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Research Progress of Wearable Flexible Sensors

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Abstract. With the growth of health monitoring and human-computer interaction needs, wearable flexible sensors have achieved rapid development due to their flexibility, comfort and integrability. This paper systematically reviews the latest research progress in this field: firstly, the flexible sensors based on different mechanisms and their performance characteristics are introduced in detail; Then, the research status of key functional materials is expounded. Then, the technical path of sensor and system integration is discussed, and its typical applications in medical health, sports science and other fields are listed. Finally, the current technical problems are summarized and the future development trend is prospected, which provides a reference for broader research and application in this field.

Keywords: flexible sensors, wearable electronics, health monitoring, functional materials, system integration.

1. Introduction

With the acceleration of global population aging, increasing public health awareness, and environmental challenges brought about by industrialization, the need for continuous and accurate health and environmental monitoring is becoming increasingly urgent [1-3]. In the field of health, continuous monitoring of physiological parameters such as blood oxygen, heart rate and pulse wave is key to preventing cardiovascular disease. At the same time, environmental safety monitoring requires systematic observation and analysis of various pollutants to ensure environmental quality and [4]. In addition, the development of human-computer interaction and intelligent Internet of Things and other technologies has also put forward new sensing requirements for achieving efficient and natural information interaction. In this context, wearable electronic devices have become the focus of scientific and technological innovation. However, traditional monitoring equipment based on silicon-based rigid electrons has limitations such as mechanical mismatch, difficulty in fitting the human body or complex surfaces, and high energy consumption, which restricts their application in long-term and seamless monitoring scenarios [2,3].

In order to break through these problems, the academic and industry have carried out extensive exploration. In terms of health monitoring, for example, Song Tao [2,3] developed a self-powered flexible sensor based on tribo nanogenerator and 3D printing technology, which realized human movement and tactile monitoring, and provided new ideas for motion tracking and human-computer interaction through wireless transmission systems. In order to improve the detection ability of weak

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signals such as pulse waves, Yang et al. [4] designed a graphene flexible pressure sensor with a multi-level branch microstructure, which significantly enhanced the sensing performance and stability. Wang et al. [5] used silk fibroin, polyvinyl alcohol, and tannins to prepare multifunctional bioflexible sensors with good mechanical properties, conductivity, and biocompatibility, drawing on the toughening mechanism of natural rubber, opening up a new path for the development of environmentally friendly "electronic skin".

Although wearable flexible sensors have made significant progress in the field of health and environmental monitoring, they still face common challenges in terms of materials, mechanisms, integration, long-term stability, accuracy, and large-scale manufacturing. This paper aims to systematically review the latest advances in this field. Firstly, the flexible sensors based on different physical/chemical mechanisms and their performance characteristics are introduced, then the research status of key functional materials is discussed, and then the typical applications and system integration paths in health and environmental monitoring are discussed, and finally the current challenges and future trends are summarized, in order to provide reference for related research and applications.

2. Sensing mechanism of flexible sensors

2.1. Physical sensing mechanism

2.1.1. Piezoresistive sensing

Piezoresistive flexible sensors are based on the piezoresistive effect, which converts external force into resistance changes to output electrical signals. Typical flexible piezoresistive materials are composed of conductive fillers and elastic polymers: when not pressurized, the conductive particles are dispersed and the resistance is high; The deformation of the elastic substrate after compression increases the contact of particles, strengthens the conductive network, and significantly decreases the resistance. This determined relationship makes it possible to measure the thrust reversal pressure by resistance.

In order to balance high performance and low-cost manufacturing, Wang et al. [6] prepared a flexible sensor based on $Ti_3C_2T_x$ MXene/black phosphorus composite coated with 3D cotton fiber, with a wide detection range and high sensitivity, and an integrated array to visualize the pressure distribution. The sensor significantly improves the uniformity and response sensitivity of stress distribution by constructing a porous conductive network on a three-dimensional cotton fiber substrate, and its composite structure is shown in Fig. 1.

