDF: polyvinylidene fluoride; NMP: N-Methyl-2-pyrrolidone; TENG: triboelectric nanogenerator; ITO: indium tin oxide; PET: polyethylene terephthalate; PI: polyimide; FEP: fluorinated ethylene propylene; PS: polystyrene beads; PPDL: porous pyramid dielectric layer; LIG: laser-induced graphene.

and wide-range detection. In summary, sensor arrays face challenges in manufacturing, anti-crosstalk, and performance enhancement during high-density development, requiring continuous innovation to promote further development and application.

High-density array fabrication strategies

The deepening of intelligence is driving sensor arrays toward higher density. Here are some recent studies on high-density sensor arrays. Shi *et al.* embedded ionic electronic sensor arrays in a flexible substrate, using PDMS as the stretchable substrate with each micro-structured sensor in a separate hole[27]. Unlike traditional layered designs, this seamless integration uses PDMS middle layer with laser-processed holes for ionic gel. The array has 784 sensing units, each 1.5 mm in diameter, spaced 2.8 mm apart, covering 100 cm^2. It can recognize single/multi-touch and hammering, and was integrated into a robotic hand for object recognition, proving the strategy's applicability. Ouyang *et al.* used screen printing to create a high-density PRSA with cross-stripe carbon-polymer composites as the active layer[92]. The PRSA achieved 1.5 mm spatial resolution with 32×32 units, capable of real-time letter writing mapping. Combined with machine learning, it recognized letter reliefs with 96% accuracy, showcasing the capability of high-density arrays in distributed pressure detection. Tian *et al.* developed a flexible high-density tactile sensor array based on the piezoresistive tunneling mechanism[28]. Conformal graphene nanowall (GNW) arrays were deposited on micro-pyramid-structured silicon substrates via plasma-enhanced chemical vapor deposition (PECVD) and used as piezoresistive electrodes, achieving 64 units/cm^{-2} spatial resolution. The sensor array, integrated into a robotic fingertip, successfully replicated 3D pulse wave shapes for diagnostic visualization, highlighting the high-density array's potential in remote health monitoring. Mei *et al.* fabricated a PDMS-based sensor film using self-assembled and patterned spiky carbon nanospheres as strain-sensing units, achieving a high array density of 100 units/cm^{-2} with good consistency[29]. This array can conformally cover various surfaces, detect strain gradients, track deformations, and monitor strains in real-time for accurate distribution mapping [Figure 5].

Zhao *et al.* developed a PRSA based on sandpaper-like spiky microstructures[93]. The array, with a density of 1,134.63 cm^{-2} and 4,096 sensing units, combined with machine learning, achieved 98.47% accuracy in recognizing 12 mahjong tile faces. Its high density and consistency enable high-resolution spatial sensors, allowing detailed pressure distribution mapping of complex 3D patterns. As shown in the fabrication process [Figure 6A], PDMS films with MWCNTs and flexible array electrodes are integrated. Experiments confirmed the relationship between sandpaper mesh count and array uniformity, with 1500-mesh sandpaper used as the pressure-sensitive layer to create an array of 4,096 sensing units. Tang *et al.* constructed a high-density tactile sensor array by monolithically integrating lanthanum-doped indium zinc oxide thin-film transistor (Ln-IZO TFT) arrays with CNTs/PDMS resistive pressure-responsive layers featuring micro-pyramid/nanopillar structures[30]. Ln-IZO TFT arrays were prepared on polyimide (PI) films, and then pressure-sensing films with 3D CNTs/PDMS hierarchical micro/nanostructures were fabricated. Finally, the Ln-IZO TFT arrays and pressure-sensing films were integrated, with each pixel containing one Ln-IZO TFT and one pressure sensor, enabling fine-texture differentiation and high-resolution pressure-distribution imaging. This work provided an effective solution to endow robotics with a human-like sense of touch.

With the increasing density, integration and multifunctionality of sensor devices, heat buildup can lead to signal drift, mechanical fatigue and even device failure, especially in wearable devices and high-density sensor networks[94]. Thermal management plays a crucial role in the performance and reliability of flexible sensor devices. Effective heat dissipation is essential not only to maintain long-term operational stability and sensing accuracy, but also to ensure user safety in wearable applications. To address these challenges, current strategies commonly involve passive and active thermal management. Kang *et al.* presented a nanocomposite of aligned boron nitride (BN) nanosheet islands with porous PDMS foam to have mechanical stability and non-thermal interference[95]. The heat pathways are then formed only in the structured BN islands of the composite. The porous PDMS foam can be applied as a thermal barrier between structured BN islands to inhibit thermal interference in multiple device arrays. The selective heat-dissipating composites with thermal barriers can work as a promising heat sink and heat guidance in multiple chip array electronics and wearable electronic systems. Peng *et al.* proposed an integrated cooling (i-Cool) textile with unique functional structure design for personal perspiration management[96]. By integrating heat-conductive pathways and water transport channels effectively, i-Cool exhibits enhanced sweat evaporative cooling efficiency - not merely a liquid sweat-wicking function. The practical feasibility of the textile design principles was demonstrated, exhibiting decent performance. This work opens a new door and provides new insights for flexible sensors in thermal management. Both of the above works involved in wearable electronics pertain to passive thermal management, which mainly relies on material properties and special structural designs to achieve heat dissipation. In contrast, active strategies cool or heat by actively transferring heat from or to the human body with external input. Lee *et al.* proposed an adaptive robotic skin with a microfluidic cooling device. The adaptive robotic skin consists of an array of uniform gallium-microgranule-based tunable pressure sensors (GM-TPSs), with top and bottom flexible electrode layers and

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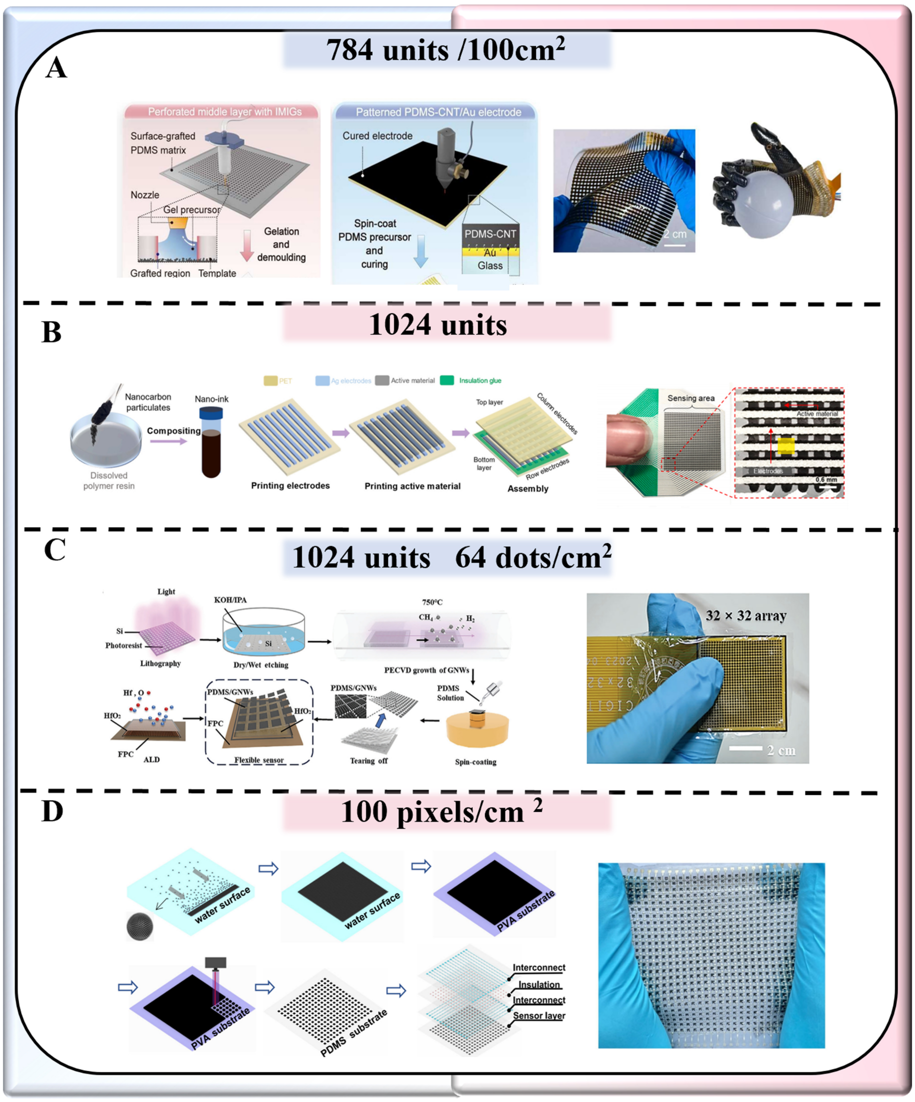

Figure 5. Fabrication strategies of high-density sensor arrays. (A) 784 units/100 cm^2 density sensor array. Reproduced with permission[27]. Copyright 2023 AAAS; (B) 1,024 units sensor array. Reproduced with permission[92]. Copyright 2024 Elsevier; (C) 64 dots/cm^2 sensor array. Reproduced with permission[28]. Copyright 2024 Wiley-VCH; (D) 100 pixels/cm^2 sensor array. Reproduced with permission[29]. Copyright 2024 Springer Nature. PDMS: Polydimethylsiloxane; CNT: carbon nanotube; GNW: graphene nanowall; PECVD: plasma-enhanced chemical vapor deposition; PVA: polyvinyl alcohol; IPA: isopropyl alcohol; FPC: flexible printed circuit; ALD: atomic layer deposition.

