Flexible Pressure Sensors: Classification, Cutting-Edge Advances and Applications

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Abstract. Research in flexible materials and conductive nanomaterials has advanced the development of flexible pressure sensors. These sensors combine flexibility while converting pressure into measurable electrical signals. Hence their value in areas such as artificial skin, medical detection, and human-computer interaction. This paper reviews the research progress of flexible pressure sensors in the past 20 years, focusing on piezoresistive, capacitive and piezoelectric types, and systematically describes their basic working principles, latest technological breakthroughs and practical applications. The study shows that piezoresistive sensors have achieved high sensitivity and wide detection range through the optimization of planar thin films, microstructures and 3D porous structures; capacitive sensors have significantly improved their response performance with the innovation of dielectric materials such as air and graphene; and piezoelectric sensors have a unique advantage in dynamic signal detection due to their self-powered characteristics. Looking ahead, these three types of sensors have great potential in human-computer interaction, medical and health monitoring, etc. Emerging features such as self-healing function and multifunctional integration provide new ideas for electronic skin and wearable devices, but the challenges of performance balance, environmental stability, and large-scale production still need to be further broken through.

Keywords: Flexile Pressure Sensors, Piezoresistive Sensors, Capacitive Sensors, Piezoelectric Sensors, Electronic Skin

1 Introduction

A sensor is a device or system capable of detecting a physical, chemical or biological quantity of the object to be measured and converting it into a measurable, processable electrical or other form of output signal. Among the many types of sensors, pressure sensors play an important role in industrial control, automotive electronics, medical devices and other fields by achieving accurate detection, transmission and feedback of pressure parameters. The development of pressure sensors has made a major breakthrough with the emergence of new flexible materials such as elastomers like Polydimethylsiloxane (PDMS) and conductive nanomaterials like carbon nanotubes [1,2]. These flexible materials not only endow the sensors with good flexibility and

A. J. Moshayedi (ed.), *Proceedings of the 2025 2nd International Conference on Electrical Engineering and Intelligent Control (EEIC 2025)*, Advances in Engineering Research 279,
https://doi.org/10.2991/978-94-6463-864-6_55

adaptability, but also promote the vigorous development of the research on flexible pressure sensors, making it important research.

Flexible pressure sensors, as an important branch of wearable electronics, have been extensively studied for their wide range of applications, such as human-machine interfaces and health monitoring [3]. These sensors demonstrate remarkable promise for implementation across diverse fields including medical health monitoring, tactile feedback interfaces, and autonomous sensing networks with self-sustaining power, thereby establishing fundamental building blocks for future intelligent systems endowed with skin-like sensory functionalities. The current breakthroughs in flexible pressure sensors, especially the self-healing and multifunctional integration features, are driving the rapid development of the next-generation electronic skin and wearable devices [4,5].

This review will present a detailed description of three widely used devices, flexible piezoresistive (Section two), piezoelectric (Section three) and capacitive (Section four) pressure sensors, respectively, in terms of their classical design, their cutting-edge design and their application areas, and finally conclude with a summary and a discussion of the future outlook (Section five).

2 Flexible piezoresistive pressure sensors

Flexible piezoresistive pressure sensors typically consist of three key structural elements: a pressure-sensitive active layer, conductive electrodes, and a flexible supporting substrate. These sensors operate on the principle of piezoresistive transduction, where applied external pressure alters either the interfacial contact resistance between conductive elements or the internal conductive network within the active material, enabling pressure quantification through corresponding resistance variations. Piezoresistive flexible pressure sensors have emerged as a prominent research focus in flexible sensing technology due to their distinct advantages, including structural simplicity, well-defined operational principles, straightforward fabrication processes, excellent cost-effectiveness, as well as the combined merits of high sensitivity and reliable signal reproducibility. It is based on these significant advantages, researchers are committed to the development of high-performance piezoresistive flexible pressure sensors, in order to promote its further development in various application areas.

2.1 Three classic flexible piezoresistive pressure sensors

Flexible piezoresistive pressure sensors, on the basis of inheriting the pressure detection function of traditional piezoresistive sensors, must have excellent flexibility and deformability characteristics at the same time. This particular requirement has led to current research focusing on sensor structure innovation, which balances flexibility and sensing performance through optimised structure design. It is worth noting, however, that although there has been a great deal of research on flexible and stretchable structures in the field of flexible electronics, there is still a relative lack of structural design explorations specifically for flexible pressure sensors.