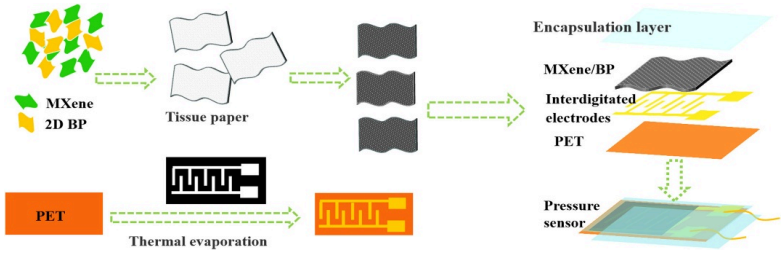

Figure 1. Schematic diagram of the structure of a porous flexible pressure sensor based on MXene/black phosphorus nanocomposites [6]

Sun J Z et al. [7] developed an MXene/graphene quantum dot/watermelon peel bioaerogel sensor with a detection limit of 0.4 Pa and a sensitivity of 323 kPa^{-1} by freeze-drying method, which can

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transmit physiological signals via Bluetooth, and is environmentally friendly and inexpensive to prepare.

To solve the problem of wearable device power supply, Li C et al. [8] designed an integrated system of photorechargeable lithium-ion capacitors driven by flexible perovskite solar cells. The system collects and stores all in one, with a photoelectric conversion efficiency of 10.2% and an output of 3.95 V for an overall efficiency of over 6%. Integration with strain sensors enables physiological signal monitoring without the need for an external power supply.

In other self-powered directions, Dong K et al. [9] reviewed the progress of self-charging textiles based on tribo-nanogenerators, and systematically analyzed the integrated structure and bottlenecks of fiber/fabric energy harvesting and storage. Sun Q J et al. [10] developed a fabric-based tribotropic nanogenerator with thermal insulation and antibacterial functions, which can be used for outdoor rescue and health monitoring. Liu et al. [11] innovatively proposed the concept of "thermoelectric rubber" and prepared an elastomer material with a ductility of >850% and a thermoelectric advantage of 0.49, which can efficiently collect human heat energy and provide a new idea for flexible and sustainable energy supply.

2.1.2. Capacitive sensing

Capacitive flexible pressure sensors have a structure similar to parallel plate capacitors, and their capacitance value changes with external forces, and the pressure can be reflected by detecting this change. The sensor usually consists of an upper and lower flexible electrode and an intermediate elastic dielectric layer, and the initial capacitance value depends on the electrode area, spacing, and dielectric constant [12]. When external force is applied, the dielectric layer is squeezed, resulting in a decrease in thickness or an increase in the effective contact area, which increases the capacitance. These sensors have the advantages of low power consumption and good temperature stability, and have a wide range of application prospects in the field of wearable health monitoring and human-computer interaction, but they also face challenges such as limited sensitivity [13].

Microstructure design is one of the key strategies to improve its performance. Yang et al. [14] developed a high signal-to-noise ratio capacitive flexible sensor using a high duty cycle regular hexagonal microstructure to optimize the stress transfer interface, which realizes high-precision collection of small pressures under dynamic interference and is suitable for cardiovascular monitoring and biometric recognition. Li K et al. [15] designed a staggered inclined cylindrical microstructure inspired by the layered structure of human skin, which overcame the problem of contact surface offset and improved the accuracy of pressure detection by alternately adjusting the tilt direction of the column, with a response speed of 0.2-0.3 s, and performed well in a wide pressure range.

The enhancement mechanism of microstructure mainly comes from two aspects: reducing the effective compression modulus of the dielectric layer to improve deformation sensitivity, and increasing the rate of change of the contact area under pressure through microscopic topography, thereby enhancing the capacitance response [16]. However, there are still challenges in the design of microstructures, such as the difficulty of balancing high sensitivity and wide range linear response for a single structure, the cumbersome preparation process of complex structures, the difficulty of scaling, and the prone to fatigue damage under cyclic loads [16].

In order to solve the above problems, research turns to the collaborative optimization of microstructure and functional materials. For example, the incorporation of high dielectric constant fillers or conductive composites into the microstructured dielectric layer can further improve the capacitance response and structural stability [14]. In addition, in order to solve the problems of

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capacitive sensors being susceptible to environmental interference and large integration area, Yao J et al. [17] developed a sensor based on hemispherical porous PDMS/carbon nanotube electrodes, which achieved sensitivity of 0.379 kPa^{-1}, 0.087 kPa^{-1}, and 0.034 kPa^{-1} in the three intervals of 0-10 kPa, 10-100 kPa, and 100-400 kPa, respectively, which can effectively monitor physiological signals such as pulse and joint movement. It can also be used for human-computer interaction control, demonstrating the potential of porous electrode structures to improve wide-range sensing performance.