a microfluidic thermal actuator, which offers active temperature control that promotes the solid-liquid phase transition of GMs[97]. Jung *et al.* presented a soft and stretchable multimodal thermoelectric skin (TES). The device was mainly designed using a composite of thermoelectric and hydrophobic materials that can function as both an energy harvester and a thermoregulator[98]. The thermoelectric materials are an ideal candidate for human thermoregulation. They can generate active cooling/heating with a single structure. Lee *et al.* reported a skin-like and bi-functional (both cold and hot sensation) thermo-haptic device[99]. The skin-like thermo-haptic (STH) device can actively cool down and heat up deformable skin surfaces with instantaneous and accurate adjustment of temperature based upon a feedback control algorithm to mimic desirable thermal sensation, as shown in Figure 7B. These efforts belong to the category of active thermal management strategies, which mainly utilize the flow of microfluidics and the properties of the

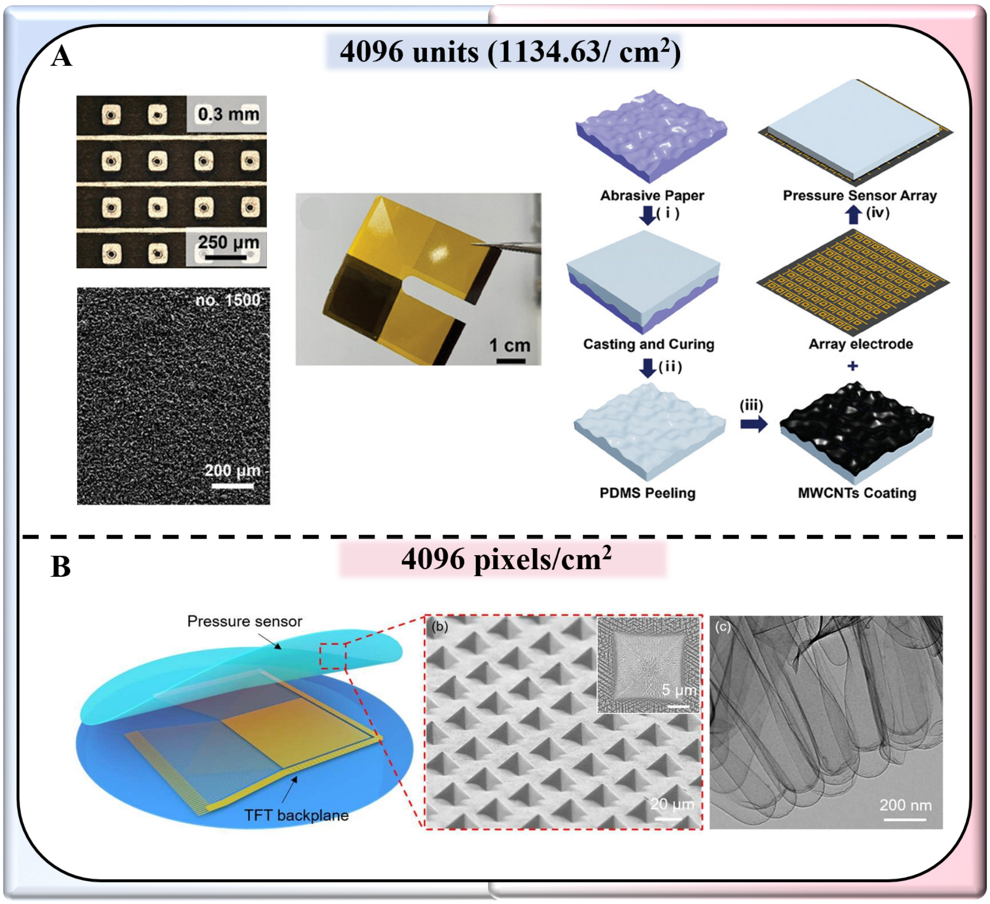

Figure 6. (A) 4,096 units sensor array. Reproduced with permission[93]. Copyright 2025 Wiley-VCH; (B) 4,096 pixels/cm^2 pressure sensor array. Reproduce with permission[30]. Copyright 2024 IEEE. PDMS: Polydimethylsiloxane; MWCNTs: multi-walled carbon nanotubes; TFT: thin-film transistor.

thermoelectric materials themselves to achieve active thermal management. Passive and active thermal management strategies have their own different advantages and disadvantages. The passive thermal management strategy does not require external components for heat transfer, but it does not allow for fine-tuning of the heat and temperature. The most significant advantage of the active thermal management strategy is that it can realize heat transfer efficiently, but it needs to rely on the support of external components[100].

Anti-crosstalk strategies

The increase in array channels offers more possibilities for precision measurement and distributed sensing but also increases crosstalk, affecting test results. Thus, anti-crosstalk is another key challenge in sensor array manufacturing. Zhang *et al.* prepared ultra-low-crosstalk sensor arrays using photo-reticulated strain localization films (prslPDMS)[35]. They doped PDMS with benzophenone to inhibit UV-induced crosslinking, forming a caged structure. This structure isolated adjacent sensing units, suppressing the spread of mechanical deformation. Compared to PET-based models, those with prslPDMS spacers had 90.3% less pixel deformation overflow and a crosstalk coefficient of 33.41 dB. Hu *et al.* proposed a flexible sensor array based on mechanical micro-lattice structures[34]. The array comprised hollow PDMS upper substrates, independent active materials/electrode arrays, and polyimide (PI) mesh support layers. This structure, combined with Young's modulus gradient design, concentrated external forces on stressed units,

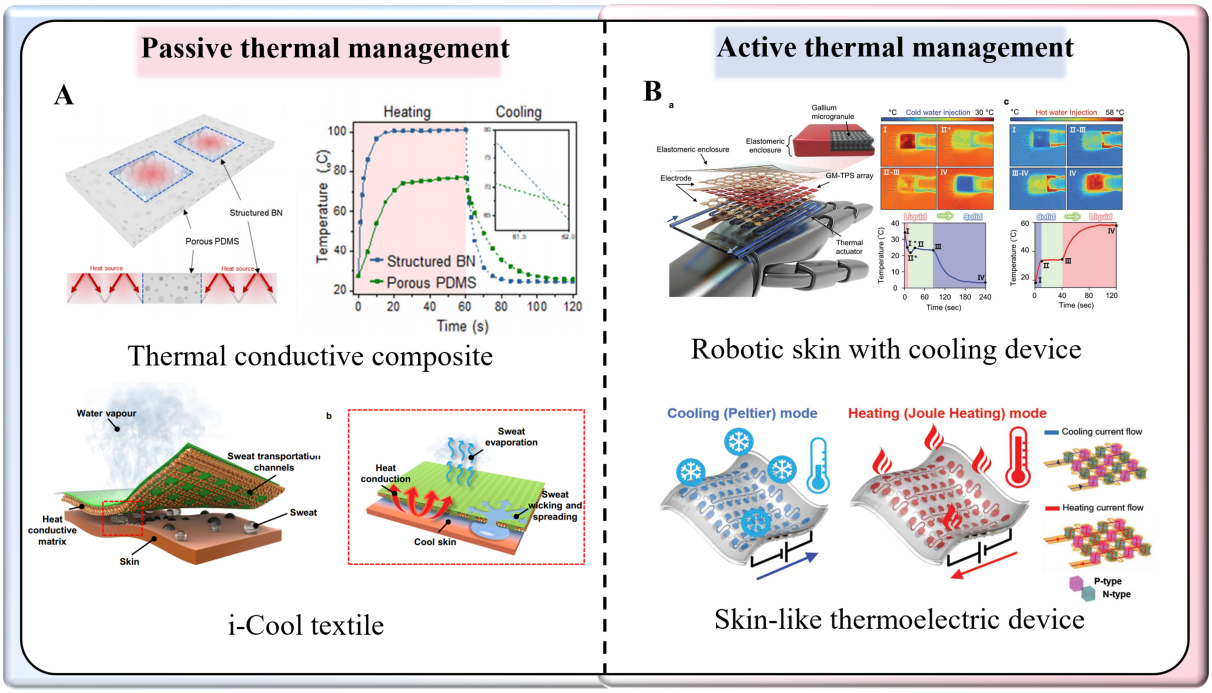

Figure 7. Thermal management strategies. (A) Passive thermal management. Thermal conductive composite with structured BN and porous PDMS. Reproduced with permission[95].Copyright 2021 Springer Nature. I-cooling textile. Reproduced with permission[96]. Copyright 2021 Springer Nature; (B) Active thermal management. Robotic skin with cooling device. Reproduced with permission[97]. Copyright 2022 Wiley-VCH. Thermoelectric skin. Reproduced with permission[99].Copyright 2020 Wiley-VCH. PDMS: Polydimethylsiloxane; BN: boron nitride; GM-TPS: gallium-microgranule-based tunable pressure sensor.

isolating unstressed ones and significantly reducing crosstalk, achieving about 1 mm ultra-high resolution. Luo *et al.*, inspired by cochlear sensing structures, developed a high-density flexible pressure sensor array with anti-crosstalk suspended sensing membranes and resolution-enhancing customized crack channels[33]. The sensing membrane was fixed on a high-stiffness substrate with cavities, creating stable support isolation structures. This design, leveraging the Young's modulus difference between hetero materials, achieved a crosstalk coefficient of 47.28 dB. Chen *et al.* fabricated a programmable micro-dome biomimetic tactile sensor array[32]. The micro-dome and isolation structures were integrally generated via nanoimprinting. The isolation structures mechanically separated dome groups, reducing signal crosstalk. The array with isolation structures had a crosstalk coefficient of 26.62 dB, compared to 0.87 dB without isolation. These works primarily achieve anti-crosstalk by creating interlayer structures such as cages, meshes, cavities, and supports. These structures isolate sensing units within a limited space, preventing mechanical deformation overflow between adjacent units [Figure 8].