Based on the differences in structural features, this study summarises piezoresistive flexible pressure sensors into three typical structure types: planar thin-film structure, surface microstructure and 3D elastic porous structure. For each structure type, its structural characteristics, preparation process, key performance parameters (including sensitivity, response range, cycling stability, etc.) and typical application scenarios will be systematically analysed to provide theoretical references for the structural design and performance optimization of flexible pressure sensors.

Planar thin-film architectures represent a prevalent design for flexible piezoresistive pressure sensors, characterized by their micro/nanoscale structural features. This configuration has been widely reported to achieve superior sensing characteristics, as shown in Fig 1. A representative study by Li et al. developed an advanced flexible piezoresistive sensor utilizing naturally formed hierarchical $SnSe_2$ nanoflowers combined with a specially designed tapered planar truncated PDMS substrate, demonstrating exceptional performance metrics [6]. Yao's team developed an ultrathin flexible piezoresistive sensor dedicated to fluid pressure measurement with an innovative micro structured thin-film design with a conductive carbon nanotube layer as the core sensing unit [7]. The overall thickness of the sensor was controlled in the range of 40 ± 10 µm, and low-cost fabrication was achieved based on biocompatible PDMS materials. Test data show that the device exhibits three significant advantages: excellent detection sensitivity (gas 0.047kPa^{-1}/liquid 5.6×10^{-3}kPa^{-1}), ultra-low operating power consumption (<180µW), and unique curved microtubule pressure monitoring function.

Three-dimensional compressible porous architectures. The fabrication strategies for such porous configurations can be primarily classified into two approaches. The first methodology focuses on engineering porous networks within bulk materials through specialized processing techniques, whereas the second approach employs naturally porous substrates like melamine foam and polyurethane sponges that possess intrinsic cellular structures. Jing et al. developed a highly responsive flexible piezoresistive sensor fabricated from a composite of silver nanowires (AgNWs) embedded in a polyvinylidene fluoride (PVDF) matrix, which self-assembles into an interconnected three-dimensional porous network [8]. This innovative architecture exhibits exceptional pressure sensitivity due to its unique deformation mechanism: under applied pressure, the compressible 3D porous framework undergoes structural rearrangement, causing immediate and significant alterations in the conductive pathways that manifest as measurable resistance variations. This elastic porous conductive architecture endows the fabricated flexible piezoresistive sensors with outstanding performance characteristics, including: (1) remarkable pressure sensitivity across a broad detection range, (2) rapid response capability (64 ms), (3) ultra-low detection threshold (25 Pa), and (4) exceptional operational stability for long-term use.

Engineered surface microarchitectures. Peng et al. developed a highly sensitive piezoresistive sensor system utilizing micro-patterned conductive PDMS films with three distinct surface geometries [9]. Through an innovative soft lithography approach replicating 3D-printed templates, they fabricated precision microstructures including pyramid arrays, hemispherical domes, and half-cylindrical ridges. The piezoresistive functionality was achieved by depositing a conformal carbon nanofiber (CNF) coating on these textured surfaces. Comparative evaluation revealed the half-cylindrical microstructure demonstrated superior performance, achieving both exceptional sensitivity (detection threshold of 1.0 Pa) and optimal pressure response characteristics. This template replication methodology, leveraging 3D printing technology, has emerged as a cost-effective platform for mass-producing high-performance micro structured sensing elements.

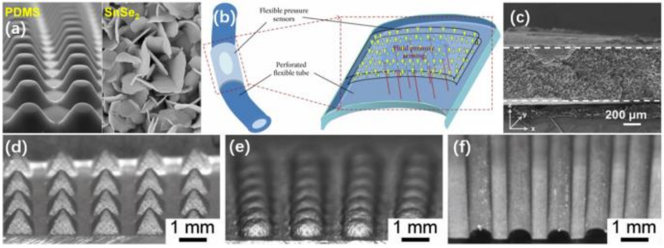

Fig. 1. (a) SEM plot of PDMS structure and SnSe2 nanoflowers structure [6]. (b) Schematic diagram of flexible microtubule pressure measurement using a flexible pressure sensor [7]. (c) SEM image of cross-section of PAPC film with 3D porous structure [8]. (d~f) Side-view optical microscope images of micro structured PDMS films coated with CNFs in pyramidal (d), hemispherical (e) and cylindrical (f) shapes [9].

