Recent Research on MXene-based Flexible Wearable Sensors in the Fields of Sports and Health

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Abstract. With the rapid development of smart wearable devices, flexible strain sensors have shown broad application prospects for their excellent flexibility, comfort and integration. Focusing on the latest research on MXene-based flexible wearable sensors, this paper systematically sorts out relevant content. Firstly, the classification and sensing mechanism of flexible strain sensors are summarized, including capacitive, piezoelectric, triboelectric and resistive strain sensors. Secondly, this paper introduces two-dimensional MXene materials and their preparation methods. In addition, the latest research on MXene-based flexible wearable sensors in the fields of sports and health is elaborated. Despite remarkable progress in theoretical and experimental research, flexible strain sensors still encounter challenges in terms of sensitivity, durability, and mass production. Thus, future research should lay emphasis on developing new materials, exploring advanced manufacturing technologies, and realizing multi-functional integration and intelligence of sensors.

Keywords: MXene; Flexible Wearable; Sensors; Sports and Health.

1. Introduction

In recent years, with the rapid development of the Internet of Things, smart medical care and wearable electronic devices, flexible wearable sensors have become a research trend in the human-computer interaction and health monitoring for their lightweight, high fit and ability to adapt to complex deformation [1]. Traditional sensors are mostly based on rigid materials (such as silicon-based semiconductors), which have problems such as poor comfort and vulnerability to mechanical stress damage, making it difficult to meet the long-term stable monitoring needs in dynamic environments. By combining highly elastic substrates with functional materials, flexible sensing technology improves the mechanical adaptability of devices and provides a new way for real-time and accurate biological signal acquisition. It has become one of the key technologies to promote the development of the next-generation smart devices [2], with various types of flexible sensors such as capacitive strain sensors [3] and piezoelectric strain sensors [4] emerging one after another.

Much attention has been attracted by two-dimensional transition metal carbon/ nitrides (MXene) for their unique physicochemical properties. As a new two-dimensional material [5] with excellent metal conductivity and hydrophilicity, MXene not only has the high conductivity of metals, outstanding mechanical flexibility and surface modifiability [6], but also has numerous hydrophilic functional groups (especially -OH and -COOH) remaining on its surface. The hydrogen bonds formed by these groups with water molecules can significantly enhance the hydrophilicity of materials [7], making them ideal candidates for flexible sensor designs [8]. For example, its high specific surface area and abundant surface functional groups can significantly enhance the sensor’s sensitivity and response speed. The layered structure endows it with good stretchability and can withstand repeated deformation without failure [9]. In addition, the unique interlayer structure of MXene generates a good electron channel variation under external force [10]. Moreover, the abundant interlayer structure produces the largest electron channel under pressure, which can maximize the performance of MXene, thus improving the comprehensive sensing performance of the pressure sensor [11].

This paper systematically reviews the latest research progress of MXene-based flexible wearable sensors. Firstly, the sensor type and sensing mechanism are discussed. Then, the structural characteristics and preparation methods of the two-dimensional MXene materials are summarized.

Finally, the main challenges faced by MXene-based flexible wearable sensors are summarized, and their future development in personalized medicine, intelligent robots and other fields are prospected.

2. Classification and Sensing Mechanism of Flexible Strain Sensors

2.1 Resistive Strain Sensor

Resistive strain sensors reflect external mechanical strains by detecting changes in capacitance values. The core principle of the sensor resistance and resistance change rate are shown in formulas (1-1) and (1-2). When this kind of sensor receives external stress [12], the sensing material undergoes mechanical deformation such as tension or compression, resulting in significant changes in its microstructure. According to the conductivity theory in solid state physics, the dynamic evolution of this microstructure leads to the highly coupled relationship between the sensor resistance value and the applied stress. Notably, during the stress unloading, thanks to the high elastic recovery characteristics of flexible materials, sensors and sensing materials can quickly return to the initial structural state, thereby simultaneously returning the resistance value to the original level.

$$R=\frac{\rho L}{S} \tag{2.1}$$

$$\frac{\Delta R}{R}=(1+2V)\ \varepsilon+\frac{\Delta P}{P} \tag{2.2}$$

Where P represents the resistivity of the mat (Ω/m), S refers to the cross-sectional area of the material (m^2), L means the material length (m), V represents the Poisson's ratio of dimensionless materials and ε refers to the dimensionless material strain.