In addition to creating interlayer isolation structures in sensor arrays to suppress crosstalk, other methods have also been employed. Shu *et al.* developed a capacitive sensor array that inhibits crosstalk by separating the dielectric layer[101]. As shown in Figure 9A, when the same pressure is applied, the PSA with an independent dielectric layer has crosstalk as low as approximately 1.3%. This strategy of cutting the shared dielectric layer improves measurement accuracy by 30 times compared to sharing a dielectric layer. Li *et al.* fabricated a self-powered single-electrode TENG sensor array based on 3D-printed soft substrates[102]. The process is illustrated in Figure 9C. AgNWs were sprayed onto a 3D-printed flexible transparent substrate as transparent electrodes, with PDMS cast on top as the triboelectric and sealing layer. The patterned substrate isolates each unit, suppressing crosstalk from different dielectric properties and avoiding manufacturing

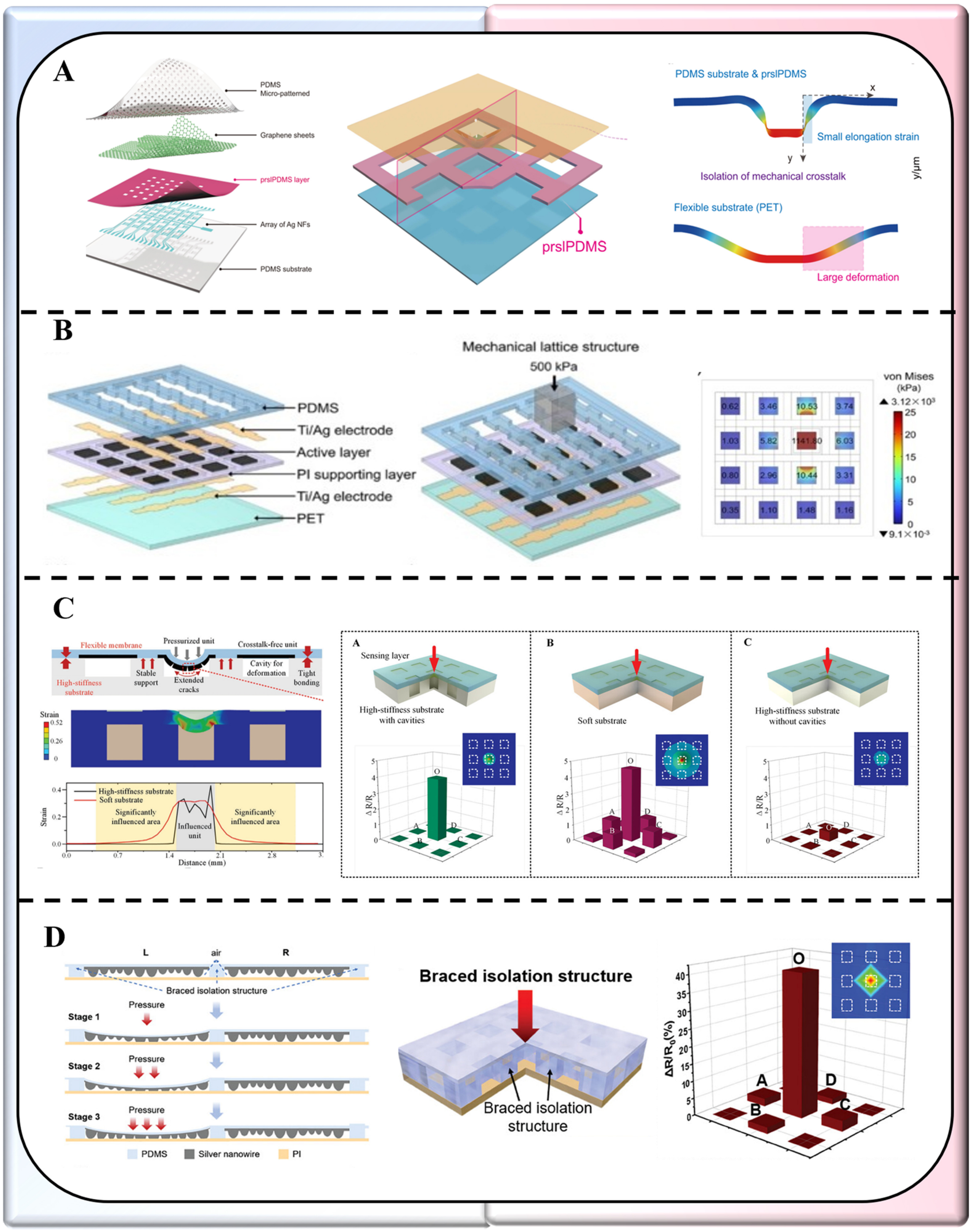

Figure 8. Anti-crosstalk strategies of sensor array (A) Micro-cage structure-based sensor array. Reproduced with permission[35]. Copyright 2023 Springer Nature; (B) Mechanical lattice structure sensor array. Reproduced with permission[34]. Copyright 2024 Elsevier; (C) High-stiffness substrate with cavity-based sensor array. Reproduced with permission[33]. Copyright 2024 Wiley-VCH; (D) Braced-isolation structure-based sensor array. Reproduced with permission[32]. Copyright 2024 Wiley-VCH. PDMS: Polydimethylsiloxane; NFs: nanofibers; PI: polyimide.

issues in multi-layer integration. Zhou *et al.* fabricated arrays using electrospun PVDF-TrFE nanofibers collected on patterned ground electrodes. Self-patterned piezoelectric nanofiber arrays were produced[103]. The integrally prepared raised piezoelectric units eliminate crosstalk between units. Li *et al.* proposed a laser-processing method to manufacture crosstalk-suppressed sensor arrays[31]. First, piezoresistive 3D graphene pixels were prepared using low-power lasers. Then, the active and substrate layers were cut, leaving interconnect patterns. The geometric shapes of these patterns were optimized through theoretical