2.2 Recent advances in flexible piezoresistive pressure sensors

Innovations in thin film structures with double-sided micro structured sensing layers. Planar thin-film based flexible piezoresistive pressure sensors have garnered significant research interest due to their promising potential in industrial monitoring systems and human-machine interface applications. Traditional planar thin film structures have microstructured sensing layers on only one face of the film, and the performance of these sensors has usually been rather outdated, failing to give a wide pressure correspondence range, high sensitivity, and fast correspondence speed, which limits their further applications. Sun et al. introduced an innovative dual-side microstructured thin-film pressure sensor design fabricated via a template-based approach [10]. Their breakthrough design features opposing surface microstructures on both sides of the planar sensing film. This bilateral architecture enables the sensor to achieve exceptional performance metrics simultaneously: a high sensitivity of 5.5 kPa^{-1} across an extended pressure range (0-140 kPa), while maintaining rapid response (120 ms) and reliable cycling stability. The demonstrated capabilities in distributed pressure mapping and industrial monitoring applications highlight the transformative potential of this dual-side microstructure strategy, establishing a significant technological advancement for next-generation flexible pressure sensing systems.

Kim's team developed a novel flexible pressure sensor based on MXene-modified porous Eco-flex sponges, which used a sugar template method to prepare porous Eco-flex substrates with high deformability and uniformly loaded Ti_3C_2Tx MXene 2D nanosheets with excellent conductivity into the porous structure by a dip-coating process [11]. The MXene material is a two-dimensional transition metal carbide, nitride or carbon-nitride with excellent electrical conductivity, mechanical strength and surface adhesion. These excellent properties allow MXene to synergise with the high deformability of the porous Eco-flex substrate, enabling the sensor to produce significant structural deformation even at low pressures, resulting in high sensitivity and fast response characteristics over a wide pressure range. This novel material-structure integration strategy offers dual benefits: (1) significant simplification of the fabrication process, and (2) enhanced functional performance for wearable motion monitoring applications. The approach establishes a new paradigm for developing high-performance flexible pressure sensors through synergistic material selection and architectural engineering.

2.3 Application directions for flexible piezoresistive pressure sensors

Flexible piezoresistive pressure sensors demonstrate considerable potential in healthcare monitoring applications, particularly for detecting vital physiological signals. Wang et al. developed an economical and scalable fabrication method for producing high-performance piezoresistive sensors and their integrated arrays, which show promising utility in both personal health monitoring and human-machine interaction systems [12]. Wang's team fabricated MXene/MoS2-based layered piezoresistive sensors through a cost-effective manufacturing process. These devices exhibit: (1) high pressure sensitivity (0.42 kPa^{-1} in 0-1.5 kPa range), (2) rapid dynamic response, and (3) exceptional mechanical stability. Experimental validation demonstrated their effectiveness in multiple biomedical applications including motion tracking, voice pattern detection, and - most notably - precise arterial pulse waveform analysis. The acquired physiological data enables real-time health anomaly detection and early warning capabilities.

Flexible piezoresistive sensors demonstrate distinctive capabilities for speech recognition and human-machine interface applications. Xiang et al. engineered a high-performance sensor system by integrating alkali-modified 3D crumpled MXene architectures with microstructured PDMS substrates [13]. This design achieved both exceptional sensitivity and an extended detection range. In a proof-of-concept demonstration, the researchers implemented the sensor on a subject's laryngeal region, where it successfully captured: (1) subtle glottal vibration patterns during phonation, and (2) distinctive articulatory signatures of specific lexemes (e.g. "past"). This technological breakthrough enables novel approaches for developing advanced vocal human-computer interaction platforms.