2.1.3. Piezoelectric sensing

In recent years, piezoelectric and triboelectric generators have become important mechanisms for promoting the development of self-powered flexible sensing because they can directly convert mechanical energy into electrical signals without the need for external power sources[18]. Piezoelectric flexible pressure sensors work based on the piezoelectric effect: when the piezoelectric material is deformed by external force, its internal positive and negative charge centers are relative offset, forming a polarized electric field, thereby converting mechanical energy into electrical energy and realizing pressure monitoring. Commonly used flexible piezoelectric materials include polyvinylidene fluoride (PVDF), zinc oxide (ZnO) nanowires, and lead zirconium titanate (PZT) composites, which can output corresponding charge signals under dynamic pressure. However, this mechanism usually only responds to dynamic or varying pressures, making it difficult to detect steady-state static forces, and the material preparation and polarization processes are often complex [18].

To improve performance and flexibility, researchers have carried out a number of material and structural innovations. Chen Z H et al. [19] prepared a (111)-oriented self-supporting PZT single crystal film with a piezoelectric coefficient of up to 585 pm/V by crystal orientation regulation and water etching sacrificial layer technology. The flexible energy harvester based on this film can work stably under a large strain of more than 3.4%, with no significant degradation after 60,000 cycles, an output voltage of 12 V, and a power density of 63.5 mW/cm^3, and the collected energy can directly power commercial electronic equipment. Liu et al. [19] used PET as a flexible substrate, prepared a cross-fingered electrode on it, transferred a PZT nanofiber film, covered it with PDMS packaging, and obtained a flexible sensor, which increased with the increase of voltage in the range of 20-60 kPa, with a maximum of about 10 V and a sensitivity of about 180 mV/kPa. In addition, PZT powder can be compounded with microfibriled cellulose, or BTO mixed with PAN in an Ecoflex substrate to make a highly sensitive piezoelectric film, which can be used for insole integration to identify gait and analyze plantar pressure distribution [18].

In terms of electrodes, Zhang X et al. [13] proposed a hydrogen bonding network regulation strategy to develop a low-eutectic gel electrode based on choline-glycerol low-eutectic solvent and gelatin cross-linking network. The electrode is easy to prepare, low cost, good biocompatibility, with a skin contact impedance of less than 6 kΩ in the frequency range of 0.1~100000 Hz, and the water retention rate remains 93% at room temperature for 5 days. The sensing system based on this electrode can achieve 48 hours of high-quality ambulatory ECG monitoring and 18 hours of steady-state EEG recording, with a signal-to-noise ratio of up to 47.8 dB, and the signal remains stable even under high-intensity exercise, providing reliable technical support for long-term, high-comfort wearable medical monitoring and brain-computer interface.

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2.1.4. Triboelectric sensing

Based on the coupling effect of triboelectric and electrostatic induction, the triboelectric flexible pressure sensor converts mechanical energy into electrical signals during the contact separation process to achieve self-powered pressure monitoring [20]. Commonly used triboelectric materials include flexible polymers such as PTFE, PDMS, PET, etc., which can be used to build sensors through microstructure design or fabric integration. This type of sensor has the advantages of simple structure and good biocompatibility [21,22]. Surface microstructure is a key strategy for improving performance. For example, the PDMS/PTFE composite structure of the micropyramid array designed by Wu et al. [23] significantly outperformed that of a single material (Figure 2).

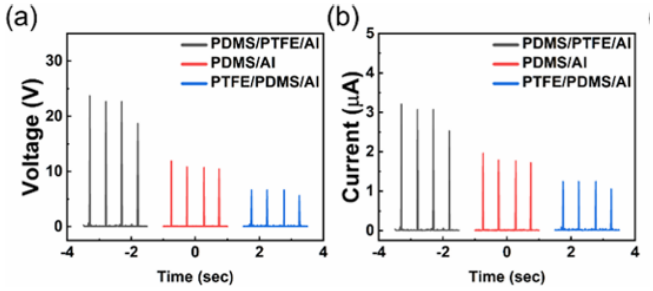

Figure 2. Electrical characterization of CS-TENGs with various structures. (a) Output voltage and (b) output current comparison among different structures [23]

Significantly improve charge transfer efficiency and output stability. In terms of material compounding, the integration of advanced materials such as graphene can further improve the comprehensive performance of devices [22].