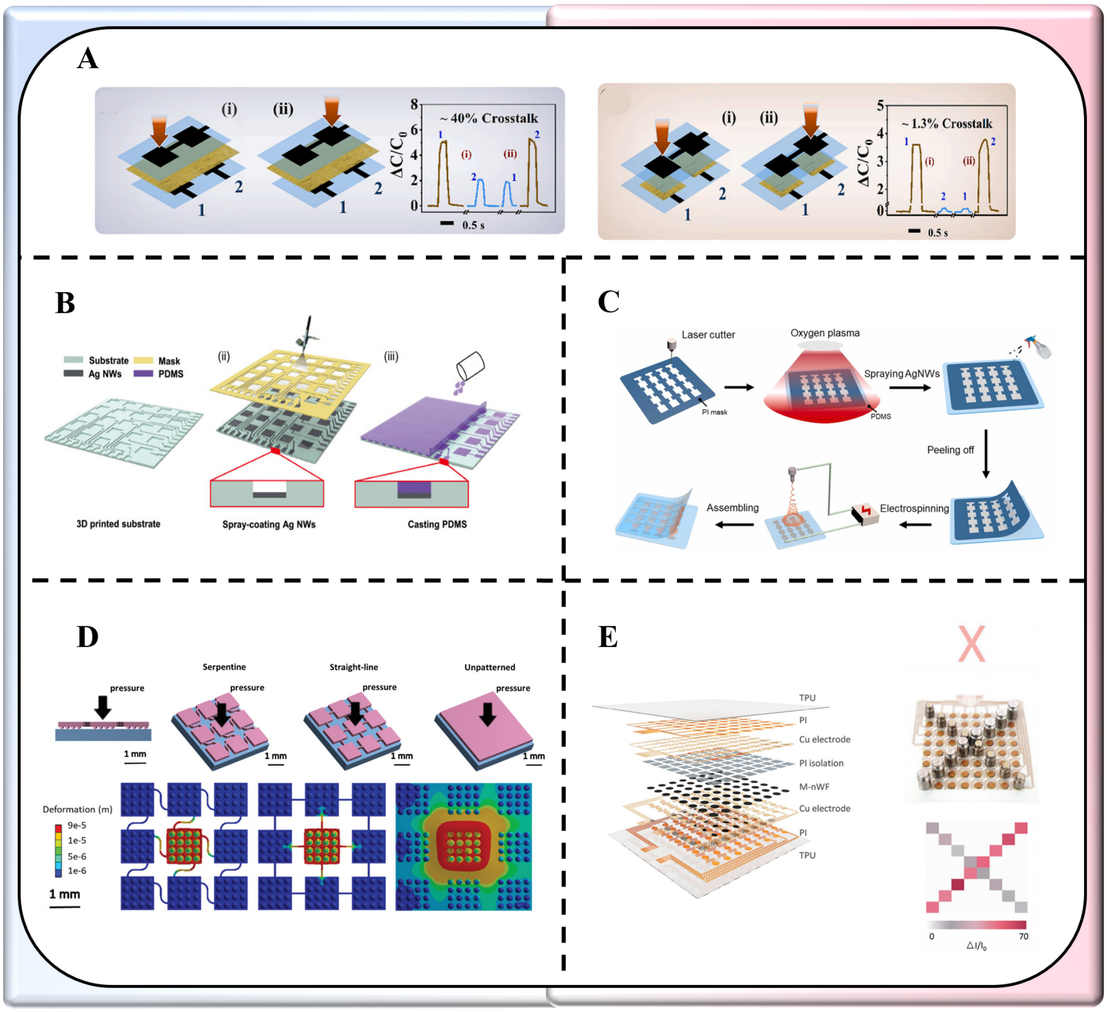

Figure 9. Anti-crosstalk strategies of sensor array. (A) Shared dielectric layer and isolated dielectric units. Reproduced with permission[101]. Copyright 2023 Elsevier; (B) Schematic illustration of the fabrication process of the crosstalk-minimized array with a 3D printed substrate. Reproduced with permission[102]. Copyright 2023 Elsevier; (C) Fabrication process of the crosstalk-free flexible piezoelectric pressure sensors. Reproduced with permission[103]. Copyright 2023 Elsevier; (D) Finite element model analysis of three models with different interconnect patterns. Reproduced with permission[31]. Copyright 2022 Wiley-VCH; (E) Exploded view of the crosstalk-free piezoresistive sensor array with serpentine electrodes and optical images of the sensor array with weights of 1 and 2 g placed in shapes of X and 2D pressure data monitored by LabView. Reproduced with permission[104]. Copyright 2024 Wiley-VCH. PDMS: Polydimethylsiloxane; NFs: nanofibers; PI: polyimide; 2D: two-dimensional; 3D: three-dimensional; TPU: thermoplastic polyurethane; M-nWF: MXene coated nonwoven fabric.

modeling and experiments. The serpentine interconnect design was found to be the most effective, significantly reducing crosstalk between units. This resulted in an 8×8 sensor array with a resolution of 0.7 mm. Inspired by the serpentine interconnect pattern's crosstalk-suppression, Yuan *et al.* developed a sensor array combining a PI microporous isolation layer (PIL) and serpentine electrodes with flexible piezoresistive sensors[104]. As shown in Figure 9E, the serpentine electrodes and PI isolation layer effectively suppressed crosstalk between array units. Experimental results demonstrated that the brightness pattern of the integrated LED array directly captured the shape of a two-dimensional (2D) figure with low crosstalk. These works, based on diverse design strategies, have realized crosstalk-resistance in flexible sensor arrays, offering novel ideas for future crosstalk-suppression approaches.

Performance enhancement strategies

Highly sensitive sensors can detect small stimulus changes, improving signal-to-noise ratio and accuracy. Thus, enhancing the sensitivity of sensing arrays is usually the focus of researchers' attention. In this section, we summarize strategies for improving the sensitivity of sensor arrays from other studies. Luo *et al.* inspired by the interface contact behavior of gecko's feet, designed a slant hierarchical microstructure to act as an electrode contacting with an ionic gel layer, fundamentally eliminating the pressure resistance and maximizing functional interface expansion to achieving ultrasensitive sensitivity. Such a structuring strategy dramatically improves the relative capacitance change both in the low- and high-pressure regions, thereby boosting the sensitivity up to 36,000 kPa^{-1} and effective measurement range up to 300 kPa[37]. Liu *et al.*, inspired by the sensitive microstructure of human skin (protective epidermis, spinous sensing structures, and neural conduction networks), prepared a self-healing, recyclable, and antibacterial polyurethane elastomer matrix via templating[105]. This matrix was integrated with microparticle arrays coated with conductive MXene nanosheets to create a biomimetic skin multifunctional sensor. Thanks to the polyurethane elastomer matrix's excellent mechanical properties and the sensor's unique skin-like microstructure, the resulting electronic biomimetic skin exhibited outstanding sensing performance for human health monitoring. It achieved an ultrahigh sensitivity of 1,573.05 kPa^{-1} within a 50 kPa detection range. Experimental verification confirmed that the device could successfully detect human activities such as pulse, speech, finger bending, and gait. Gang Li *et al.*, drawing inspiration from the filiform papillae on cat tongues, developed a flexible pressure sensor with a sensitivity of 504.5 kPa^{-1}[36]. The authors introduced a novel stress-transfer strategy to achieve this high sensitivity. As shown in Figure 10C, the flexible pressure sensor array consists of two CNT/PDMS (CNTs/PDMS) micro-structured arrays integrated face-to-face, forming an interlocking structure. This filamentary structure can continuously shift the stress concentration position under increasing loads, preventing structural compressibility reduction from stress accumulation, thus maintaining high sensitivity within its detection range. Additionally, experiments confirmed the developed flexible pressure sensor array's capability to monitor human physiological signals and motion states, making it suitable as a human-machine interaction interface. The sensitivity enhancement of sensor arrays mainly relies on microstructures. Both aforementioned works adopted a biomimetic approach to fabricate high-sensitivity sensor arrays, providing valuable references for future high-sensitivity sensor manufacturing.

Most sensors have sufficient sensitivity for common applications. However, a significant issue in mechanical sensors is the trade-off between sensitivity and sensing range, particularly in pressure sensor arrays. Typically, high-modulus materials are used to achieve a large measurement range, which greatly reduces sensitivity. In contrast, high-sensitivity sensor arrays often have a detection range of only kilopascals due to innovative structural designs, failing to meet higher detection needs. Chen *et al.* used conical carbon foam arrays as the sensing layer and elastomer shims as stiffness regulators, achieving a high sensitivity of 24.6 kPa^{-1} and an ultra-wide linear range of 1.4 MPa[38]. To realize high sensitivity, they adopted double-sided pyramidal carbon foam arrays with conical microstructures and micro-porosity, which enhanced the piezoresistive sensitivity of the carbon-foam-based sensing layer. Its hierarchical 3D porous structure and high compressibility gave it highly nonlinear piezoresistive properties. To expand the pressure sensing range, a stiffness regulator (SR) was introduced around the sensing layer to adjust the load distribution. The SR's nonlinear elasticity with the sensing layer's piezo-resistivity achieved the piezoresistive pressure sensor's wide detection range. Similarly, inspired by this work, Xiang *et al.* proposed a multiscale design for an all-carbon wearable PRSA, achieving high sensitivity and a wide linear range[39]. The array used double-sided pyramidal carbon aerogels (DPA) with pyramidal and porous microstructures as the sensing layer. A silicone framework as an elastic support (ES) effectively distributed loads and expanded the linear range. Additionally, conductive graphene sheets were transferred to superhydrophobic nylon fabric to form breathable conductive substrates (BCS). This PRSA, made of all-carbon components, had a simple