3 Flexible Capacitive Pressure Sensors

Capacitive pressure sensors operate fundamentally through modulation of parallel-plate capacitance, achieved through three primary mechanisms: interelectrode gap variation, overlapping area adjustment, or dielectric constant alteration. For pressure sensing applications, gap distance modulation remains the predominant operational principle. Applied mechanical forces induce proportional compression/expansion of the electrode spacing, generating measurable capacitance changes that correlate directly with input pressure magnitude. In flexible capacitive sensor architectures, the dielectric layer's material properties and structural design constitute critical determinants of overall device performance, influencing key parameters including sensitivity, dynamic range, and response characteristics. Different dielectric materials have unique mechanical and electrical properties, such as modulus of elasticity, dielectric constant, and compressibility, which affect the response speed and sensitivity of the sensor to external pressure. In recent years, researchers have significantly improved the performance of dielectric layers by introducing strategies such as porous structures, microstructures or composites, enabling sensors to detect small pressure changes more accurately while maintaining good flexibility and durability.

3.1 Three classic three flexible capacitive pressure sensors

The performance enhancement of capacitive pressure sensors critically depends on the strategic selection and engineering of dielectric materials, as their intrinsic properties fundamentally govern the device's capacitive response characteristics. Consequently, dielectric layer optimization represents a pivotal research focus for advancing sensor performance. The following discussion systematically examines the dielectric material innovations implemented in state-of-the-art flexible capacitive pressure sensors in recent years, categorizing them by their distinctive material compositions and structural designs, as shown in Fig 2.

Air as dielectric material. Zheng et al. developed a high-performance flexible capacitive pressure sensor utilizing air as the dielectric layer in a unique PDMS-AgNWs composite architecture [14]. The sensor was fabricated through a two-step process involving blade-coated deposition of interdigitated silver electrodes on a bottom PDMS substrate followed by integration of AgNWs networks into an upper PDMS layer, which spontaneously formed precisely tunable air gaps between the electrodes. The thickness of these air gaps could be accurately controlled by varying the number of AgNWs layers during fabrication. This innovative air-gap design provided significant performance advantages by effectively minimizing the off-state current in unpressurized conditions while enhancing capacitive response sensitivity under applied pressure. Through systematic optimization of critical parameters including air gap thickness, AgNWs distribution pattern, and electrode channel dimensions, the researchers achieved an exceptional sensitivity of 16.1 kPa^{-1}, conclusively demonstrating the superior performance characteristics achievable with air-dielectric configurations in flexible pressure sensing applications. The study highlights the importance of dielectric engineering in developing high-sensitivity capacitive sensors while maintaining structural flexibility. Huang et al. developed a novel high-sensitivity pressure sensing platform by combining conductive microstructured air-gap dielectrics with two-dimensional semiconductor transistors [15]. In this innovative architecture, the overall capacitance is predominantly governed by the highly compressible air gap, with minimal influence from the relatively incompressible thick elastomer layer. This distinctive design approach enabled precise performance tuning, resulting in a pressure sensor exhibiting an average sensitivity of 44 kPa^{-1} across the 0-5 kPa range while achieving remarkable peak sensitivity up to 770 kPa^{-1} under optimized conditions. Importantly, the design maintains flexible adjustability of the pressure sensing range, demonstrating the effectiveness of air-gap modulation for advanced pressure sensing applications.

Graphene as dielectric. Paul's team developed a capacitive pressure sensor based on a corrugated graphene structure with an innovative design that utilises the unique electronic properties of graphene to achieve highly sensitive detection [16]. The sensor uses parallel aligned corrugated graphene as the electrode material, and its surface morphology forms a series of ridges with sharp edges. When pressure is applied, a significant strain effect occurs at these sharp edges, leading to a large increase in local charge density. Since the corrugated graphene of the top and bottom electrodes form regions of high charge concentration at the sharp edges, the sensor exhibits enhanced response characteristics to external pressure. Through this mechanism of cleverly exploiting graphene's surface morphology change, the sensor achieved a high sensitivity of 1.2×10^{-4} Pa^{-1} in the dynamic range of 125-980 Pa, demonstrating the unique advantages of graphene as a dielectric material in the field of pressure sensing. Huang et al developed a novel flexible capacitive pressure sensor, which uses a composite structure of laser-induced graphene (LIG) and porous PDMS foam, and successfully constructed a pressure sensing structure with integrated plate-foam-plate features by transferring LIG electrode materials onto a porous PDMS foam substrate [17]. This unique structural design enables the sensor to have both high sensitivity and fast response characteristics, and shows excellent response stability and very low signal hysteresis in dynamic pressure testing, demonstrating the potential of combining LIG and porous PDMS foam in the field of flexible sensing.