Generally, when external deformation is applied, the resistance and size of the sensor will change at the same time, giving rise to the change of resistance under the combined action. When conductive materials with different internal structures are subjected to tensile deformation, their internal conductive network changes greatly, mainly including sensor geometry changes, separation mechanism [13], crack propagation [14] and tunneling effect [15]. Resistive strain sensors usually consist of a flexible substrate, a conductive electrode, and a dielectric layer. The sensing device shows significant advantages in the performance, which are embodied in the following four core features: high sensitivity, wide detection range, low power consumption and multi-modal compatibility [16].

2.2 Piezoelectric Strain Sensor

The working principle of a piezoelectric strain sensor is that when external pressure/strain acts on the piezoelectric material, electric charges will be generated on both sides. When the material is subjected to strain and pressure, a piezoelectric effect occurs instantly [17]. When the piezoelectric material is subjected to an external force, the crystal inside the piezoelectric material polarizes, which manifests that the two opposite surfaces of the piezoelectric material produce opposite charges. The electrical signal is proportional to the applied strain, and the strain magnitude can be deduced by measuring the change in the electrical signal. Its core formula is:

$$Q=d\sigma \tag{2.3}$$

Where Q represents the amount of charge generated, d refers to the piezoelectric constant, and σ means the stress applied.

In piezoelectric sensors, the amount of charge depends on the amount of deformation. In other words, the greater the material deformation, the more significant the separation of positive and negative charges caused by lattice distortion, and the more charge is generated. Its structure mainly consists of a piezoelectric active layer, a flexible electrode and a packaging layer. A piezoelectric strain sensor has apparent advantages in dynamic mechanical measurement for its electromechanical coupling characteristics. The core includes high response speed, self-power mechanism, high sensitivity and broadband detection ability.

2.3 Friction Strain Sensor

The triboelectric strain sensor realizes strain detection based on the triboelectric effect [18]. When two different materials come into contact and separate, due to the difference in electron affinity, positive and negative charges will be accumulated on the surface of the materials, respectively, resulting in a potential difference. By measuring the change of potential difference, the magnitude of external mechanical strain can be indirectly reflected. Triboelectric sensors can directly convert external mechanical force stimulation into electrical signals without an external power supply. Friction between different materials will cause electrons to be transferred between different materials, thus converting mechanical forces into electrical signals. Its core formula is:

$$V=\frac{\varepsilon\sigma}{d} \tag{2.4}$$

Where V refers to the output voltage, σ represents the surface charge density, d means the tribolayer spacing, and ε refers to the vacuum dielectric constant. The frictional strain sensor mainly includes a friction layer and an electrode layer [19]. Its significant performance advantages are mainly reflected in: self-power supply (directly converting mechanical energy into electrical energy); high sensitivity (detecting micro-strain and low-frequency vibration such as breathing and pulse) [20]; rich material selection (suitable for various scenarios); simple structure, low cost, and its suitability for large-area manufacturing [21], such as roll-to-roll process.

2.4 Capacitive Strain Sensor

A capacitive strain sensor is a sensor that converts strain change into capacitance change. By designing a measurement circuit, electrical signals for processing and analysis can be obtained. Its typical structure is a "sandwich" layered composite system, which consists of a pair of flexible electrodes, with the flexible dielectric layer superimposed in an orderly manner. According to the theory of parallel plate capacitors [22], the working mechanism of this sensor is essentially to convert external mechanical strains into changes in capacitance parameters. As for its working principle, when the capacitive flexible strain sensor is deformed by external stress stimulation, the change of internal structural parameters leads to the change of capacitance value responsiveness, and then the quantitative characterization of the external stimulation intensity is realized through the change of capacitance. According to the classical capacitance calculation formula, there is

$$C=\frac{\varepsilon A}{d} \tag{2.5}$$

Where C represents the capacitance value, ε means the dielectric constant, A refers to the electrode area, and d represents the electrode spacing. The main structure includes a flexible substrate, a conductive electrode and a dielectric layer [23], which has the advantages of high sensitivity, a wide strain detection range, stable performance, accurate measurement and good environmental adaptability [24].

