Innovative Advances in Materials for Flexible Sensors

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Abstract. Flexible sensors are an emerging technology in the field of sensors, which are widely used because of their softness and plasticity, and enable people to apply sensing technology more effectively in wearable devices, and medical field. In recent studies, researchers have done excellent work. This paper comprehensively discusses the development and latest research of flexible sensor devices from the perspective of material innovation, including capacitive, resistive, and other types of flexible sensors such as hybrid, friction electric. And then this paper compares the advancement of the performance in the areas of sensitivity, linear range, response rime, etc. Further, applications of flexible sensors are discussed, including wearable Health Monitoring，robot sensing and control， human-robot interface and environmental adaptive sensing. Finally, this paper summarizes the future trends of flexible sensors. The applications and challenges of flexible sensors are discussed, and the future development trend of flexible sensors is summarized for better future development.

Keywords: Flexible Sensor, Human-Interaction, Material

1 Introduction

In the background of the Internet of Everything, the limitations of traditional rigid electronic devices in terms of flexibility, biocompatibility, and environmental adaptability have become increasingly prominent. Human skin is capable of sensing external stimuli with a pressure sensitivity of <10 kPa, and at the same time withstands more than 50% tensile deformation without impairing the sensing function. In contrast, conventional silicon-based sensors fail irreversibly at more than 5% strain and are difficult to capture multimodal signals simultaneously.

Flexible sensors, as a new generation of sensing technology carriers in the field of sensors, have aroused extensive research interest, and the core mission of flexible sensors is to mimic and exceed the performance of biosensing systems. The core advantage of flexible sensors is their ability to withstand mechanical deformations such as bending, stretching, and twisting while maintaining stable electrical properties. This characteristic makes it show irreplaceable in many fields. However, the traditional flexible sensors in the sensitivity, durability, degree of portability,

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flexibility, ductility and biocompatibility and material safety cannot meet the requirement of the performance

The prerequisite for the development of high-performance flexible sensors is to break through the bottleneck of material innovation - how to develop functional materials with both wide strain and high sensitivity through molecular structure design, multi-scale composite or biomimetic strategies. In recent years, with the emergence of new functional materials, flexible sensors in mechanical properties, sensing accuracy and functional integration, etc., to achieve leapfrog development, graphene and other two-dimensional materials because of its unique electron transport properties to give the sensor ultra-high sensitivity, more breakthroughs in the traditional deformation limit of the flexible electronics, these innovations allow sensors to have higher sensitivity, lower response time, more convenient production process, these diverse sensors have a wide range of applications in high comfort wearable medical devices, human-computer interaction, human movement detection, etc.

In this paper, recent advancements in flexible sensor devices from the standpoint of material innovation is examined. The pioneering advancements in key material systems are also examined. Furthermore, the scientific challenges and development opportunities in this field are discussed.

2 Classification of Flexible Sensors and Their Materials and Structures

The development of flexible electronics technology has prompted the evolution of sensor technology toward extensible, lightweight, and biocompatible sensors. These sensors can be divided into two categories: resistive sensor and capacitive sensor. Resistive flexible sensors represent a pivotal branch due to their simple structure, cost-effectiveness, rapid response, and a range of other advantages. These sensors have demonstrated considerable potential for application in fields such as medical and health monitoring, human-computer interaction, and intelligent robotics. Capacitive flexible sensors are capable of detecting external pressure, deformation, proximity, or other physical quantities by measuring changes in capacitance between electrodes. The utilization of these sensors in wearable devices, human-machine interaction, and the medical and healthcare fields is indicative of their notable advantages, a consequence of their distinctive physical properties and material adaptability.

2.1 Resistive Flexible Sensors

Resistive flexible sensors are devices that detect physical signals (e.g., pressure, stretching, bending) by converting them into electrical signals. These sensors are based on the principle of resistive deformation, which occurs when the internal resistance of a material changes due to its physical state. Sensors can be broadly divided into two categories based on the nature of the resistive deformation: -Intrinsic resistance changes: These sensors rely on conductive materials that undergo microstructural changes, resulting in alterations to the overall resistivity of the material. - Contact resistance modulation is defined as the modification of the conductive layer's properties on the flexible substrate, specifically in the external load under the contact area or interface spacing. This modulation is achieved through alterations in the density of the conductive pathway, thereby altering the resistance value.