3D porous elastomer/foam/sponge/composite as dielectric. Qiao's team innovatively used the sacrificial sucrose template method to prepare porous PDMS materials with a sponge-like breathable structure, which undergoes compressive deformation and expels air from the pores under external forces [18]. Since the dielectric constant of PDMS itself is significantly higher than that of air, this dynamic change of the pore structure will effectively enhance the overall dielectric constant of the material, thus substantially enhancing the sensitivity of capacitive pressure sensors based on this material.

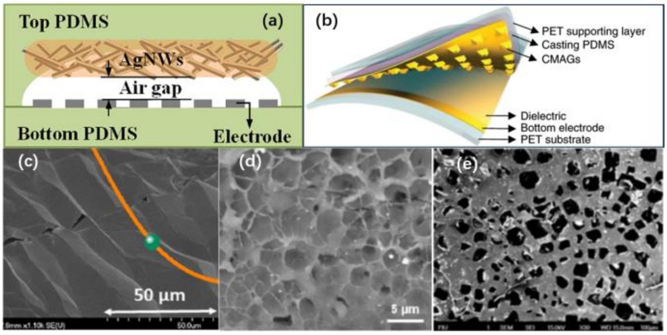

Fig. 2. (a) Air Gaps in Sensor Structures [14]. (b) Enlarged view of the equipment structure [15]. (c) SEM images of corrugated graphene structures (The orange lines in the picture are from the original picture and do not affect the readability) [16]. (d) High resolution SEM images of LIG and PDMS electrodes [17]. (e) Cross-sectional SEM image of porous gas PDMS [18].

3.2 Recent Advances in Flexible Capacitive Pressure Sensors

Zheng et al. addressed a critical limitation in conventional air-dielectric capacitive pressure sensors, where excessive compression of air gaps under high-pressure loading restricts sensitivity across broad measurement ranges [19]. Their innovative solution involved incorporating liquid metal (LM) into the interconnected porous matrix of flexible composite foams. The incompressible nature of the LM-infused fluid phase substantially enhanced the foam's mechanical robustness under high-pressure conditions, effectively maintaining optimal air gap dimensions even under significant compressive loads. This breakthrough design enabled an exceptional pressure detection range spanning from 10 Pa to 260 kPa while simultaneously achieving high sensitivity (1.91 kPa^{-1}). The unique combination of metallic conductivity and fluidic deformability inherent to the LM component further endowed the composite sensors with superior mechanical flexibility and enhanced pressure-responsive characteristics.

Most studies have focused on improving the sensitivity of devices by increasing the deformability and dielectric constant on flat electrodes. However, efforts to improve sensitivity and linearity by increasing the effective area between the electrodes during deformation have been neglected. Ni's team broke through the limitation of traditional research focusing on enhancing the dielectric constant and electrode deformation ability, and innovated the use of AgNWs-coated microneedle array (MNA) structure instead of the traditional flat metal electrode structure [20]. The MNA structure has many protruding micrometre-scale needle-like structures compared with the planar structure, and these needle-like structures result in a larger effective electrode area.

3.3 Flexible Capacitive Pressure Sensor Application Direction

Flexible capacitive pressure sensors have made significant progress over the past few years, with a variety of proven dielectric materials being successfully used in their manufacture, including elastomeric foams, silicone rubber, aerogels, and nanoparticle-filled composites. These materials not only have excellent dielectric properties, but can also be adapted to different application scenarios. For example, porous dielectric materials can achieve high sensitivity due to their high compressibility, while nanocomposites further optimise the response characteristics of sensors by modulating the dielectric constant. Based on these advantages, flexible capacitive pressure sensors show a wide range of application prospects in the field of electronic skin, covering human-computer interaction (e.g. gesture recognition), motion detection (e.g. gait analysis and yoga movement monitoring), marine detection (e.g. marine skin), and health monitoring (e.g. blood pressure and respiratory rate detection). In the future, with the continuous development of new dielectric materials, flexible capacitive pressure sensors are expected to achieve a wider range of applications in medical monitoring, electronic skin and wearable devices.