In response to the energy supply needs of wearable devices, Qiu Q et al. [20] developed flexible power generation fabrics that can convert human movement energy into electrical energy. Si Wang et al. [24] developed a self-powered respiratory sensor that can simultaneously monitor respiratory behavior and trace gases. The stretchable luminescent fiber developed by Wu et al. [25] has achieved electrical-optical dual-mode sensing, expanding its application boundaries in multiple scenarios.

2.2. Chemical sensing mechanisms

2.2.1. Electrochemical sensing

Electrochemical sensors have become key technologies in biochemical detection due to their high sensitivity, strong selectivity, fast response and real-time monitoring. Commonly used detection methods include ampere method, differential pulse voltammetry method, square wave voltammetry method and fast scanning cyclic voltammetry method. The detection process mainly relies on a three-electrode system (working electrode, reference electrode, and pair electrode), where the reaction occurs on the surface of the working electrode. Selectivity can be significantly improved by modifying the electrode surface, and commonly used modification materials include carbon nanomaterials, metal nanoparticles, metal-organic frameworks, and molecularly printed polymers [26].

In terms of application review, Ferreira et al. [27] systematically summarized the progress, challenges, and future trends of wearable electrochemical sensors in the forensic and clinical fields. In terms of device preparation, Zhao Z et al. [28] developed a self-supporting metal-organic frame

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electronic skin, which realized the detection of non-invasive lactic acid, glucose, and other molecules that can adhere to the skin through sacrificial layer-assisted transfer printing technology. Bariya et al. [29] used roll-to-roll gravure printing technology to efficiently prepare electrochemical sensors on flexible PET substrates.

To solve the problem of real-time monitoring of neurotransmitters, Liu Y et al. [30] constructed a flexible carbon fiber sensor based on thioaptamer modification, combined with a wireless transmission module, to achieve high-spatiotemporal resolution dynamic monitoring of dopamine in the brains of freely active animals, and the sensor showed good anti-digestion stability in the physiological environment.

In the direction of wearable health monitoring, Smith R E et al. [31] prepared highly conductive flexible fiber electrodes by immersing cotton yarn in PEDOT:PSS and multi-walled carbon nanotube dispersions through the "impregnation-drying" process, and electropolymerized and deposited polyaniline, constructing a wearable pH sensor with biocompatibility and antibacterial properties, which is suitable for wound healing and other scenarios.

In addition, in response to the relatively insufficient research on 2D graphene-based flexible sensors, Xie T et al. [32] used polymetaloxylate and 2D graphene nanosheets to prepare POM/2D GNs nanocomposites. Characterization confirmed that POM was uniformly dispersed on the graphene surface, and electrochemical tests showed that the material had excellent cyclic stability. Based on this, they developed a highly sensitive sensor deposited on a flexible viscous substrate, which can effectively monitor the human pulse through water droplet pressure testing, providing a new design idea for carbon-based wearable electronic devices.

2.2.2. Photochemical sensing

Photochemical sensing has shown significant potential in the field of biomedicine and environmental monitoring due to its advantages of anti-electromagnetic interference, rapid response, and remote real-time monitoring. In recent years, with the advancement of functional materials and probe design, photochemical sensing has made significant progress in the direction of flexible wearable monitoring and in vivo multi-target imaging.

In terms of neurotransmitter detection, Li Y L et al. [33] developed a fluorescent probe based on far-red light, GRABHaloDA1.0. The probe combines chemogenetic strategies with far-red fluorescent dyes to achieve sub-second kinetic responses, and can be combined with green and red fluorescent probes to achieve three-color imaging of neurotransmitters such as dopamine and acetylcholine in the living brain of mice, providing a powerful tool for the elucidation of neural regulatory networks.

In the field of flexible non-invasive monitoring, Zhou H et al. [34] constructed a flexible photoelectrochemical sensing platform. The platform achieves high sensitivity detection of dopamine through screen printing technology, and has good flexibility and stability, providing a new way for non-invasive neurochemical monitoring.

In the direction of ambient gas sensing, Liu M et al. [35] developed a nitrogen-doped carbon quantum dot colorimetric sensing system. The system uses N-CQD as a metal-free photocatalyst to regulate the color change of redox dyes, realize the visual and quantitative analysis of oxygen, and expand to application scenarios such as erasable photoprinting.

In addition, rare earth-doped upconversion nanoprobes have become important materials for deep tissue photochemical detection due to their anti-Stokes shift and good biocompatibility, and their applications in ion, reactive oxygen species, and biomolecule detection have been systematically

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reviewed, providing support for the development of sensing technologies related to clinical diagnosis [36].