A variety of resistive flexible sensors exist, each with its own unique mechanism that can induce changes in resistance. Among these, conductive fillers (e.g., carbon nanotubes, graphene, carbon fibers) have garnered significant attention due to their ability to establish diverse conductive networks within elastomers (e.g., PDMS, PVC). These fillers exhibit remarkable sensitivity in converting physical signals (e.g., pressure, stretching, bending) into electrical signals. For instance, Mengjuan Zhong et al. developed a highly sensitive composite flexible sensor [1]. In this study, the team used carbon fiber (1D) and nanoparticles (0D) as materials to construct a multi-scale network in PDMS, achieving a wide linear range (20 Pa-600 kPa) and high sensitivity (26.6kPa^{-1}) through physical contact and tunneling effects.

In another study, Hao Zhang et al. developed a flexible sensor with a wide linear range of nanosilver composites with high conductivity [2]. The high conductivity of silver nanoflowers (AgNFs) dominates the response at low strains, while multi-walled carbon nanotubes (MWCNTs) maintain the conductive network connections at high strains. The utilization of the AgNFs and MWCNTs synergistic effect is such that the AgNFs enhance conductivity, thereby enhancing sensitivity, and the MWCNTs connect the nanoflower network, thus extending the strain range.

The surface microstructure of the resistive sensor is susceptible to alterations induced by strain. Consequently, contemporary research endeavors are directed towards the manipulation of microstructure to achieve a linear resistive response, contingent upon the alterations in microstructure within the flexible sensor. A composite flexible sensor was developed by Mengjuan Zhong et al [1]. The team designed the microstructure of the flexible sensor to emulate human fingerprints, with the objective of optimizing pressure distribution. The material was combined with a micro- and nano-hybrid conductive elastomer (1D carbon fibers + 0D carbon nanoparticles/PDMS substrate) to ensure the sensitivity remained linear over the entire range of pressures (20 Pa-600 kPa).

In the realm of microstructure design, a number of researchers have conceptualized innovative three-dimensional structures that facilitate enhanced performance in flexible sensors. In their study, Ye Wang and colleagues developed a highly sensitive, flexible sensor [3]. As shown in Fig 1, this sensor was based on expandable microspheres, which were mixed with PVC paste and cured at a high temperature (120°C) after printing. The curing process caused the microspheres to expand, forming a porous structure. The thermally expandable microspheres are doped with conductive pastes (e.g., carbon black), and the compression/expansion of the microspheres under an external force changes the filler density and dynamically adjusts the conductive pathway, thereby changing the resistance. The microspheres undergo expansion, resulting in the formation of a compressible structure. In a related development, Weihua Gao et al. have devised a flexible sensor that exhibits a circumferential negative Poisson's ratio [4]. This innovative design aims to enhance the performance of composite foams by embedding an elastic skeleton structure. The team utilized a silica gel group A/B fraction, which was mixed and injected into a mold. This mixture was then cured to obtain a porous structure of pure foam. Subsequently, an elastic skeleton (negative Poisson's ratio structure) was prepared through 3D printing, embedded in the silica gel foam to form a composite foam, and then impregnated with graphite to form a conductive network. When the material is pressurized, the negative Poisson's ratio skeleton undergoes a circumferential shrinkage during compression, resulting in the conductive network coming into close proximity. This, in turn, leads to an augmentation of lateral expansion, thereby reducing the overall resistance. It has been demonstrated that a synergistic improvement in both the sensing range and load capacity is achieved.

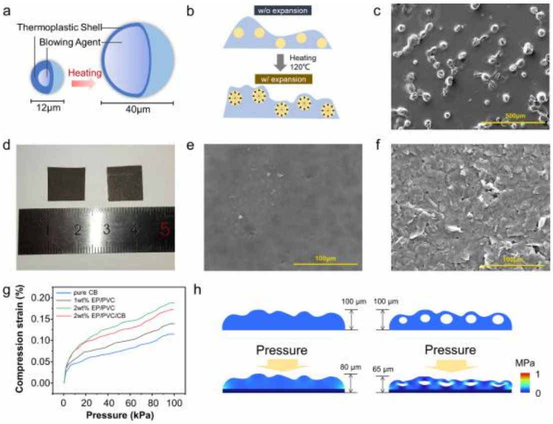

Fig. 1. Schematic and characterization of the thermal expansion microspheres microstructure. (a) The expansion mechanism of microspheres. (b) Expanded structure in the conductive sensing layer due to expansion of microspheres. (c) SEM observation of the expanded microspheres among the PVC film. (d) Photograph of sensing layer with/without microstructure. (e) and (f) SEM observation of the sensing layers with and without microstructure. (g) Compression-pressure curve of films with different microstructures. (h) Simulation of mechanical deformation and stress distribution of the microstructure film [3].