3. Two-dimensional MXene Materials

3.1 Introduction of MXene Material

As a sort of two-dimensional inorganic compounds, MXene is composed of transition metal carbides, nitrides or carbonitride compounds with a thickness of 1-5 atomic layers, which features metal conductivity and hydrophilicity. Its general formula is $M_{n+1}X_nT_x$, where M is early transition metals such as Ti, V, and Mo, X is nitrogen or carbon, and Tx refers to functional groups such as -OH, -F, and -O on the surface. These functional groups are endowed with rich chemical activity that can significantly affect electrical, optical and mechanical properties, making them great potential in energy storage, catalysis, sensors and other fields [25]. MXene is divided into two major systems, single transition metal (MTM) and double transition metal (DTM), according to the transition metal composition [26]. The transition metal layer of the MTM system is a single element, and 14 typical materials have been reported: Ti_3C_2Tx can improve the rate of charge and discharge as well as cycle stability of the anode of lithium-ion batteries with its two-dimensional layered structure and high conductivity; V_2CTx has excellent electrocatalytic hydrogen evolution activity for its abundant functional groups on the surfaces [27]. Furthermore, the DTM system contains two transition metals (M' and M"). Although it is in the early stage of research, it has remarkable potential in heterogeneous catalysis and electromagnetic shielding.

3.2 MXene Preparation Method

1. Etching

Etching is the most commonly used method to prepare MXene. Its core principle is to remove the A-layer elements in the MAX phase by chemical or physical means to obtain MXene materials.

(1) F-containing Ion Etching

1. HF Etching and In-situ HF Etching

HF etching: Taking Ti_3AlC_2 etching to prepare $Ti_3C_2T_x$ as an example, the chemical formula of the reaction is:

$$TI_3ALC_2+3HF=ALF_3+\frac{3}{2}H_2+TI_3C_2 \tag{3.1}$$

$$TI_3C_2+2H_2O=TI_2VC_2\left(OH\right)+H_2 \tag{3.2}$$

$$TI_3C_2+2HF=TI_3C_2F_2+H_2 \tag{3.3}$$

The MAX phase was soaked in an acid solution, and the M-A bond was reacted with HF under heating and stirring to generate water-insoluble AlF_3 and hydrogen. The exposed Ti layer continues to react with water and HF to generate functional groups with -F and -OH. After the reaction, MXene is separated. Meanwhile, fluoride salt is mixed with hydrochloric acid to generate hydrofluoric acid, and then etched. In other words, the following steps are added on the basis of HF etching.

$$RF+HCL=RCL+HF \tag{3.4}$$

(2) F-free Ion Etching

1. Alkali etching: It utilizes the amphoteric properties of Al (strongly combined with strong alkali) to generate a stable aluminate complex ion, $Al(OH)_4^-$, through reaction to achieve selective etching of the Al layer in the MAX phase. Compared with traditional HF etching, this method avoids the potential impact of F^- residue on performance. 2. Electrochemical etching: It uses the low electrode potential of Al in an alkaline medium to accelerate the oxidation and dissolution of the Al layer by applying an electric field. 3. Molten salt etching: This method uses molten salts such as LiF and NaCl as etchants. The MAX phase powder is mixed with the molten salt and then reacts at high temperature. The molten salt provides a highly active ion environment to promote the reaction between the A-layer elements and the salt to generate soluble compounds and remove the A layer.

2. Other Preparation Methods

In addition to etching, some other preparation methods are also used for the synthesis of MXene materials, such as ball milling [28], pyrolysis [29], chemical vapor deposition [30], mechanical stripping, etc. [31].