In response to the invasiveness and susceptibility to interference of traditional transdermal oxygen monitoring techniques, Lim C-J and Park J-W et al. [37] developed a wearable band-aid photoluminescent oxygen sensor. The device integrates an oxygen sensing film, ITO heater, microLED array, and organic photodiode to promote oxygen diffusion through local heating combined with optical isolation and signal correction, significantly improving the sensitivity and stability of monitoring. Experiments have shown that the sensor has a faster response speed and smaller measurement deviation than the commercial device PeriFlux 5000 in dynamic monitoring, providing a viable wearable solution for continuous and non-invasive blood oxygen monitoring.

2.3. Other emerging sensing mechanisms

In addition to electrochemical and photochemical sensing, emerging sensing technologies based on thermistor resistance effects and gas adsorption resistance changes have developed rapidly in the fields of safety monitoring and health management with their unique flexible adaptability and scenario pertinence. In the field of flexible thermal sensing, Zhang H et al. [38] used in-situ synthesis/decomposition to prepare NiO/carbon nanotube fiber (CNTF) flexible composites, which have both wide operating temperature range and ultra-high sensitivity, which can not only achieve accurate monitoring of human contact heat signals and non-contact heat signals (such as respiration), but also integrate and construct temperature warning systems. It has been successfully applied to thermal runaway monitoring of lithium-ion batteries and smartphones, effectively reducing the risk of fire. In the field of flexible gas sensing, in response to the problem that the high-temperature preparation of traditional gas sensors limits the application of flexible substrates, researchers have developed flexible ammonia sensors based on copper bromide (CuBr) films [39]. The deposition of CuBr film on the plastic substrate is completed through the low-temperature solution process to achieve highly sensitive detection of ppm ammonia, and the performance stability is maintained after 1000 repeated bending tests. The sensor can not only be used for ammonia leakage monitoring in agricultural greenhouses and chemical workshops, but also provide technical support for the early diagnosis of metabolic diseases such as abnormal renal function by monitoring the changes in ammonia concentration in the exhaled breath of the human body, showing the dual application value of industrial safety and medical health.

3. Key materials

3.1. Flexible substrate material

In recent years, polymer-based, natural polymer-based and other diversified substrate material systems have been iteratively upgraded, promoting the development of flexible sensing technology in the direction of high performance, low cost, and green environmental protection. In the field of polymer substrates, polyimide (PI) has become the preferred substrate for high-precision flexible sensing due to its excellent high temperature resistance and mechanical stability, Zhang L et al. [40]. The team prepared a porous MXene/cellulose nanofiber composite sensitive layer with surface patch-like protrusions on the PI membrane substrate by combining vacuum filtration and acid-base neutralization reaction, and combined with a cross-finger electrode prepared by magnetron sputtering, the constructed piezoresistive sensor achieved a high sensitivity of 21.457 kPa^{-1} and a fast response of 41.84 ms, and the sensor array based on this substrate could accurately recognize 9

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gestures, with a recognition accuracy of 98.22%. In the field of natural polymer substrates, cellulose nanofibers (CNFs) have received widespread attention due to their renewable and biocompatible advantages, and Lian H et al. [40] further found that the porous structure formed by CNF and MXene can not only improve the mechanical strength of the substrate, but also enhance the sensing signal transduction efficiency through interfacial action, providing a new path for the green preparation of flexible electronic skin [41]. In addition, Lai W Y et al. [42] innovatively proposed an interface preassembly directed growth (IPOG) strategy to prepare controllable thickness (100~300 nm) at the oil-water interface by regulating the hydrophilic interaction at the molecular interface by regulating the hydrophilic interaction at the molecular interface. The photoelectric conversion efficiency of the COF-based flexible OLED prototype device built based on this flexible crystalline conjugated organic frame (COF) film with an area of up to 20 cm^2, which can withstand repeated bending and even stretching without breaking, provides a new idea for the design of high-performance flexible sensing substrate materials.