The development of sensors that exhibit both flexibility and high ductility without compromising performance has emerged as a prominent area of research interest. Liquid metals, such as Ga-based alloys, and ionic liquids, due to their superior fluidity, have garnered significant attention as materials of choice, owing to their enhanced ductility compared to solid counterparts. The application of stress within microchannels induces alterations in the length or cross-sectional area of conductive pathways, thereby resulting in changes in electrical resistance. Tianyun Dong et al. proposed a liquid metal (EGaIn)-based microchannel-type flexible strain sensor [5]. The team utilized a non-uniform strain distribution design, whereby the cross-sectional area of the microchannel was altered by 3D-printed molds. This design resulted in increased sensitivity while maintaining low hysteresis and high durability, due to the local strain difference. It is noteworthy that liquid metals can be amalgamated with other materials through a specialized process, thereby yielding more convenient materials with alternative properties for the fabrication of flexible sensors. Pengcheng Wu mixed nanoclay with liquid metal (EGaIn) to form conductive nanoclay analogous to "printing clay" [6]. The nanoclay functions as a "fulcrum," thereby enhancing the adhesion of the substrate and reducing the fluidity of the liquid metal. This allows for direct use in stamp printing, thus enhancing the convenience of the fabrication process. The conductive nanoclay exhibits the property of expanding in a vacuum, a property that can be exploited to fabricate vacuum touch switches that do not require complex structures, thereby expanding the applications of these switches to extreme environments, such as space. The material is meticulously cut and reconnected through nanoclay "pivot points," where liquid metal is introduced to fill the voids, thereby restoring conductivity. In the event that the material requires recycling, the liquid metal can be separated and recycled by means of dissolving the Ga_2O_3 film in a 2 M HCl solution, which is characterized by its high level of reusability.

2.2 Capacitive Sensors

Capacitive flexible sensors are constructed based on the principle of a parallel-plate capacitor. In contrast to conventional rigid structures, the flexible system utilizes parameter modulation through the elastic deformation of the dielectric layer. When external stress is applied, the compression of the dielectric layer thickness d or the expansion of the effective area A of the electrodes can induce a change in capacitance (ΔC). Typical structures adopt a configuration that can be likened to a sandwich, wherein the Young's modulus (0.1–3 MPa) of the elastic dielectric layer (PDMS, Ecoflex, etc.) is mechanically matched to the ductility of the electrode material (e.g., ionic gel, liquid metal) to ensure stable operation of the device under more than 30% strain.