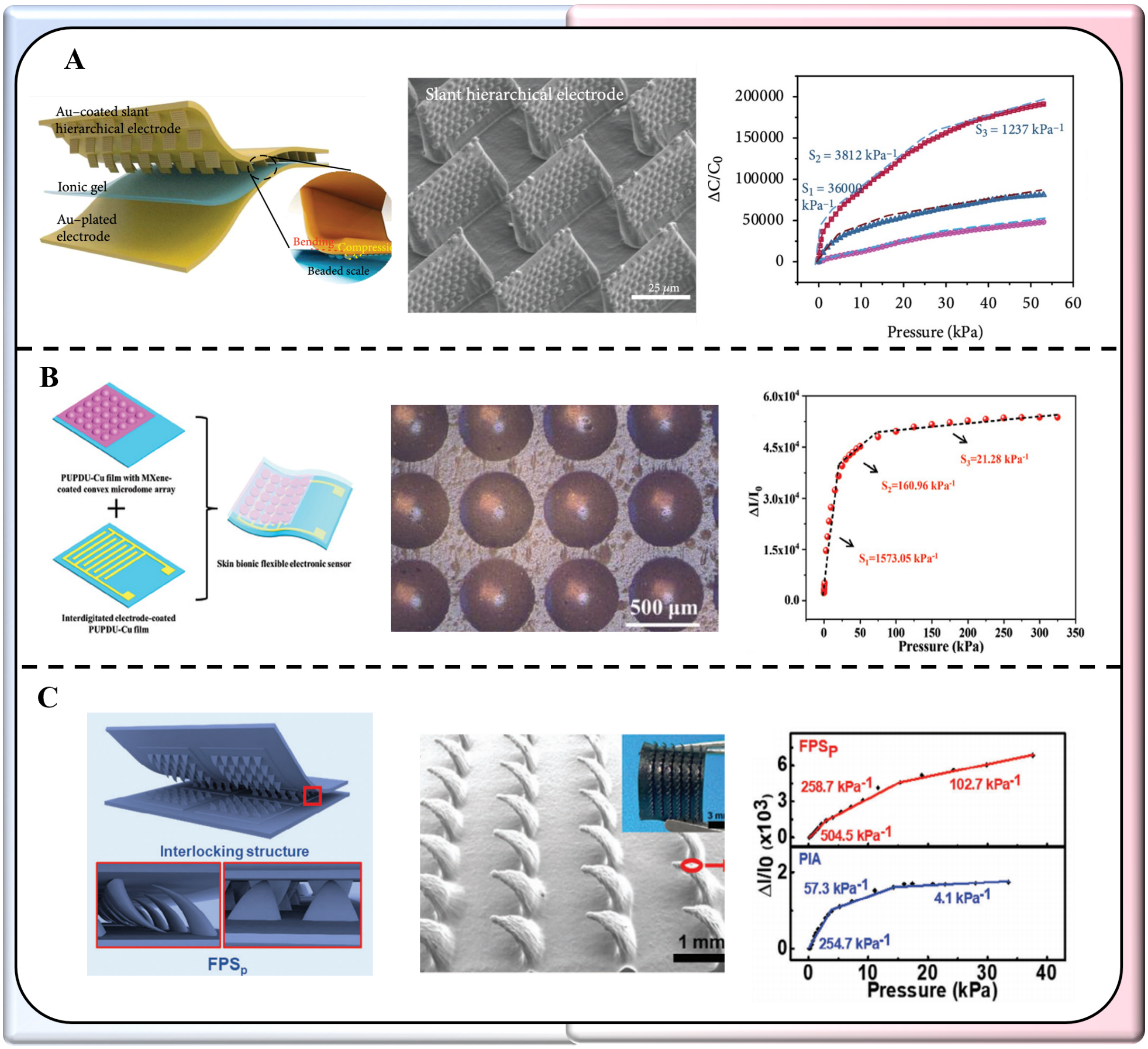

Figure 10. High sensitivity sensor array. (A) Gecko-inspired slant hierarchical microstructure-based sensor array with high sensitivity as 36,000 kpa^{-1}, schematic illustration of the iontronic pressure sensor with slant hierarchically structured electrode and ionic gel layer and SEM images of the structured electrode. Reproduced with permission[37]. Copyright 2022 AAAS; (B) Skin bionic flexible electronic sensor with high sensitivity of 1,573.05 KPa^{-1}, the structure of the sensor and the SEM image of the microstructure. Reproduced with permission[105]. Copyright 2023 Wiley-VCH; (C) Interlocking structure flexible pressure sensor array with high sensitivity as 504.5 kpa^{-1}, structure of the sensor and the SEM image of the filiform papillae-inspired array. Reproduced with permission[36]. Copyright 2024 Wiley-VCH. PUPDU: polysiloxane, Cu (II)ions-coordinated dimethylglyoxime (DMG) and urethane groups; FPS$_P$: flexible pressure sensor; PIA: papillae-inspired array.

manufacturing process, low cost, good stability, and excellent wearability, with a high sensitivity of 37.3 kPa^{-1}, a wide linear range of 0-1.4 MPa, and usability stability over 30,000 cycles. It could monitor human physiological signals under various pressures and simulate the human auditory system for voice recognition, accurately identifying words when combined with machine learning algorithms. These two works innovatively resolved the contradiction between high sensitivity and a wide linear range. They used specific materials and structural designs, such as pyramidal carbon-foam arrays and carbon aerogels, to achieve high-sensitivity sensor arrays. They also incorporated elastomers as supports or stiffness regulators to realize wide linear ranges, emphasizing the synergistic improvement of sensor performance through the combination of nonlinear piezoresistive and nonlinear elastic properties. This microstructure-coordinated multi-gradient structural design addressed the manufacturing challenge of balancing high sensitivity and wide linear range in flexible sensor arrays, offering new ideas for future sensors with even higher sensitivity and wider detection ranges [Figure 11].

In addition to the aforementioned trade-offs in sensitivity and operating range, the long-term stability and reliability of flexible sensor arrays in a variety of test environments with high-frequency pressure and extreme deformations are one of the challenges that researchers should be aware of. In wearable health monitoring (e.g., pulse, heartbeat) and human-machine interaction scenarios such as haptic feedback, sensor array is often exposed to harsh conditions such as high-frequency pressure, cyclic loading, and complex deformation. Such operating environments may lead to fatigue of the sensor layer materials, fracture of the conductive network, and failure of the microstructure, thus affecting the reliability and repeatability of the sensing performance. Therefore, most of the work focuses on improving the performance of sensing arrays under high-frequency dynamic forces and extreme deformations through strategies such as structural modulation and material optimization. Hu *et al.* developed a fully bionic E-skin (FBE-skin) with top-down architecture of magnetized micro-cilia, conductive micro-domes and flexible electrodes by mimicking the "hair-epidermis-dermis-subcutaneous" layers of human skin. The electromagnetic induction from micro-cilia allows the FBE-skin to capture dynamic signals with a frequency of up to 100 Hz[106]. Zhang *et al.* proposed a piezoelectric tactile sensor using a rigid-soft hybrid force-transmission-layer in combination with a soft bottom substrate inspired by finger structure-rigid skeleton embedded in muscle. Experiments show that this sensor exhibits a super-high sensitivity, wide bandwidth of 5-600 Hz and a linear force detection range of 0.009-4.3 N[107]. Both works were inspired by the structure of human skin, and innovative structures were developed to realize high-frequency dynamic force responses. Wu *et al.* developed a facile solvent-replacement strategy to fabricate ethylene glycol (Eg)/glycerol (Gl)-water binary anti-freezing and anti-drying organohydrogels for ultra-stretchable and sensitive strain sensing within a wide temperature range. The strain sensor exhibits a relatively wide strain range (0.5%-950%) even at -18 °C[108]. This work provides new insight into the fabrication of stable, ultra-stretchable, and ultrasensitive strain sensors for emerging wearable electronics.

APPLICATIONS OF FLEXIBLE PRESSURE SENSOR ARRAYS

As IoT advances, flexible sensor arrays are gaining attention in healthcare monitoring, human-machine interaction, intelligent interaction and equipment. So, researchers are exploring more application scenarios to better apply sensor arrays to real life.

Human health monitoring

Wearable technology integrates flexible sensors onto human skin to monitor health and enhance comfort and intelligence in daily life. When applied to the feet, these sensor arrays measure the pressure between the foot's sole and the floor, crucial for detecting and diagnosing sports injuries. Luo *et al.* developed a high-density sensor array used to identify warning signals and compare right/wrong operations during the process of intubation. When the guide wire gently slides across the epiglottis, each sensor on the designed array strip that comes into contact with the human tissue is activated from the head of the guide wire to the tail, inducing strain on the upper sensor pixels and producing signals, showcasing promising adaptation in the medical field. Tao *et al.* developed a smart insole system with capacitive pressure sensors and a data acquisition system[21]. It features a vertically porous dielectric layer and can map foot pressure in various states. Li *et al.* proposed a perception and interaction strategy for a 3D-stacked wearable Electroluminescent and Triboelectric device (ETD)[109]. The ETD uses a bottom triboelectric sensor array to obtain tactile physiological information. After processing and analysis, it triggers selective illumination in the top electroluminescent array via an external power circuit. Experiments show it can capture physiological