In aerospace applications, precision pressure monitoring across wide measurement ranges is critical for various operational requirements, including altitude determination, meteorological analysis, aerodynamic performance assessment, and military payload management in unmanned aerial vehicles, orbital satellites, and space vehicles. To address these demanding specifications, Lu et al. developed an innovative micro-pressure sensor employing superelastic polymer materials with parallel-plate capacitive architecture. This flexible sensing device incorporates sensitivity compensation mechanisms and demonstrates exceptional performance in measuring subtle pressure variations (0-6 kPa range) on vehicle surfaces [21]. The sensor's combined attributes of high sensitivity and mechanical compliance make it particularly suitable for aircraft applications requiring accurate micro-pressure detection under dynamic operating conditions.

Huang et al. developed an innovative fabrication approach for creating layered porous PDMS composites through a cost-effective process utilizing sugar particles and water-in-oil emulsion [22]. These engineered composites served as high-performance dielectric layers in flexible capacitive pressure sensors, demonstrating remarkable improvements over conventional bulk PDMS designs. The optimized sensor architecture exhibited a 22.5-fold enhancement in sensitivity (0.18 kPa^{-1}) while maintaining an extensive operational range (0-400 kPa). Through comprehensive evaluation in practical wearable applications - including finger-mounted sensing systems, respiratory pattern monitoring, and pressure-sensitive arrays - the researchers validated the device's superior performance characteristics and confirmed its strong potential for integration into next-generation wearable electronic platforms.

4 Flexible Piezoelectric Pressure Sensors

Flexible, sensitive and self-powered pressure sensors that can mimic the tactile sensing function of human skin have become an important research and development direction in the fields of electronic skin (e-skin), prosthetics and soft robotics. Currently, state-of-the-art pressure sensors, such as piezoresistive, capacitive, and friction electric sensors, have excellent performance but usually rely on bulky external power supplies in practical applications, which not only limits their portability, but also increases the size of the overall device, making it difficult to meet the e-skin's need for lightness and flexibility. Therefore, the development of self-powered pressure sensors with high sensitivity and mechanical flexibility has become an urgent need. Flexible piezoelectric pressure sensors have emerged as a prominent research focus in the field of wearable technology, owing to their unique self-powered operational capability. This distinctive characteristic positions them as particularly promising candidates for advancing next-generation electronic skin systems and autonomous wearable devices, eliminating the need for external power sources while maintaining robust sensing performance.

4.1 Three classic flexible piezoelectric pressure sensors

Flexible piezoelectric composites are mainly classified into types 0-3 and 1-3 according to their connection structure, as shown in Fig 3.

0-3 Type. Drawing inspiration from biological hierarchical architectures, Li et al. developed an innovative fabrication method combining solid-state shear milling with salt-template leaching to engineer PVDF foams with multiscale nested porosity [23]. The resulting material exhibits a distinctive bimodal pore size distribution, featuring interconnected macropores (20-50 μm) and mesopores (0.3-4 μm) that synergistically confer exceptional compressibility while maintaining structural integrity. This biomimetic design approach successfully reconciles the typically competing demands of high porosity (~85%) and mechanical flexibility in piezoelectric polymer foams. Jiang et al. developed an innovative 0-3 type piezoelectric composite by uniformly dispersing PZT-5A ceramic particles within a silicone polymer matrix. Through systematic experimental investigation, they established a critical relationship between the composite's piezoelectric response and polarization parameters [24]. The research identified an optimal polarization protocol consisting of: 25 minutes duration at 100°C under a 4 kV/mm electric field for samples containing 50 vol% PZT-5A particles (170-212 μm size fraction), which yielded maximum pressure sensitivity. This comprehensive optimization of material composition and poling conditions resulted in a high-performance flexible piezoelectric composite with tailored electromechanical properties.