The focal point of research endeavors in this domain encompasses the study of electroactive materials and dielectrics. These materials exhibit a high degree of susceptibility to modification through alterations in their composition, which, when coupled with the strategic design of capacitive sensors, can result in enhanced performance outcomes. Electrodes must possess high conductivity, ductility, and mechanical stability. Electrodes fabricated from diverse materials (e.g., conductive fabrics/knits, carbon-based materials, liquid metals) exhibit superior performance in terms of sensitivity, flexibility, stability, and other metrics. In diverse application environments, there exists a range of requirements for flexible sensors, with the selection of dielectric materials being of particular significance. Yogeenth Kumaresan et al. concentrated on soft dielectric materials (e.g., Ecoflex and PDMS) in capacitive pressure sensors, analyzing the effect of stiffness on performance. The team prepared ~125 μm-thick layers of Ecoflex or PDMS (PDMS mixing ratios of 10:1, 7.5:1, and 5:1, respectively) on electrodes by means of the spin-coating method [7]. The team's findings indicated that Ecoflex exhibited the highest sensitivity ($4.11 kPa^{-1}$) in the low-pressure region (<1 kPa), attributable to its low stiffness and deformability. This characteristic led to substantial alterations in capacitance. In contrast, PDMS demonstrated superior performance in the high-pressure region (10-160 kPa), with the 7.5:1 mixing ratio exhibiting optimal sensitivity ($2.32 kPa^{-1}$ and $0.08 kPa^{-1}$ in the high pressure region). Low-stiffness materials (e.g., Ecoflex) exhibit increased propensity for deformation and substantial capacitance alterations at low pressures. Conversely, higher-stiffness materials (e.g., PDMS) demonstrate capacity to preserve structural integrity under high pressures, thereby circumventing sensitivity degradation resulting from excessive deformation. Through a comparative analysis of the performance disparities among various dielectric materials, the research team elucidated the regulatory mechanism of stiffness on sensor sensitivity. This finding offers a valuable reference point for the optimal design of biomimetic electronic skin. Yongshi Guo et al. The team successfully developed a flexible metal-ceramic fork finger electrode that can be scaled up and produced [8]. They employed an ultrasonic cavitation strategy to regulate the arrangement of TEOS (ethyl orthosilicate) molecular chains, combined with electrospinning. The team used an ultrasonic cavitation strategy to modulate the molecular chain arrangement of TEOS (ethyl orthosilicate), combined with electrospinning technology to prepare a flexible SiO_2 nanofiber membrane. The Cu/Au nanolayers were deposited sequentially via chemical plating, and the $CuSiO_3$ and Au_3Cu interfacial phases were formed through 800°C heat treatment. The issue of unstable ceramic-metal bonding was addressed by means of stiffness matching and interfacial phase reaction. In conjunction with a deep learning model, the initial high-temperature stabilized sensors were utilized in fire-fighting scenarios, thus providing a novel concept for the development of high-temperature flexible electronic devices.

Electrodes and dielectrics frequently exhibit synergistic functionality, and the integration of electrodes and dielectrics composed of specialized materials often yields flexible sensors characterized by enhanced sensitivity, expanded linear range, augmented flexibility, and enhanced safety. In a notable study, Ozgur Atalay et al. employed barium titanate (BTO) elastomeric composites as a substrate, in conjunction with printed carbon black (CB) electrodes, to develop a remarkably stretchable capacitive sensor [9]. The following text is intended to provide a comprehensive overview of the subject matter. The carbon black-to-Ecoflex™ weight ratio is 1:5. The solution was prepared by first diluting it with silicone oil to reduce its viscosity and ensure smoothness during three-dimensional printing. This was achieved by mixing it using a planetary centrifugal mixer to optimize the balance between conductivity and printability. Next, BTO nanoparticles (200 nanometers) were mixed with Ecoflex™, dispersed homogeneously through a planetary mixer, and then cured. BTO has been demonstrated to enhance the dielectric constant of CB/Ecoflex™ electrodes, thereby ensuring enhanced stretchability and biosafety. These electrodes have been shown to withstand 100% stretch while maintaining stability and reproducibility after 1,000 stretch-relax cycles. BTO has been shown to boost the dielectric constant of CB/Ecoflex™ electrodes, ensuring high stretchability and biosafety.

It is noteworthy that in certain studies, specific materials can undergo a particular processing method, thereby concurrently transmitting their material properties to yield a distinctive structure that enhances the performance of the flexible sensor. Xiaoguang Hu et al. have successfully developed a capacitive strain sensor that exhibits both high sensitivity (GF=2.07) and remarkable extensibility [10]. The research team applied CNT to a Tegaderm film, forming the electrodes through a spray application technique. Subsequently, they released the pre-stretching VHB tape and affixed the electrodes, thereby constructing a pleated structure. The team applied CNT to Tegaderm film to create electrodes, pre-stretched VHB tape, and then laminated the electrodes, releasing the pre-stretching to form a pleated structure. The resultant pleated CNT electrodes maintained continuity during stretching. SEM analysis revealed that the pores of the CNT clusters increased after stretching, but the structure remained intact. The pleats unfolded during the stretching process, thereby increasing the electrode area and achieving high sensitivity.

2.3 Other types of sensors

In certain instances, researchers may employ traditional sensors in the development of flexible sensors. The latter are packaged with special materials to obtain the desired characteristics. For instance, Matthew Guess' team developed a wireless, battery-less, soft capacitive sensor that uses laser micromachining to etch capacitive and inductive structures on a copper foil with a polyimide (PI) substrate and encapsulated elastomers in the outer layer (Ecoflex) [11]. The sensor uses a laser micromachining technique to etch capacitive and inductive structures on copper foil. The ductility of the copper conductor is enhanced by a serpentine structure design, and a silicone adhesive is used to achieve a high degree of adhesion to the skin. The sensor and the external receiving antenna are inductively coupled to form an LC resonant circuit for wireless transmission. The sensor demonstrates a high level of sensitivity in signal detection, and its clinical applicability has been validated through human trials.