3.2. Sensitive functional materials

3.2.1. Carbon-based nanomaterials

Today, graphene-based nanomaterials, especially two-dimensional graphene-based nanomaterials and their nanocomposites, continue to attract attention in the field of nanomaterials due to their desirable advantages such as singular physical, chemical, biological, and mechanical properties [43]. Carbon-based nanomaterials have become the core functional materials for sensitive layers and electrode modifications of flexible sensors due to their high specific surface area, excellent conductivity, good biocompatibility and tunable electronic structure, and have made a series of breakthroughs in preparation process innovation and multi-scenario application expansion in the past two years. In the field of carbon nanotube-based flexible sensing preparation technology, Chen et al. [19]. The hemispherical porous carbon nanotube/polydimethicone (PDMS) composite flexible pressure sensor was developed, which significantly improved the force sensing sensitivity and wide pressure range adaptability of the sensor by constructing a unique hemispherical porous electrode structure. The prepared flexible sensor maintains high sensitivity of 0.379 kPa^{-1}, 0.087 kPa^{-1} and 0.034 kPa^{-1} in the three pressure zones of 0-10 kPa, 10-100 kPa and 100-400 kPa respectively. It shows great application potential in wearable physiological monitoring and human-computer interaction scenarios. In terms of optimization of graphene-based sensing performance, Zhang et al [44]. introduced an amino functionalization modification strategy to prepare amino-modified graphene/polypyrrole composite sensitive materials in response to the problem of easy agglomeration of the graphene sheet layer and the decrease in sensing sensitivity, and applied it to the working electrode modification of flexible electrochemical sensors to achieve highly sensitive detection of carcinoembryonic antigen (CEA), a tumor marker in serum. And it shows excellent anti-interference ability in complex biological matrices. In the field of carbon quantum dot-based multi-mode sensing, researchers have developed nitrogen-doped carbon quantum dot/graphene composite film materials, and the flexible photoelectrochemical sensor constructed can simultaneously realize electrochemical detection and fluorescence imaging of glucose, with high detection accuracy and visual monitoring advantages, showing great application potential in the field of non-invasive blood glucose monitoring in diabetes.

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3.2.2. Conductive polymers

Conductive polymers are a class of functional materials that combine the flexibility, lightweight characteristics and conductivity of polymer materials, and have attracted widespread attention since their discovery in the 70s of the 20th century. Its conductivity comes from the conjugated π electronic system in the molecular chain, and the precise regulation of conductivity can be achieved through chemical doping or electrochemical doping. Common types include polyaniline (PANI), polypyrrole (PPy), polythiophene (PTh) and poly(3,4-ethylene dioxophene): polystyrene sulfonate (PEDOT: PSS). Compared with traditional inorganic conductive materials, conductive polymers have significant advantages such as low preparation cost, excellent biocompatibility, and solution-solublable processing, and have become core materials in the fields of flexible electronics, energy storage, and biosensing [45]. On this basis, significant breakthroughs have been made in the application of conductive polymers in the field of wearable health monitoring in recent years, Capuano R et al. [46]. A respiratory sensing mask based on conductive polymer was developed, the core design of which was as follows: coating the surface of the silver electrode with conductive polymer, and improving the sensing sensitivity by porphyrin molecular modification; The modified electrode is then embedded between the two layers of the medical mask, and an electronic readout device is integrated. When the wearer's exhaled gas specifically interacts with the conductive polymer, it triggers a characteristic change in electrode resistance, which can be captured and analyzed by the system in real time, enabling rapid screening for chronic kidney disease (CKD). Clinical test results show that the sensor has a correct recognition rate of 84% for CKD patients and 88% for non-patients among 100 subjects, and can effectively reflect the progression stage of the disease, providing an important reference for clinical disease evaluation. In addition, Ghanbari K et al. [47] aimed at the high specificity and sensitivity of neurotransmitter detection [47]. A flexible electrode with polypyrrole/graphene composite modification was constructed. By regulating the electropolymerization process parameters, the team accurately controlled the morphology and film thickness of polypyrrole, and significantly improved the adsorption capacity and electron transfer efficiency of serotonin in serum by electrodes. Combined with differential pulsed voltammetry detection technology, the highly sensitive quantitative analysis of serotonin was realized. At the same time, the composite electrode can effectively resist the interference of biomolecules such as proteins and other neurotransmitters in serum, providing a new technical solution for the non-invasive diagnosis of neurological diseases such as depression.