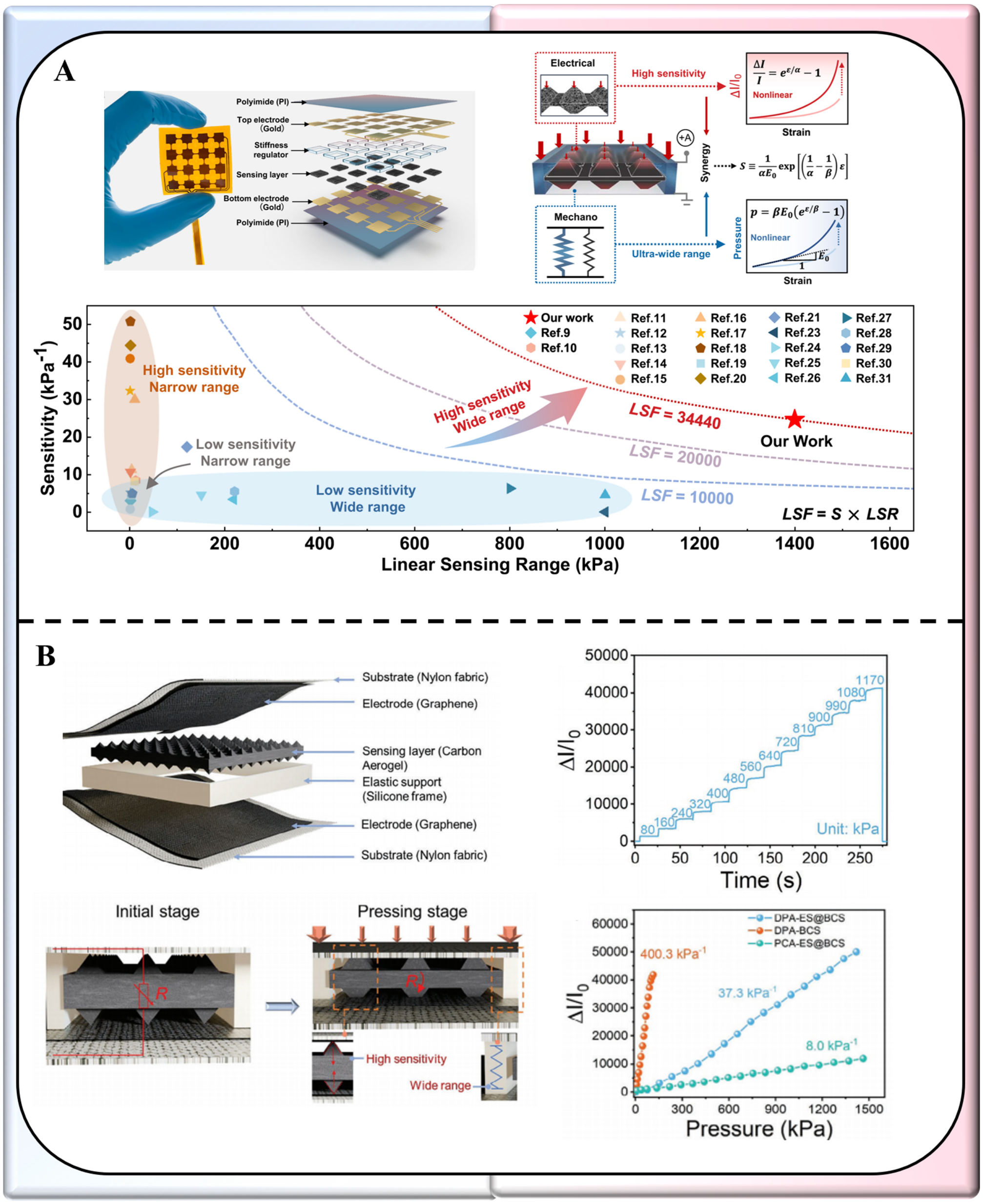

Figure 11. Sensor array with high sensitivity-ultra-wide range. (A) The structure of stiffness regulator-based sensor array. Reproduced with permission[38]. Copyright 2023 Springer Nature; (B) The structure elastic support-based sensor array. Reproduced with permission[39]. Copyright 2024 Wiley-VCH.

signals like pulse and respiration, aiding elderly self-monitoring. These works highlight the great application prospects of sensor arrays in medical health monitoring [Figure 12].

Intelligent interaction

Human-machine interaction, enabled by pressure sensors monitoring spatial pressure distribution and real-time trajectories, benefits from flexible sensor arrays. Smart gloves are also widely used in daily human-computer interaction, with one significant application being the development of smart glove systems. As shown in Figure 13A, Sundaram *et al.* fabricated a tactile glove with a 548 units sensor array on a knitted glove[110]. Using an expandable tactile glove and a deep convolutional neural network, it proves that sensors

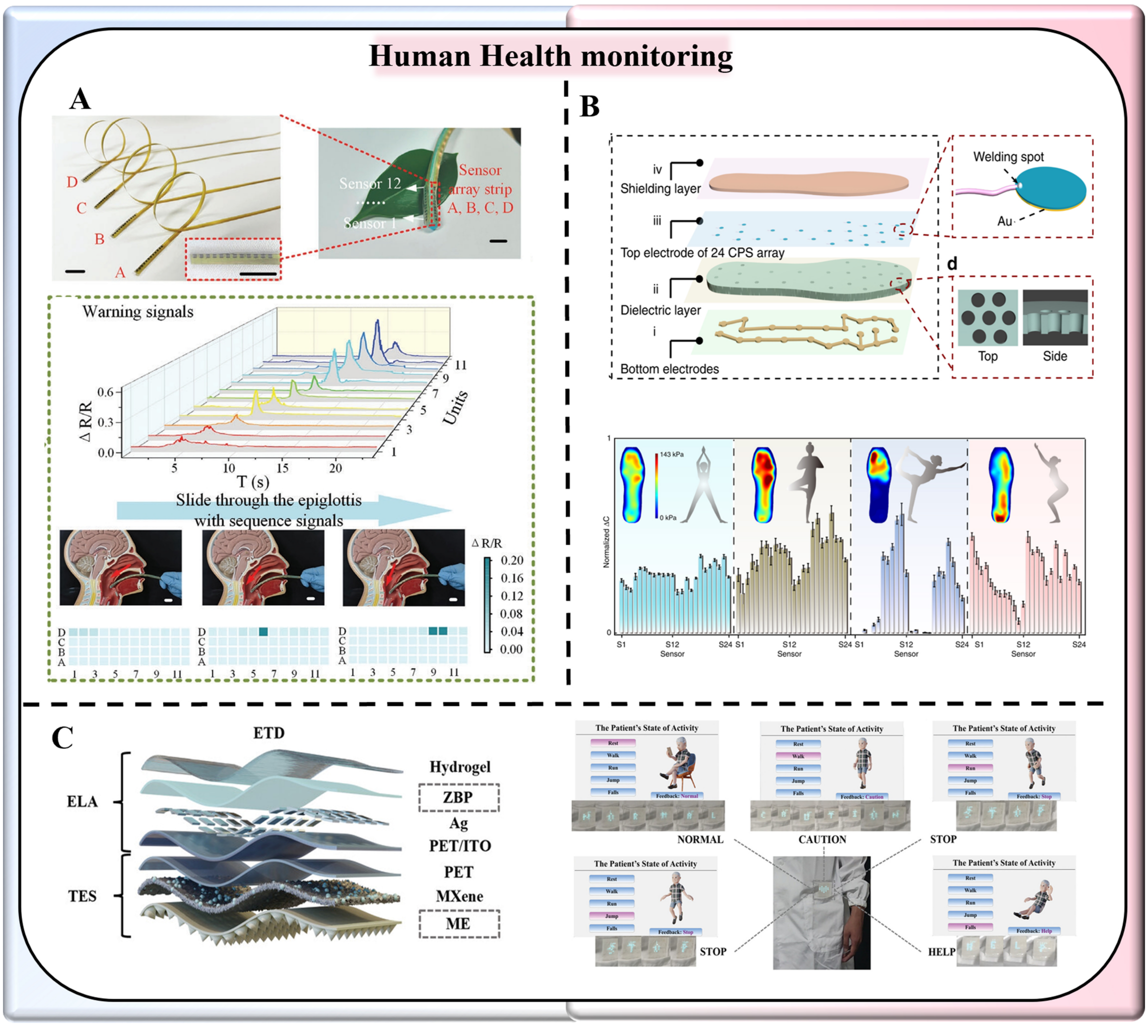

Figure 12. Sensor array for health monitoring. (A) Sensor array and the sensing guide wire for the intubation operation and a sequential response of the pressure signal when the intubation guide wire slides through the epiglottis. Reproduced with permission[33]. Copyright 2024 Wiley-VCH; (B) Smart wearable insole system: basic structure of the insole consisting of four layers, diagram of the thermodynamic pressure, and four kinds of yoga postures, dynamic plantar pressure mapping based on the insole system. Reproduced with permission[21]. Copyright 2020 Springer Nature; (C) Healthcare based on electroluminescent display and triboelectric sensor array: structure of the device, SEM image of the microstructure on the surface of MXene and Ecoflex, and the result diagrams of the integrated system of remote interfaces for monitoring. Reproduced with permission[109]. Copyright 2024 Wiley-VCH. CPS: Capacitive pressure sensor; ETD: Electroluminescent and Triboelectric device; TES: thermoelectric skin; PET: polyethylene terephthalate; ITO: indium tin oxide; ELA: electroluminescent array; ZBP: ZnS:Cu, $BaTiO_3$, and Poly(vinylidene fluoride-co-hexafluoropropylene) (PVDF-HFP); ME: MXene and Ecoflex.

on the hand can identify single objects and estimate their weight, demonstrating the broad application prospects of sensor arrays in tactile sensing for human-machine interaction. Li *et al.* reported a robot skin (R-skin) with mechanically gated electron channels, achieving ultrasensitive and fast-response sliding tactile perception via pyramidal artificial fingerprint-triggered opening-closing of electron gates. Two R-skins were attached to the thumb and the index finger to detect slipping state. When a mobile phone slipped suddenly during a stable grasp, the signals of both fingers showed an instantaneous jump due to the sliding-induced tension of the R-skin. This work further demonstrated the reliability and stability of our R-skin to perceive sliding state and provide tactile feedback for grasping[111]. Luo *et al.*, inspired by the interface contact behavior of gecko's feet, designed a pressure sensor for intelligent interaction. The sensor is integrated with