Wei Fan et al. successfully developed a 3D PVDF nanoyarn fabric piezoelectric sensor with breathability and ultra-high strength. This sensor is made of PVDF powder, silver-plated nylon yarn (conductive layer), Coolmax yarn (moisture conductive), viscose yarn (moisture absorbing), and polyester yarn (supportive)[12]. The charge carriers in sweat form a defective state, which reduces PVDF insulation and promotes polarized charge release, i.e., sweat-enhanced piezoelectric output. The sensor's versatility extends to medical monitoring, smart clothing, and other domains.

Tao Liu et al. successfully developed strain sensors based on customized flexible electrodes. The team prepared flexible electrodes by embedding MCNTs in plasticized PVC through solvent casting, and constructed resistive (sandwich structure) and capacitive (multilayer stacked structure) sensors based on these electrodes [13]. The resistive type of MCNTs relies on the network tunneling effect of the MCNTs, which leads to the destruction of the conductive pathway and the rise of the resistance when stretched. The capacitive type is predicated on the geometrical deformation of the electrodes (increase in area, thinning of the dielectric layer) and the capacitance is linearly related to the strain. The two sensors exhibit high stretchability (>100%), low Young's modulus (<200 kPa), and rapid response (<140 milliseconds). The resistive type exhibits higher sensitivity (1.16 vs. 0.44) and superior immunity to interference, while the capacitive type demonstrates enhanced linearity and long-term repeatability. The team's research results offer complementary solutions for the diverse needs of wearable devices.

3 Breakthroughs in the Performance of Flexible Sensors

3.1 Sensitivity

The incorporation of high dielectric constant materials serves to augm sugar particles or salt crystals within the dielectric layer gives rise to the formation of a microporous structure, thereby enhancing compressibility and attaining sensitivity levels reaching 121 × 10^{-4} kPa^{-1} [9]. FCT-structured honeycomb PDMS dielectric layers have been shown to optimize compressive deformation by precisely controlling filament width and spacing. The FCT structure has been demonstrated to have the lowest elastic modulus due to the staggered interlayer alignment (Smith et al., 2021). This structure has been shown to have the lowest modulus of elasticity (0.38 kPa) and the highest sensitivity (1.23kPa^{-1}), which is superior to AABB (0.15kPa^{-1}) and ABAB (0.32kPa^{-1}) (Brown et al., 2020). An increase in the FCT structure line spacing from 400 μm to 1600 μm resulted in an enhancement of the sensitivity from 0.37kPa^{-1} to 2.14kPa^{-1} (0-0.4 kPa range). However, the 800 μm spacing was ultimately selected after taking the linear range into consideration (sensitivity: 1.23kPa^{-1}, stable in the 0-10 kPa range) [14]. The vinyl carbonate-based gel has a dielectric constant of 30, which provides a 6-fold increase in sensitivity compared to conventional materials (e.g., VHB), while maintaining transparency and high stretchability [15].

The microstructural design has been demonstrated to enhance the signal response through localized strain concentration or conductive pathway changes. Arch-shaped micropatterned arrays that emulate human fingerprints have been shown to optimize pressure distribution and achieve a linear sensitivity of 26.6kPa^{-1} [16]. The conductive pathway was altered by thermally expanding microspheres doped with carbon black paste and expanding microspheres under pressure, resulting in a sensitivity of 37.16kPa^{-1} [17]. The design of variable cross-solds, resulting in an 18% increase in sensitivity due to local strain concentration [5].