4. Research on Mxene-based Flexible Wearable Sensors in the Fields of Sports and Health

4.1 Research on Mxene-based Flexible Wearable Sensors in the Field of Sports

In the field of sports, MXene-based flexible wearable sensors present great potential for wide application prospects for their excellent flexibility, high sensitivity and stable sensing performance. For example, Cao et al. constructed an MXene-based interdigital electrode on a nonwoven flexible substrate by screen printing, and constructed an MXene/PEDOT: PSS composite sensing electrode on a nonwoven substrate by alternating deposition technology. In addition, they assembled the prepared MXene-based interdigital electrode and sensing electrode to prepare an all-textile structure flexible pressure sensor [32]. Due to the all-textile structure and interdigital configuration design, the sensor exhibits extraordinary flexibility, air and moisture permeability, and sensing performance, including high sensitivity (754.5 kPa^{-1}), fast response recovery time (180/110 ms), good cyclic stability, good biocompatibility and histocompatibility, which can realize full-scale motion monitoring and health monitoring of human body, as well as various physiological signal monitoring. Thus, outstanding application potential in the wearable and implantable sensing is shown. The fiber mat made of TPU fiber as the skeleton can also form a composite sensor with excellent performance with MXene. Dong et al. used a porous electrospun thermoplastic polyurethane (TPU) mat as the skeleton and prepared a Ti_3C_2TX/MXene/carbon nanotubes (CNTs)/TPU composite membrane strain sensor with a double-layer conductive structure through a simple and scalable vacuum filtration process [33]. The sensor consists of a brittle, densely stacked upper sheet of MXene and a flexible MXene/CNT-decorated lower layer of fiber network. Its excellent performance, wide operating range (up to 330%), high sensitivity (maximum GF of 2911), and excellent long-term durability (2600 cycles at 50% strain) result from the synergistic effect of the two parts and the hydrogen bonding interaction between the porous TPU fiber mat and the MXene sheet. The sensor can be successfully used for human motion monitoring, including tiny facial expressions, breathing, pulse beats, and a wide range of finger and elbow bending, which has desirable application prospects in wearable devices and human-computer interaction.

Meanwhile, MXene-based flexible wearable sensors based on hydrogels have core advantages in performance and application due to the characteristics of hydrogels. For example, Den et al. combined temperature-sensitive poly (N-acryloylglycinamide) (PNAGA) hydrogel with catechol-functionalized polyvinyl alcohol (Pc)/MXene hydrogel featuring the self-powering. They also adjusted the mixing ratio of the two to prepare a new PcNA-M dual network MXene-based hydrogel to make an MXene-based wearable multi-signal sensor [34]. With excellent performance, good tensile, compression and resilience properties, the sensor can quickly self-repair and has characteristics of temperature sensing. Its conductivity comes from ion and electron conduction. As a multi-signal sensor, it can generate different forms of electrical signals to various signal sources, with high sensitivity, strong identifiability and good reliability. It can be used to monitor resistance and voltage signals during human movement (such as joint bending, handwriting movements), as well as temperature changes. It shows good prospects in the field of self-powered wearable sensors and low-frequency mechanical energy collection, which provides new possibilities for real-time monitoring of different signals related to human movement.

In addition to the double-network hydrogel composite, hydrophobic association and surface waterproofing treatment are also effective methods to prepare high-performance sensors. Ni et al. adopted the hydrophobic association, using gelatin, acrylamide, octadecyl methacrylate, and MXene as raw materials, and made hydrophobic monomers and hydrophilic monomers form a dynamic hydrophobic association through micelle polymerization as physical crosslinking centers to prepare conductive hydrogels. Then, PDMS/TritonX-100 is used to construct a surface waterproof layer through surface packaging to make an MXene-based flexible wearable sensor [35]. The sensor has excellent performance, with high tensile properties (1224%), high sensing linearity (R^2=0.999), and a wide strain range (2%~700%). It still has stable resistance, responsiveness and repeatability after 1200 loading-unloading cycles under 500% strain, which has a wide range of pressure sensing performance. At the same time, because the surface waterproof layer presents outstanding underwater stability, adhesion and anti-swelling properties, it can be applied to intelligent underwater communication (information transmission through Morse code) and underwater motion monitoring (detecting bending, compression and non-contact water level changes).

Inspired by biological structure, the preparation of anisotropic hydrogel sensors can obtain unique properties. Feng et al. used directional freezing to prepare anisotropic MXene conductive hydrogels inspired by the ordered structure of muscles, and then made MXene-based flexible wearable sensors through solvent substitution treatment [36]. Due to anisotropy, the sensor has enhanced mechanical properties and electrical conductivity in specific directions with a wide temperature resistance range. It can be used as a wearable flexible sensor, and the induction signal is displayed on the mobile phone in the form of images through wireless technology to realize motion detection. Multiple sensors can also be assembled into a three-dimensional sensor array to detect the magnitude and spatial distribution of force or strain. The rapid polymerization can improve the preparation efficiency. On this basis, sensors with excellent performance can also be made. Zou et al. integrated tannic acid (TA) and silver nanoparticles as catalysts in conductive MXene nanosheets in binary solvents of water and glycerol, and designed a rapid polymerization of polyacrylic acid/gelatin dual network organic hydrogel to make an MXene-based flexible wearable sensor [37]. The sensor exhibits remarkable stretchability (1740%) and high tensile strength (184 kPa). Moreover, the strain sensor based on it has ultra-high sensitivity (GF=3.86), low detection limit (0.1%), and excellent stability with good temperature resistance, which can be applied to human movement monitoring. Free radical polymerization is also a common method to prepare three-dimensional porous hydrogel sensors. Bai et al. used a free radical polymerization strategy to prepare MXene/PAA hydrogels with a three-dimensional porous structure. In addition, PAA was obtained by free radical polymerization of acrylic acid monomer with N, N'-methylenebisacrylamide as chemical crosslinking agent and ammonium persulfate as initiator. Meanwhile, the abundant functional groups (-0, -F, and -OH) on the surface of MXene nanosheets exist in hydrogen bonding with carboxyl groups on PAA [38]. The sensor has outstanding performance, high sensitivity (GF≈4.94), a wide detection range (0-1081%), and stable signal output (cycled 500 times). Thus, it is used to monitor human movement and manipulate the robotic arm in real time.