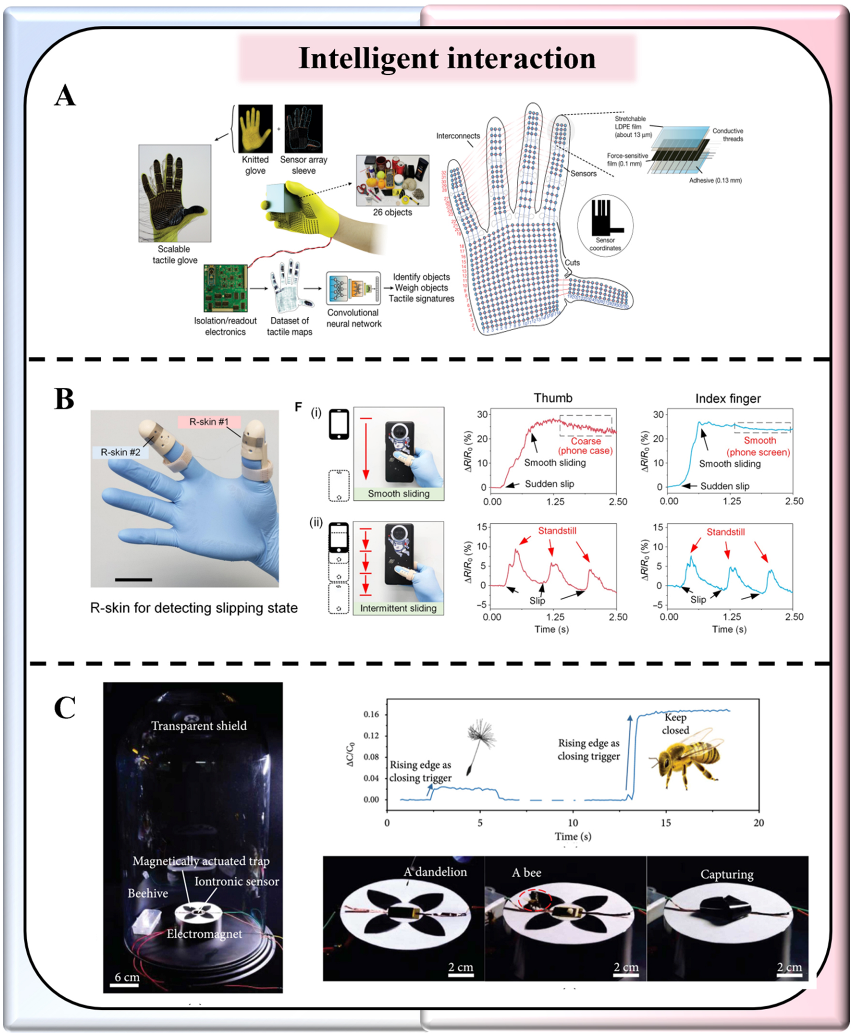

Figure 13. Sensor array for intelligent interaction. (A)Tactile glove: a sensor array with 548 elements attached to a custom knit glove. Reproduced with permission[110]. Copyright 2019 Springer Nature; (B) Photograph of the R-skins attached on fingers for detecting slipping state during grasping and the photograph of the signals of thumb and R-skin index finger. Reproduced with permission[111]. Copyright 2022 AAAS; (C)Self-built experimental flying object automatic capture device; capacitance response used as the feedback signal for automatically capturing objects and Schematic diagram of the active intelligent grabbing system. Reproduced with permission[37]. Copyright 2022 AAAS. R-skin: Robot skin.

a soft magnetic robot to demonstrate a biomimetic Venus flytrap. The ability to perceive weak stimuli allows the sensor to be used as a sensory and feedback window, realizing the capture of small live insects and the transportation of fragile objects[37].

Intelligent equipment

In recent years, the demand for flexible sensor arrays in the aerospace field has been increasing. For instance, to measure pressure in wind flow environments, Xiong *et al.* developed a conformable, programmable-range capacitive sensor array with high sensitivity[112]. It overcomes the limitations of traditional sensors with fixed sensing ranges and shows high sensitivity under initial pressure conditions. The capacitive sensor array was tested in a wind tunnel on a NACA0012-type aircraft. Experiments proved it could successfully detect positive and negative stresses on the aircraft's curved surface. Additionally, inspired by the integrated perception of flying creatures, the team developed an intelligent flexible sensing (iFlexSense) skin with components analogous to skin, neurons, the immune system, and the brain[18]. The iFlexSense skin provides substantial improvements to aircraft through multifunctionality, including airflow perception, state awareness, and self-diagnosis of complex surfaces. It was experimentally verified via wind tunnel tests on a NACA0012 wing profile. Results showed the array could accurately measure pressure, temperature, wall shear stress, and flutter on the wing surface, locate impacts, and predict flow separation and stall. This work shows the great potential of sensor arrays in future wind tunnel tests and for enhancing the capabilities of unmanned aerial vehicles and underwater vehicles. Chen *et al.* presented an ultrathin and customized-crack strain-sensing network for strain monitoring, fabricated through transfer printed technology. The sensor can be adhered to various curved surfaces to achieve long-term, high-fidelity strain monitoring. The strategy was employed to fabricate the substrate-free sensing network, offering the potential for improved capabilities for intelligent equipment[113]. The above-mentioned research shows that with the development of the IoT, flexible sensor arrays have gained wide attention in intelligent equipment [Figure 14].

Flexible sensor arrays have a wide range of applications in human-machine interaction, such as health monitoring and intelligent equipment. These applications require high sensitivity and resolution, as well as stable electrical performance and structural integrity of the devices under long-term cyclic loading and environmental exposure. These are the key factors that enable sensors to be used in real-world applications. Sensor devices are typically subjected to long-term cyclic loading, which can be problematic due to material fatigue and performance degradation. In addition, environmental factors such as moisture and ultraviolet (UV) can also reduce the lifetime of the device. Therefore, to improve the reliability in real-world applications, researchers are exploring more stable material systems, fatigue-resistant structural designs, and effective packaging strategies to ensure that flexible sensing arrays can maintain stable sensing performance in complex real-world environments. Li *et al.* developed an intelligent blood pressure and cardiac function monitoring system based on a conformal and flexible strain sensor array and deep learning neural networks[114]. The sensor showed high stability and durability in long-term strain loading-unloading cycles because the elastic fabric electrode had a relatively stable resistance to mechanical deformation. Its resistance increases by less than 1% of the whole system resistance even under 35% tensile strain. The experiment result also showed no change in performance before and after the thirty-day cycle. This demonstrates the reliability of the prepared sensor devices for practical applications. He *et al.* prepared a high-precision $CuO/TiO_2/MXene$ ethanol sensor operating at room temperature[115]. The response tests of the sensor were conducted six times every 7 days at 1, 5, and 20 ppm ethanol, respectively, indicating that the sensor has good long-term stability, which is mainly attributed to the p-n heterojunction formed by CuO and TiO_2, as well as the rich functional groups and large specific surface area of MXene. Luo *et al.* propose an in situ post-processing approach utilizing electrochemical reactions between metals (Zn, *etc.*) and hydrogels to synergistically achieve strong adhesion of the hydrogel-electrode interface due to the structural densification of the hydrogel network[116]. The prepared sensor demonstrates multimodal sensing capabilities, encompassing highly sensitive strain perception and simultaneous perception of temperature, humidity, and oxygen content unaffected by strain interference. Lee *et al.* developed an ultrathin and, ultrasoft strain sensor comprising a PU nanomesh as a friction-protective layer and an Au on PDMS-PU nanomesh as a strain-sensitive layer designed for on-skin applications[117]. The Au on a PDMS-PU nanomesh layer demonstrated stable operation under various environmental conditions, including changes in temperature and humidity and the presence of a saline solution. Gao *et al.* developed a novel multifunctional conductive hydrogel based on methylcellulose and cellulose nanocrystals, which exhibited excellent UV shielding behavior[118]. Flexible strain sensors assembled by the prepared hydrogels can be used to detect human body motions, including subtle and large motions, and exhibit good sensitivity and stability over a wide temperature range with UV-filtering properties. The above studies offered various strategies to the problems of long-term stability and reliability in real-world applications and exposed them to different