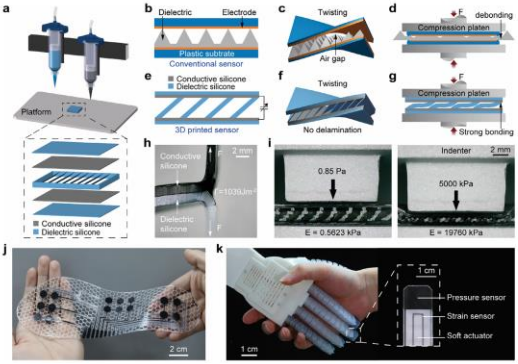

Fig. 2. Fully 3D-printed soft capacitive sensor of high toughness and large measurement range. a) Illustration of 3D-printed soft capacitive sensor with tilted thin-plates dielectric via DIW technique. b–d) Conventional soft capacitive sensors may suffer delamination and/or debonding. e–g) Fully 3D printed soft sensors have strongly bonded interfaces to resist both normal and shear stresses. h) The conductive silicone and dielectric silicone exhibit a high toughness of more than 1000 J·m−2 due to strong chemical crosslinks. i) The sensors can accurately measure a pressure within a large range from 0.85 Pa to 5000 kPa. j) Demonstration of fully 3D-printed intelligent insole consisting of 16 soft sensors, which can perform real-time monitoring of pressure distribution. k) Demonstration of fully 3D-printed soft robotic hand combining soft pneumatic actuators, capacitive pressure sensors, and resistive strain sensors [18].

3.2 Linear Range

Concurrently, researchers have engineered the microstructure by manipulating stress distribution. Gao et al. have proposed composite foam materials that are embedded with a skeleton possessing a negative Poisson's ratio [4]. When subjected to pressurization, the material underwent circumferential contraction rather than expansion, thereby enhancing the contact tightness of the internal conductive filler. In comparison to the pure foam, the composite material demonstrates an augmented linear range of 150 kPa, yielding linear sensitivities of 0.50 and 1.17 in the low-strain (15%-40%) and high-strain (65%-78%) phases, respectively. The bionic structure and negative Poisson's ratio properties regulate the material deformation mode in stages, thereby avoiding the nonlinear response that would otherwise be caused by a single deformation mechanism.

Multi-material 3D printing and interface integration design reduce the risk of interlayer peeling through an integrated fabrication process, while utilizing the stiffness gradient of the dielectric layer to extend the measurement range. Xiao et al. used multi-material 3D printing to synchronously cure conductive silica gel (elastic modulus of 840 kPa) and dielectric silica gel (elastic modulus of 580 kPa) [18]. As shown in Fig 2, the design of the inclined sheet dielectric layer permits the sensor stiffness to vary from 0.56 kPa to 19.76 MPa, thereby extending the measurement range from 0.85 Pa to 5000 kPa. The interface molecular network chemical bonding (interface toughness up to 1036 $J \cdot m^{-2}$) overcomes the peeling problem associated with traditional laminate structures. The stiffness gradient of the dielectric layer enables the sensor to adaptively deform at different pressure stages, thereby realizing a full-range linear response.

3.3 Stretching Performance

Flexible sensors must maintain adequate performance when subjected to stress deformation. One method of enhancing the stretching performance of sensors is to use flexible materials. Plasticized PVC/MCNTs composites exhibit favorable stretchability, and the optimization of the PVC to plasticizer ratio is imperative [1]. At a PVC:DOP ratio of 1:5, the modulus is reduced to 0.03 MPa, approaching the modulus of biological soft tissues. However, this results in a significant reduction in tensile strain to 221%. In contrast, PVC1 (1:1) exhibited a higher modulus (0.69 MPa) but a maximum strain of 530%, suggesting that a trade-off between modulus and strain is necessary for the optimal plasticizer ratio. The content of MCNTs also impacts the material's tensile behavior, with a tensile strain of up to 774% at 1 wt.% MCNTs, but a low electrical conductivity (4×10^{-5} S/cm). The electrical conductivity of the 3 wt.% MCNTs was measured to be 2.7×10^{-4} S/cm. The strain was increased to 300% by means of overfilling (5 wt.%) and by applying strain (300%), and the strain dropped to 224% due to defects.

In the context of flexible sensors that utilize liquid metal as the material, the fluidity of the liquid metal electrodes contributes to the attainment of high tensile properties [19]. Liquid metal fork is the term given to capacitive strain sensors (LMICSS). These sensors utilize the fluidity of the liquid metal electrode and the elasticity of the PDMS substrate to achieve high tensile properties (100% strain). During stretching, gallium-based alloy (LM) flows to maintain the conductive path, avoiding solid-state filler breakage and supporting stable operation at 100% strain. The elasticity of the PDMS substrate provides mechanical support, but the tensile capability is limited by the properties of the PDMS itself.