In addition, there are several MXene-based flexible wearable sensors based on different materials, which feature good performance and a wide application range through unique preparation and structural designs. Wang et al. loaded Mxene/PANI conductive composites onto a melamine sponge skeleton and used flexible printed interdigital electrodes to prepare a highly sensitive Mxene-based flexible pressure sensor wearable sensor [39]. MXene improves the conductivity of the sponge, an appropriate amount of nanorod PANI increases the surface roughness of the sponge skeleton to improve the contact resistance, and the interdigital electrode increases the effective contact area with the sponge to further improve the sensitivity. For its excellent performance, such as fast response/recovery (55 ms/50 ms), detection limit (10.2 Pa), good repeatability and long-term stability (10,000 cycles), the sensor can be applied to wearable detection (such as human physiological signal detection). Inspired by biological surface structures, sensors with special properties can also be designed. Apart from that, inspired by the surface microstructure of rose petals, Chen et al. designed and constructed a periodic array structure that transcends the surface structure of petals to prepare an MXene/PDMS flexible piezoresistive sensor [40], which also has wide application prospects in motion detection, robot touch and other fields.

4.2 Research on MXene-based Flexible Wearable Sensors in the Field of Health

With its excellent biocompatibility, accurate detection capabilities and diverse functional characteristics, MXene-based flexible wearable sensors have shown extremely valuable and wide application prospects in the health field.

With thermoplastic polyurethane (TPU) as a crucial material, Mxene-based flexible wearable sensors exhibit diverse properties and applications with the help of the properties of TPU and different processes. For example, Wan et al. prepared an Mxene-based multifunctional flexible breathable electronic sensor [41] with excellent sensing performance and outstanding photothermal conversion performance by assembling conductive Mxene nanosheets and AgNWs onto CS-coated electrospun TPU elastic nanofiber networks. The flexible and breathable electronic sensor assembled from TPU/CS/MXene/AgNWs film has a wide strain working range (~120% strain), ultra-high sensitivity (up to 4720), low detection limit (~0.0645%), and excellent reliability and durability. Therefore, it can be used to monitor various movements of the human body and human-computer interaction. Hu et al. first grew AgNPs in situ on MXene nanosheet layers through chemical reduction to prepare MXene/AgNPs heterostructure electrode materials, and then used a mixture of ionic liquid and thermoplastic polyurethane (TPU) as the ionic polymer intermediate layer, which was hot-pressed into a flexible piezoelectric ion sensor [42]. Wang et al. not only fabricated MXene/TPU fibers as stretchable axial cores by wet spinning, but also used electrostatic adsorption and hydrogen bonding interactions to self-assemble layer by layer on their surface to form PPy@MXene coating. Finally, they encapsulated and protected with WPU to fabricate layered structured MXene-based ($Ti_3C_2T_X$) fiber strain sensors [43]. The sensor has excellent performance, ultra-high sensitivity coefficient, wide measurement range (0 ~ 106%), high stretchability (> 750%), modulus of about 12 MPa, and good Joule thermal effect. It can monitor the movement and deformation of various joints of the human body in real time, which is attached to medical pressure socks to monitor the swelling degree of the legs of patients with varicose veins. Liu et al. constructed an MXene/CNTs/TPU flexible resistance sensor (MCT/FRS) with a layered structure (tightly warped inner layer and outer deformable spring structure) with TPU as the substrate, combined with MXene and CNTs through steps such as electrospinning, ultrasonic coating, rolling twisting, and brushing coating [44]. The sensor has outstanding performance, an operating range of up to 700% in tensile mode, excellent durability (7500 cycles), and good piezoresistive characteristics. As a result, it can be used to monitor various human movements (such as finger, wrist, elbow, knee bending, walking, sitting down, breathing, facial expression, pronunciation, etc.), and can also help patients with Guillain-Barré syndrome in stretching and compression mode for hand rehabilitation.