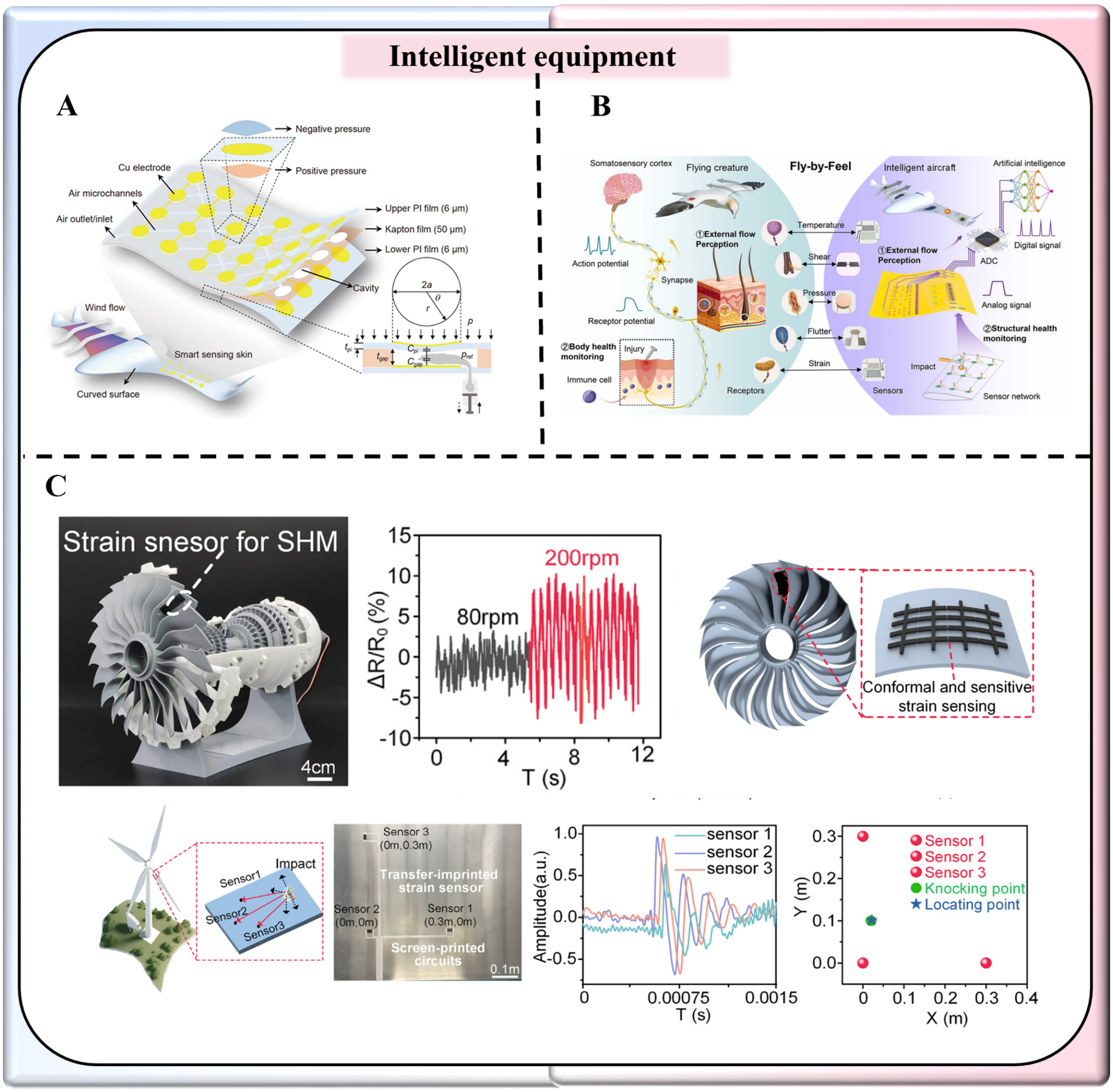

Figure 14. Sensor array for intelligent equipment. (A) Sensor array for large-range wind pressure on curved surfaced. Reproduced with permission[112]. Copyright 2020 Springer Nature; (B) Flexible sensor array for multifunctional flying perception. Reproduced with permission[18]. Copyright 2021 Elsevier; (C) A flexible strain sensor was attached to the curved surface of the engine blade model to monitor the operation conditions under various rotational speeds. Illustration and experiment of the sensor for structural impact monitoring; impact signals obtained by three sensors in different positions, the analysis result of the knocking position using data obtained by the sensor. Reproduced with permission[113]. Copyright 2025 Elsevier. PI: Polyimide; ADC: analog-to-digital converter; SHM: structural health monitoring.

environments.

CONCLUSION AND OUTLOOK

This review explores the current state of flexible pressure sensor arrays, covering their working mechanisms, materials, structural design, manufacturing methods and current challenges and strategies. Firstly, it presents the background of sensor technology and the broad application prospects of flexible pressure sensor arrays. It then mainly sums up and analyzes the research from anti-crosstalk design of multi-pixel units, high-precision manufacturing technology for array structures, performance control methods for miniaturized sensing units, to intelligent device array sensing applications. As a key technology in flexible electronics, pressure sensor arrays have shown great application potential in health monitoring, intelligent interaction and equipment. However, continuous optimization and innovation are needed for their practical application. Based on the current research, challenges, and solutions discussed, the following three future development directions are proposed:

(1) Development of high-performance materials and optimization of complex structures

The selection of materials and the design of structures have been the key aspects of concern in the fabrication of sensor devices. Material selection directly affects the performance of flexible sensor arrays, including sensitivity, durability, and stability. At the material level, the future development of flexible sensor arrays can further focus on the design and application of multifunctional composite materials, such as conductive polymers (e.g., PEDOT: PSS) and two-dimensional materials (e.g., MXene, graphene) or liquid metals (e.g., Ga-In alloys) composite, to simultaneously improve conductivity, flexibility, and environmental stability. Besides, "adaptive materials" that respond to environmental changes such as temperature, humidity, or electrical stimulation can be used to build sensor units with dynamic tuning capabilities. For example, materials that automatically adjust their mechanical fit or electrical conductivity under different external conditions are expected to increase the robustness of sensors in complex scenarios. Meanwhile, self-healing materials are a key development for achieving long-term stability. It can realize rapid repair after micro-damage and prolong device lifetime. In addition, biodegradability and green manufacturing properties of materials will be the focus of future development, especially in wearable medical devices, which require good biocompatibility and sustainability.

In terms of structure, more attention should be paid in the future to the combination of stretchability and structural programmability. On the one hand, by introducing mechanical configurations such as negative Poisson's ratio structure, helical electrode design, island-bridge structure, *etc*., the working reliability of the device under large deformation environment can be significantly improved; on the other hand, programmable morphological designs such as origami/paper-cutting structure and pneumatically driven structure are utilized to realize the precise fit and functional stability of the flexible device on 3D surfaces.

(2) Intelligent data processing

High-density integrated sensor devices tend to be limited by data post-processing. Therefore, intelligent data processing methods are also more important in the future development of the device. In many research works, intelligent data processing has become an indispensable core link to realize high-performance applications. Since the sensor arrays usually contain tens or even hundreds of pixel units, they generate a huge amount of high-dimensional, multi-noise signals in practical applications. These signals not only have significant temporal and spatial redundancy, but are also susceptible to interference from environmental variables such as temperature, humidity, and mechanical fatigue, thus affecting sensing accuracy and system stability. One of the future directions is to be deeply integrated with artificial intelligence (AI). By embedding neural networks directly into the sensor system, real-time feature extraction and signal classification can be realized at the front end. It can also significantly reduce data transmission and processing delays. This "sense-computing" strategy is especially critical for real-time feedback scenarios such as wearable devices and robotic skin. On the other hand, multiple information fusion technology will become an important way to improve the intelligence level of the sensing system. By fusing multimodal signals such as pressure, temperature, strain, capacitance, *etc*., comprehensive recognition of complex external stimuli can be realized. For example, neural networks and other methods can be used to process time series data to realize complex gesture recognition, gait analysis and other functions.

In addition, future flexible sensor arrays must realize self-calibration, self-learning, and self-adaptation. On the one hand, the integration of online self-calibration mechanisms helps to compensate for errors caused by long-term sensor drift or environmental changes. On the other hand, the introduction of advanced algorithms can enable the sensor to adapt to individual differences and the diversity of the usage environment, and enhance the universality and extensibility of the system.

(3) Industrialization and standardization

Flexible sensor arrays have seen many breakthroughs in laboratory research, but large-scale commercialization requires further optimization. First, in terms of large-scale manufacturing, the current mainstream laboratory preparation methods, such as scratch coating, transfer printing, and laser etching, are still difficult to meet the industrial demand for high consistency, and low cost. In the future, we should focus on the development of scalable processing technologies, such as flexible printing, and other processes, which can take into account the accuracy and capacity, and are suitable for large-scale manufacturing of various flexible substrates. At the same time, it is necessary to focus on packaging and integration processes to support the integration of complex array structures and integrated components. The current lack of unified performance evaluation standards is one of the barriers to realizing the industrialization of sensors. Different research organizations tend to use self-made test platforms, resulting in a lack of comparability and reproducibility of results. Therefore, in the future, we should promote the development of unified standards covering key indicators such as sensitivity, response time, stability, flexibility, durability, and environmental adaptability. In addition, taking into account the special needs in wearable applications and other fields, application-oriented tests should also be established in the future, such as dynamic response testing in real-world environments, stability evaluation after multiple bends, and durability testing in different environments. This will not only help improve the reliability of the device, but also accelerate the industrialization of the use of sensor parts.

In summary, by improving the industrial chain synergy mechanism and developing standardized manufacturing and testing systems, flexible sensors can be transformed from 'laboratory concepts' to 'practical products' [Figure 15].

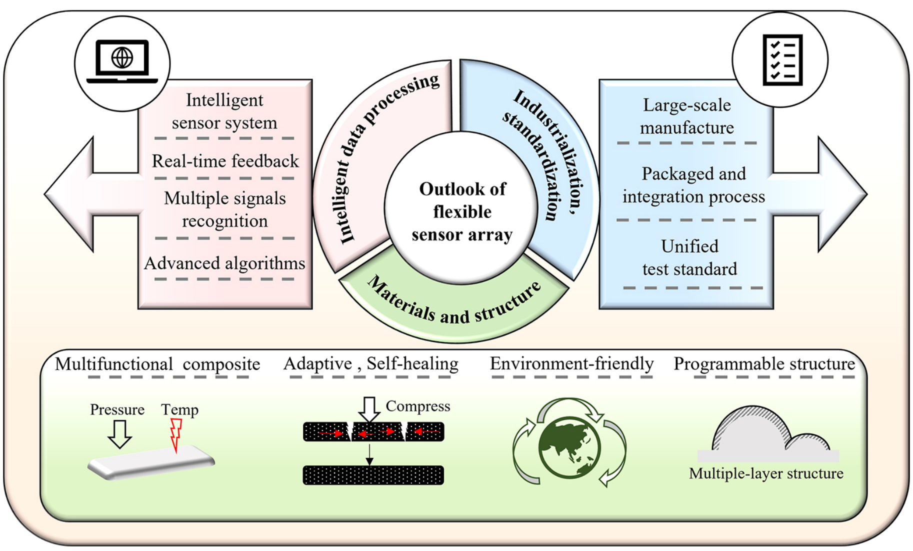

Figure 15. Outlook of flexible sensor array including material and structure, intelligent data processing, industrialization and standardization.

DECLARATIONS

Authors' contributions

Led the manuscript writing and figure preparation: Wang, S.; Chen, X.L.

Conducted the literature survey and analysis: Li, S.; Chen, X.M.; Sun, B.

Helped revise the manuscript and refine the content: Tian, H.; Wang C.; Li X.

Supervised the overall structure, provided critical feedback, and finalized the manuscript: Shao, J.; Chen, X.L.

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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