3.4 Response Time

The dielectric constant and elastic properties of dielectric materials directly affect the sensitivity and response speed of capacitive sensors. Researchers employed barium titanate (BaTiO3) to enhance the dielectric constant of the Ecoflex substrate (from 2.8 to 15,000-25,000), which resulted in a substantial increase in the amplitude of capacitance change [20]. This, in turn, led to a reduction in external parasitic capacitance interferences and an improvement in the signal-to-noise ratio (SNR). This high sensitivity facilitates the rapid detection of minute strains, thereby indirectly reducing the response time.

The stability and microstructure of the conductive material are the core factors affecting the dynamic response of resistive/capacitive sensors.

Carbon black (CB)/Ecoflex printed electrode with spherical particle morphology ensures conductive network uniformity under stretching [20]. A comparison of the stable contact resistance of the carbon black electrode with that of carbon nanotubes (CNTs) reveals that the former reduces signal fluctuations and improves response consistency in cyclic testing, with stable performance observed after 1,000 cycles.

The sensor structure design directly reduces the response/recovery time by optimizing the deformation path and interfacial bonding. The researcher utilizes expandable microspheres (EPs) in carbon black slurry to form a porous microstructure [3]. The design facilitates expeditious alterations in contact area via a compression-rebound mechanism, exhibiting response/recovery times of 126 milliseconds (ms) and 52 ms, respectively. These values are demonstrably superior to those of conventional unstructured thin-film sensors, which typically exhibit response times greater than 200 milliseconds. The researcher synchronizes the curing of the conductive and dielectric layers through multi-material 3D printing with an interface toughness of 1036 J-m-^{2} to avoid signal hysteresis caused by delamination [17]. The design of the inclined thin plate dielectric layer serves to reduce the initial stiffness, thereby enabling the sensor to respond quickly at low pressures (0.85 Pa detection limit).

4 The Applications of Flexible Sensors

4.1 Wearable Health Monitoring

P-HCF sensors monitor arterial pulse and aid in the diagnosis of Parkinson's disease [16]. AgNFs/MWCNTs sensors analyze gait through joint bending signals [2]. Flexible pressure sensor arrays (e.g., MXene textile arrays) have been demonstrated to facilitate multi-point pressure distribution detection on the skin surface, thereby enabling tactile feedback in prosthetic limbs [3,20].

4.2 Robot Sensing and Control

The following studies were conducted on the use of carbon nanotube strain sensors for real-time deformation feedback in soft pneumatic robots [10]and 3D-printed sensors integrated with soft actuators to enhance grip force control of robotic hands [18]. Microporous dielectric layer sensors endow the gripper with sensitive haptics for precise soft target grasping [16]. If for any reason you must use mixed units, the units used for each quantity in an equation must be stated.

4.3 Human-robot interface

A recent study has demonstrated the potential of highly transparent dielectric gels to combine touch sensing and screen protection [15]. These gels may potentially replace glass layers in the future.

Liquid metal fork-finger capacitive sensors are suitable for e-skin by virtue of their in-plane strain selective detection, which obviates normal pressure interference [19]. MXene textile sensors, when combined with proximal machine learning models (99.5% accuracy) for gesture tracking and robot control [21], have been demonstrated to be effective. The utilization of resistive sensor-based data gloves facilitates the mapping of gestures and interaction within a meta-universe [21].

4.4 Environmental Adaptive Sensing

Sensors based on a barium titanate-silica composite dielectric layer exhibit 100% stretching capacity and are compatible with irregular surfaces [20]. The researcher have demonstrated that dielectric gel sensors can expand the application scenarios of wearable devices by maintaining transparency while improving sensitivity sixfold. The integration of textile sensors into clothing facilitates wireless monitoring of movement [15], offering a level of comfort that traditional sensors cannot match [22]. Liquid metal electronic tattoos, when applied to the skin, can monitor wrist flexion with a high degree of accuracy [6].

5 The Challenges Facing Flexible Sensors

5.1 Trade-offs between sensitivity and other properties

The sensitivity (GF) of capacitive sensors is generally constrained by parallel-plate configurations, with a theoretical maximum of 1 [23]. Hyperextensional sensors, such as CNT electrodes, require a balance between sensitivity and mechanical durability [19]. Hybrid elastomers based on carbon fibers and nanoparticles (P-HCF) achieve a wide linear range (20 Pa-600 kPa) and high sensitivity ($26.6kPa^{-1}$) through a microarchitectural design. However, these materials still face the problem of sensitivity saturation at very high pressures [16].