3.2.3. Liquid metal

Liquid metal is a new type of flexible electronic material with high conductivity, excellent fluidity and deformation adaptability, showing unique potential in the field of flexible sensing and self-powered wearables. However, its industrialization still faces a series of challenges, including complex packaging processes, easy leakage, weak interface bonding with polymer matrix, and structural control difficulties caused by high surface tension. Among them, interfacial bonding and structural stability are the key to its practical application—the poor compatibility of liquid metals and polymers, which are easy to peel off during repeated deformation, and their high surface tension and oxidation sensitivity also increase the difficulty of fine processing and long-term stable operation [48].

In order to break through the bottlenecks such as weak interface combination and limited patterning accuracy, the current research focus has shifted from passive packaging to active interface design and integrated integration. The main progress is focused on two strategies:

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The first is interface modification and functionalization. For example, inspired by mussel adhesion proteins, Hu et al. [49] enhanced interfacial adhesion and durability with elastomers such as PDMS by constructing polydopamine-modified layers on liquid metal surfaces. The polydopamine modification layer significantly improves the interfacial bond strength of liquid metal and polymer, and the tensile and interfacial microstructure of the composite are shown in Fig. 3.

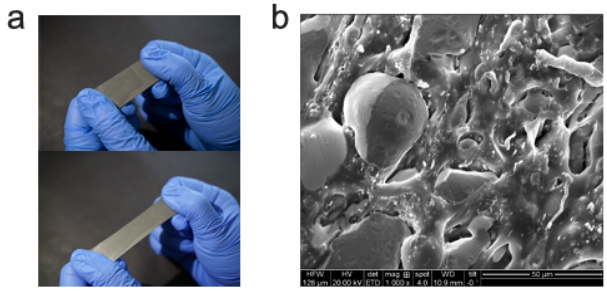

Figure 3. (a) Photographs showing the stretchability of PDA-GO/ LM/PDMScomposites. (b) Cross-sectional SEM image of PDA-GO/ LM/PDMS composites [49]

In order to achieve long-term reliability and environmental adaptability, self-healing and reconfigurable capabilities have become important directions. Niu H et al. [50] prepared conductive composites that can repair damage autonomously at room temperature by introducing a polymer network containing dynamic disulfide bonds.

The second is structural reconfigurability and intelligent design. Li et al. [51] developed a flexible device that can reconstruct circuit patterns in real time and reversibly through non-contact magnetic fields using the fluidity and magnetic response characteristics of liquid metals, providing a new paradigm for adaptive sensing systems.

From the perspective of application trends, liquid metal is moving from a single sensing unit to multi-functional system integration, and the exploration of cutting-edge fields such as flexible drives and biomedical electrodes is deepening. With the maturity of interface engineering and large-scale manufacturing technology, liquid metal is expected to become the core material system to promote the development of health monitoring, human-computer interaction, and precision medicine.

4. System integration and application

4.1. Flexible energy supply technology

To move from laboratory to practicality, flexible electronic systems need to overcome three key issues: energy supply, signal processing and communication, and seamless integration with the human body. Important progress has been made in related research in recent years.

In terms of energy supply, research focuses on collecting energy from the environment and developing flexible energy storage devices that match it. Yang et al. [52] integrated tribotrogen in the form of a textile that efficiently collects mechanical energy from human movement to provide continuous energy for wearable devices.

At the same time, flexible energy storage devices are developing in the direction of high energy density and deformation resistance, such as Yang J [53] et al. prepared deformable supercapacitors with negative Poisson's ratio structure by 3D printing technology, Its all-solid-state symmetrical device structure is shown in (Fig. 4a). The composite electrode material exhibits significantly improved electrochemical properties under the synergistic action of carbon nanotubes (Fig. 4b),

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maintaining stable capacitance output even under complex deformations such as stretching and bending, providing a reliable and flexible power source for integrated systems.

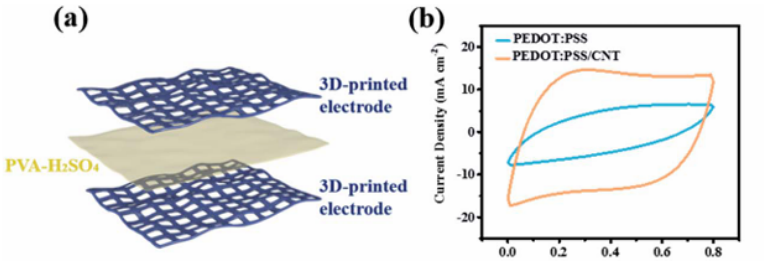

Figure 4. (a) Schematic of the full device with 3D printed electrodes. (b) Comparison of the CV curves of thePEDOT: PSS/CNTSSCandPEDOT: PSSSSCtestedat ascanrateof20mVs 1 [53]

In terms of signal processing and wireless transmission, Xu G et al. [54] developed a passive sensing system based on flexible electrochemical tags that can wirelessly power and transmit data through a reader without batteries. Wang et al. [55] further used flexible organic electrochemical transistors to construct a "sensor-computing integration" neuromorphic processing system, which can directly complete signal recognition and classification at the hardware level, and achieve localized intelligent processing with very low power consumption.