Types 1-3. Wang et al. engineered a high-performance needle ultrasonic transducer utilizing a 0.70Pb(Mg1/3Nb2/3)O3-0.30PbTiO3 single crystal/epoxy 1-3 piezoelectric composite fabricated through the dice-and-fill technique [25]. This advanced transducer exhibited exceptional operational characteristics, including: (1) ultrahigh center frequency exceeding 42 MHz, (2) broad -6 dB bandwidth reaching 90.6%, (3) moderate insertion loss of 16 dB, and (4) outstanding transmission sensitivity measuring 314 mV/V. The study demonstrated how optimized 1-3 composite architecture can simultaneously achieve high-frequency operation and superior electromechanical performance in miniaturized ultrasonic devices. Hao et al. developed an innovative flexible piezoelectric composite hydroacoustic transducer employing a 1-3 PZT-5A/silicone rubber composite structure with integrated island-bridge electrode architecture [26]. This design offers distinct advantages over conventional PDMS-based systems by enabling robust electrical interconnection of piezoelectric elements through flexible conductive bridges, eliminating the requirement for sophisticated nano-silver wire electrode fabrication processes. Experimental characterization revealed the composite's exceptional mechanical compliance, demonstrating stable operation under bending deformation with curvature radii between 100-200 mm. These findings establish important design principles for next-generation underwater sensing devices that simultaneously achieve enhanced acoustic sensitivity and mechanical flexibility.

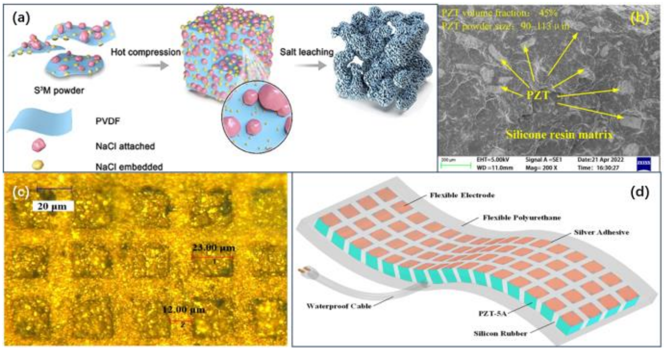

Fig. 3. (a) Schematic of the layered structure of PVDF foam [23]. (b) SEM plot of 0–3 PZT/silicone resin piezoelectric composites [24]. (c) PMN-PT and epoxy resin 1-3 Optical images of piezoelectric composite surfaces [25]. (d) Structure of a flexible piezoelectric composite hydroacoustic transducer [26].

4.2 Two new flexible piezoelectric pressure sensors

Wang et al presented a piezoelectric nanocomposite-based pressure sensor fabricated using hybrid chitosan-BaTiO3 nanoparticles [27]. The sensor has a high sensitivity of 238 mV/kPa and 1705 mV/Hz, excellent cycling stability greater than 103 cycles and superior biocompatibility. The results show a significant increase in pressure and frequency sensitivity by nearly 10 and 6 times, respectively, compared to the pure chitosan film. This is due to the higher piezoelectric coefficient of the composite (d33 = 13 pC/N), which is approximately twice as high. This proposed organic-inorganic hybrid composite provides a solid foundation for the future development of high-performance sensors for next-generation prosthetics and soft robotics applications.

The wearing comfort of current PVDF piezoelectric sensors still needs to be improved, mainly because they usually use less breathable materials such as polyethylene terephthalate, polyimide, or PDMS as the encapsulation layer, which leads to a poor experience for the wearer when used for a long period of time, and restricts the wide application of the products. To solve this problem, Yang et al innovatively designed a new type of flexible piezoelectric pressure sensor with a three-layer structural design: an electrostatically spun PVDF functional layer, a printed Ag electrode layer, and an electrostatically spun TPU encapsulation layer [28]. The innovative design achieves dual performance advantages, demonstrating both high sensitivity (0.04 V/N) and rapid response characteristics (25 ms). Crucially, the electrospinning fabrication process endows the sensor with exceptional breathability and moisture-wicking properties, dramatically enhancing wearer comfort during prolonged use without causing skin irritation. This technological advancement establishes a new paradigm for developing wearable piezoelectric sensors that successfully balance electromechanical performance with physiological compatibility.