5.2 Interfacial adhesion and durability issues

Sensor interlayer delamination and interfacial peeling are common failure modes. Traditional fabrication methods (e.g., die casting) are prone to delamination due to material stiffness mismatch [18]. 3D printing technology improves the interface toughness up to 1036 $J\text{-}m^{-2}$ by curing conductive silica and dielectric layers simultaneously, but complex microstructures (e.g., tilted thin plates) are still exposed to localized peeling risk under shear stress [10]. However, complex microstructures (such as tilted thin plates) still face the risk of localized peeling under shear stress.

5.3 Material-substrate compatibility

Stabilization of conductive materials with flexible substrates is another challenge. For example, liquid metal sensors are prone to delamination or interfacial mismatch due to the difference in modulus between the liquid metal and the flexible substrate (e.g., Ecoflex) [5], while electrodes made of plasticized polyvinyl chloride (PVC) filled multi-walled carbon nanotubes (MCNTs) have a decreasing electrical conductivity with the increase of the plasticizer although they achieve a low modulus (0.1 MPa) and a high tensile ratio (300%) [1]. In addition, although carbon-based materials (e.g., carbon nanotubes, graphene) are more compatible with PDMS, they are prone to performance degradation due to fatigue fracture after long-term use [2].

5.4 Signal Interference and Noise Suppression

Capacitive sensors are susceptible to electromagnetic interference and fringing electric fields, especially in biomedical applications [11]. Shielding has been demonstrated to have a dual effect on interference: it can either reduce it or increase it [23]. However, this phenomenon comes with the concomitant increase in thickness of the sensor.

5.5 Complexity of Materials and Fabrication Processes

Microstructured dielectric layers, such as honeycomb structures and microvias, are typically fabricated using photolithography or particle leaching processes. These methods are both time-consuming and costly [24]. Batch production techniques, such as laser-cut sensor arrays, have been demonstrated to enhance efficiency [23]. However, concerns regarding the alignment accuracy of electrodes and dielectric layers persist. The design of micro- and nanostructures (e.g., microarches, microspheres) frequently relies on precision processing techniques. For instance, controlled sintering temperatures are employed to optimize porosity for sensors with thermally expanding microspheres doped with carbon paste [4]. Additionally, precise spraying processes are utilized for multilayer stacking of MXene textile sensors [22]. These processes are not only costly but also limit mass production.

6 Conclusion

In recent years, flexible sensors have achieved significant advancements in the domain of material innovation. The crux of this innovation lies in the synergistic optimization of material properties through interdisciplinary crossover. The advent of novel materials, including conductive polymers and nanocomposites, has led to the emergence of flexible sensors that exhibit distinct advantages over traditional rigid devices in terms of mechanical flexibility, environmental adaptability, and functional diversity. Innovations in microfluidic structures that incorporate liquid metal have been shown to achieve a breakthrough in tensile rate while preserving stable conductive properties.

Flexible sensors are undergoing rapid development; however, there are still problems to be addressed. Materials innovation is still facing three core challenges: Firstly, the material system of intrinsic contradiction resolution has not yet been fully realized. The current conductivity-flexibility-durability of the "impossible triangle" must be overcome. Secondly, the issue of manufacturing bottlenecks must be addressed. The existing laboratory preparation methods for controlling yield rate and cost must be examined to determine their effectiveness in large-scale manufacturing contexts. It is evident that these methods exhibit shortcomings, particularly in terms of adaptability to extreme temperatures and other conditions that can compromise their performance. Addressing these challenges is imperative to ensure the reliability and efficiency of prominent materials in extreme environments. In the future, the exploration of novel conductive materials will be undertaken to achieve a balance between sensitivity and mechanical properties. The combination of edge computing and machine learning will be investigated to enhance the real-time signal processing capability. Materials science must overcome the performance limitations of intrinsic flexible conductors. Artificial intelligence will facilitate the reverse design of material-structure-performance. The advent of dynamic response materials, heterogeneous integration processes, and self-supply systems has led to the expectation that flexible sensors will achieve subversive applications in such cutting-edge fields as meta-universe interaction and brain-computer interfaces. Ultimately, these developments will drive human society towards the "ubiquitous sensing" era of intelligence.

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