In terms of integration with the human body, in order to achieve long-term comfortable and reliable integration, Baik S et al. [56] developed a skin patch with a microstructured array inspired by octopus suction cups, which combines high breathability with strong painless adhesion and is suitable for multi-day continuous monitoring. In terms of fabric integration, Wang et al. [57] prepared intrinsically stretchable and washable elastic conductive fibers through "fiber-in-fiber" design, and woven them into intelligent fabrics that can withstand daily wear and washing, achieving stable and comfortable pressure sensing.

4.2. Typical applications-medical health monitoring

The core advantage of flexible electronics is that it can fit the curved surface of the human body and achieve long-term, high-fidelity monitoring. Current research has expanded from traditional ECG and EMG monitoring to multimodal physiological signal synchronous capture and non-invasive biochemical analysis. For example, Chung H U et al. [58] developed an ultra-thin and flexible multiparameter skin sensing system that can simultaneously and continuously monitor electrocardiogram, skin temperature, sweat loss, and subcutaneous blood oxygen, providing a comprehensive data view for cardiovascular disease management and exercise physiology research. In terms of biochemical monitoring, Gao W et al. [59] reported a fully integrated wearable sensor array that can continuously monitor various indicators such as glucose, lactate, sodium, and potassium in sweat by integrating microfluidics and flexible electrochemical sensing, providing a platform tool for personalized health and exercise analysis.

In the field of sports science, flexible sensor networks provide high spatiotemporal resolution data for human motion capture. Zhang R et al. [60] weaved a flexible strain sensor into smart clothing, combined with deep learning algorithms, to identify movement patterns and reconstruct the continuous motion angle of joints, which is useful for motion analysis and rehabilitation assessment. Antonio M T et al. [61] developed a pressure sensor through additive manufacturing, which can effectively distinguish gait characteristics from healthy people and Parkinson's disease patients by

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monitoring gait pressure distribution and center of gravity trajectory, providing an objective tool for early screening and rehabilitation assessment.

In the direction of human-computer interaction and virtual reality, flexible electronics is committed to achieving high-fidelity motion capture and realistic tactile feedback. Negre M et al. [62] developed a biomimetic soft electronic skin that uses a spiral pyramid microstructure to distinguish between normal and tangential forces in real time, with high sensitivity, low hysteresis, and millisecond response, providing a solution for robot haptic feedback. In terms of tactile feedback output, Yuk H et al. [63] developed a hydrogel hydraulic actuation network that controls the fluid distribution through programming to drive the surface actuation unit to produce complex mechanical outputs such as expansion and vibration, providing an implementation scheme for simulating the interactive interface of real touch.

Despite the promising prospects, the application of flexible electronics in the fields of medical, sports and human-computer interaction still faces challenges such as standard validation, long-term reliability, data security, and large-scale manufacturing. In the future, through interdisciplinary collaborative innovation and the integration of edge intelligence and wireless energy supply technology, flexible electronics are expected to move from "wearable" to "integrable", becoming a natural extension of human body functions, and promoting the development of personalized medicine, digital health, and the next generation of human-machine integration ecology.

5. Conclusion

As a cutting-edge cross-cutting field, wearable flexible sensors are promoting the development of health monitoring, environmental perception and human-computer interaction towards flexibility, intelligence and personalization. It has continued to make breakthroughs in physical and chemical sensing mechanisms, improved performance by relying on new materials and structural design, and gradually solved the problems of energy supply and wearable adaptation through system integration, and has been widely used in medical, sports and interactive scenarios. However, the field still faces challenges such as long-term stability, balance of sensitivity and detection range, signal crosstalk, large-scale manufacturing, and data security. In the future, through multidisciplinary integration and system innovation, flexible sensors will evolve in the direction of intelligent response, integration of sensing and computing, and deep integration with digital health, becoming a natural extension of human capabilities and providing key technical support for building an intelligent and healthy society.

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