MXene-based sensors based on non-woven fabrics or cellulose non-woven materials have good air permeability and flexibility, which provides the sensor with unique advantages in health monitoring and other fields. For example, Lin et al. used conductive MOF (Ni_3HITP_2) and MXene as raw materials and non-woven fabrics as substrates to prepare MOF/MXene electrodes through vacuum-assisted impregnation of MXene and in-situ anchoring of MOF. Then, they also made MXene-based multifunctional biosensors [45]. Compared with the MXene electrode, the MOF/MXene electrode has lower solution impedance, higher charge storage capacity and stability. As an epidermal electrode, the skin electrode has low interface impedance, which can record high-fidelity electrophysiological signals and quickly respond to electrical stimulation signals. Based on the electrochemical activity of conductive MOF, it has good sensing performance for uric acid and glucose. In addition to realizing real-time metabolite detection in sweat, epidermal electrophysiological signal monitoring can relieve muscle dysfunction through electrical stimulation. Thus, it is used for health monitoring with application value in the diagnosis and treatment of metabolic diseases. Han et al. first prepared MXene by etching and layering MAX phase precursors, and modified it with polydopamine (PD) to obtain PDMM. Then, they made a composite membrane with oxidized cellulose nanofibers (TOCNFs) through vacuum filtration, which was immersed in LiCl solution and sandwiched between copper foil and aluminum foil to make a high-performance electrochemical humidity sensor [46]. Featuring excellent performance, the sensor can generate spontaneous voltage in a wide humidity range of 11-91% RH, with 13/50 s as the response/recovery duration, 0.54V as the maximum output voltage at 91% RH, and good stability. Its composite membrane can be used as a humidity actuator to convert humidity energy into mechanical energy under a humidity gradient. The sensor can be used for self-powered humidity sensing, providing new ideas for portable and wearable passive devices.

In addition, there are some MXene-based sensors using different substrates such as screen-printed electrodes, polyetherimide, and polydimethylsiloxane. They have their own characteristics in sensing performance and application scenarios by virtue of their different material properties and preparation. Tu et al. made a non-invasive wearable electrochemical aptamer sensor by modifying MXene and gold nanoparticles (AuNPs) on a screen-printed electrode (SPE), combining conformationally altered aptamers (using methylene blue as an electrochemical indicator, connected to gold nanoparticles via gold-sulfur bonds to capture cortisol), and integrating a microfluidic sampler [47]. In this sensor, MXene/AuNPs increase the specific surface area of the working electrode and promote aptamer immobilization, and the microfluidic sampler can efficiently collect sweat to prevent evaporation and contamination. The specificity ranges from 0.5-500 ng/ml (1.38-1379 nmol) with a detection limit of 0.1 ng/ml as assessed by differential pulse voltammetry (DPV). This sensor aims to detect cortisol in human sweat and explore its potential expansion in other sweat biomarkers. In addition to screen-printed electrodes, sensors suitable for extreme environments can be prepared by using fiber networks of high and low temperature resistant materials as substrates. Cheng et al. built a fiber network with high and low-temperature-resistant polyetherimide (PEI), introduced MXene nanosheets into the network to build conductive pathways, strictly encapsulated to prevent MXene oxidation, and supplemented by a PEI isolation layer to make a three-dimensional network structure. The MXene-based flexible piezoresistive sensor [48] can be used to monitor human activities (such as pulse and joint movement) in real time, measure pressure distribution, human-computer interaction and Joule heating, etc. Wearable smart textiles and personal heating systems are of great potential in harsh temperature and environments.

4.3 Research on Mxene-based Flexible Wearable Sensors in Other Fields

With its excellent versatility, good environmental adaptability, and reliable signal output, MXene-based flexible wearable sensors have shown extremely valuable and wide application prospects in robot tactile, extreme environment monitoring, electromagnetism and other fields.