4.3 Application directions for flexible piezoelectric pressure sensors

Flexible pressure sensors have emerged as a significant research focus owing to their vast potential across multiple application domains, including wearable electronics, human-machine interfaces, and biomedical monitoring systems. Nevertheless, existing commercial wearable piezoelectric sensors predominantly employ conventional electronic encapsulation methods. While these packaging technologies provide reliable signal stability and environmental resistance, their inherently low breathability substantially compromises user comfort, creating a critical limitation for long-term wearable applications. To address this critical issue, Fan et al innovatively developed a solution based on PVDF piezoelectric nanoyarns, and they successfully prepared three-dimensional piezoelectric fabric (3DPF) sensors by weaving PVDF nanoyarns with ultra-high strength of 313.3 MPa together with other yarns through advanced 3D textile techniques [29]. The 3DPF sensor demonstrates exceptional mechanical properties with a tensile strength reaching 46.0 MPa, while simultaneously incorporating an innovative gravity-defying moisture transport mechanism. This unique feature enables rapid sweat migration (under 4 seconds) from the skin-contacting inner layer to the outer surface, ensuring optimal wearer comfort by maintaining a dry microenvironment. Remarkably, the 3DPF material achieves comparable durability and comfort to conventional cotton textiles, establishing this work as a groundbreaking approach for developing next-generation wearable electronics that seamlessly integrate high performance with superior wearability.

In the field of human motion monitoring, Ye's team made an important breakthrough through an innovative material preparation process [30]. They used a solution casting method to prepare a new flexible piezoelectric pressure sensor consisting of polydopamine (PDA)-modified barium titanate (PDA@BTO) nanoparticles composite with a PVDF matrix. Experimental results show that the PDA-modified BTO/PVDF sensor exhibits significantly enhanced output voltage performance and excellent energy supply capability under high load resistance conditions. In real-world application tests, the sensor was able to accurately recognise joint flexion and human body movements in a variety of movement styles with different signal profiles. These results indicate that the sensor has great potential for human motion monitoring and wearable electronics applications.

In the domain of blood pressure monitoring, Min et al. designed an advanced wearable piezoelectric blood pressure sensor (WPBPS) capable of high-precision continuous non-invasive arterial pressure measurement [31]. The device achieved a notable normalized sensitivity of 0.062 kPa^{-1} along with a rapid 23 ms response time. To enable accurate conversion of the flexible piezoelectric sensor's output into blood pressure readings, the researchers developed a dedicated transfer function for the linear regression model—a novel method offering a simple yet efficient calibration solution. To demonstrate real-world applicability, the team integrated the WPBPS into a smartwatch, creating a user-friendly, wearable system for continuous blood pressure tracking. This advancement holds significant potential for cardiovascular health monitoring and represents a promising technological approach for enabling round-the-clock blood pressure measurement in daily life.

5 Conclusion

As an important research direction in the field of sensing technology, flexible pressure sensors have made remarkable progress in recent years in terms of material innovation, device design, and application expansion. In this paper, the classical designs, cutting-edge technologies and their application areas of flexible piezoresistive, piezoelectric and capacitive pressure sensors are reviewed in Sections I-III, showing their great potentials in the fields of medical and health monitoring, human-computer interaction, and electronic skin.

In conclusion, through the in-depth analysis of the three types of sensors, this review finds that the development of material science is the core driving force for the progress in this field, and the introduction of new elastomers, nanomaterials and composite structures significantly improves the flexibility, sensitivity, and environmental adaptability of the sensors. In terms of device design, from the initial development of single-function detection to today's multifunctional integrated systems, flexible sensors are rapidly evolving towards intelligence and networking. Of particular interest are the breakthroughs in self-powered technologies and self-repairing materials, which provide the possibility of building wearable systems that work stably over a long period of time. However, although flexible pressure sensors have shown many advantages, their future development still faces many challenges, and also contains a vast space for innovation.

Research on flexible pressure sensors still faces several key challenges. Firstly, the balanced optimisation of performance parameters requires more innovative ideas, such as how to improve sensitivity without sacrificing linearity, or how to ensure signal stability while maintaining stretchability. Second, environmental stability issues need to be addressed, including the impact of factors such as humidity, temperature changes and mechanical fatigue on the long-term operation of sensors. Thirdly, the leap from laboratory research to industrial applications requires a breakthrough in the bottleneck of scale manufacturing and the development of low-cost, high-efficiency production processes. At the application level, the research on how to achieve better comfort of flexible pressure sensors in human wear, as well as the construction of a complete signal acquisition-processing-transmission system and so on, are all directions that need to be focused on in the future.

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