Wang et al. prepared MXene cellulose nanofiber (CNF) composite aerogel by vacuum freeze-drying, and then immersed it in PDMS diluent and dried it to obtain super-elastic and super-soft MXene/CNF aerogel @ PDMS. This material is used as a triboelectric layer and a piezoresistive sensitive layer simultaneously. Besides, the bottom copper electrode with a three-separation structure is used to make a dual-mode MXene-based pressure sensor [49], which can be used to monitor complex physiological and physical signals, such as pronunciation, gesture, tone recognition, etc. Deng et al. first prepared $SrTiO_3$ and MXene by solvothermal and chemical exfoliation. After that, they mixed the PI precursor of polyamic acid/triethylamine mixture, $SrTiO_3$ nanoparticles and MXene dispersion to make PI-MXene/$SrTiO_3$ nanocomposite aerogel by freeze-drying and heat-treatment. Then, they obtained a multifunctional flexible tactile sensor [50], which can be assembled on robot fingers with broad application prospects in the field of robot tactile sensing. Yong et al. used eutectic solvent (DES) as the antifreeze medium and MXene as the conductive component to prepare a dual-network eutectic gel composed of polyvinyl alcohol and polyacrylic acid, and made an MXene-based flexible wearable sensor [51]. The sensor has excellent performance, with good tensile properties (strain up to 570%), reliable repeatability and outstanding anti-freeze performance. The introduction of MXene effectively increases the sensitivity of the sensor to 12.25, which is 6.5 times that without MXene. It is expected to be used in flexible sensing in extreme environments. Li et al. prepared a flexible substrate Ecoflex by replicating the microstructure of a sandpaper mold, and spin-coated MXene and PEDOT: PSS composite materials on it (optimized mass ratio 2: 1, spin-coating speed 1500 r/min, sandpaper template microstructure 250 μm). Moreover, they made an MXene-based piezoresistive flexible pressure sensor [52] through face-to-face assembly. The sensor has a sensitivity of 42.31 kPa^{-1} in the range of 0~2.5 kPa, a response/recovery duration of < 150 ms, and a stable performance of 10,000 compression-release cycles. It can be applied to communication for people with language impairments, human-computer interaction and other fields. MXene is made into conductive ink, which can develop flexible and transparent electronic skin.

5. Conclusion and Prospect

This paper systematically reviews the latest research on MXene-based flexible wearable sensors. As an emerging two-dimensional material, MXene has been an ideal core material for building high-performance flexible wearable sensors thanks to its high conductivity, excellent flexibility, abundant surface functional groups, and good hydrophilicity. Through composite modification, structural design and functional integration, its comprehensive performance continues to improve, further expanding its application potential in wearable electronics, smart medical and other fields. In addition, it is expected to promote the innovation and industrialization of the next-generation flexible electronics technology.

Although the related research has made significant progress, it still faces multiple challenges, such as insufficient long-term stability, high cost, complex steps, and limited multi-functional integration. Future research can focus on the following directions to seek breakthroughs:

(1) Material modification and performance optimization. Strategies such as surface coating (i.e., polydopamine modification) and heterostructure construction (i.e., MXene/MOF composite) are used to improve the oxidation resistance and stability of MXene. New composite systems can be developed (i.e., MXene composite with natural biomaterials) to balance high performance and biocompatibility.

(2) Development of advanced manufacturing technology. Low-cost and large-scale preparation processes (i.e., roll-to-roll printing and 3D printing) should be explored to simplify the production. It is necessary to adopt intelligent control methods for precise customization of sensor performance.

(3) Multi-functional integration and intelligence. We should promote the integration of sensors, micro-energy devices (i.e., triboelectric nanogenerators) and wireless transmission modules, and build a closed-loop system with self-energy supply and self-transmission. The combination with artificial intelligence algorithms (i.e. deep learning), multi-signal analysis and scenario-based applications (such as disease warning and gesture control) should be realized.

(4) Expand application scenarios. In the field of personalized medicine, we should develop flexible patches that can monitor multiple physiological indicators in real time. In the field of extreme environments, the sensor’s high and low temperature resistance and corrosion resistance are strengthened to meet the needs of aerospace, deep sea and other scenarios. In the field of human-computer interaction, it is advised to deepen the integration of flexible sensors with robots and virtual reality equipment to improve the naturalness of interaction.

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