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REVIEW ARTICLE

Research progress of flexible wearable stress sensor

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ABSTRACT

Flexible wearable pressure sensors are widely used in health diagnosis, sports monitoring, rehabilitation medicine, entertainment, and other fields due to some factors such as the stretch ability, bendability, light weight, portability, and excellent electrical properties. In recent years, significant progress has been made in flexible pressure sensors, and a variety of flexible pressure sensors that able to measure health status have been applied to the pulse wave, movement, respiration, and electrocardiogram (ECG) detection. However, there are still many problems to be solved in the development of flexible pressure sensors. This article summarizes the development of flexible pressure sensors in recent years, from the working principle to the structural design of the flexible pressure sensors; designs to build a high-performance flexible pressure sensors; discusses the problems existing in current flexible pressure sensors and envisions the development trend of flexible pressure sensors in the future. Flexible pressure sensors with excellent flexibility, good biocompatibility, rapid response, high sensitivity, and multifunctional integration have shown a broad application prospect.

Keywords: wearable; pressure sensor; flexible; sensor; health monitoring

1. Introduction

In recent years, the development of flexible electronics has made significant progress and has a broad market in personalized healthcare, movement monitoring, robotics, and human-machine interfaces. According to the authoritative view and statistical analysis of IDTechEx in the industry, the market share of flexible electronics will increase from USD 41.2 billion in 2020 to USDD 74 billion in 2030[1]. With the rapid expansion of the flexible electronics market, flexible electronics is expected to become an important strategic emerging industry of the country.

Monitoring of physiological health parameters is key to the prevention and diagnosis of disease. At present, the conventional rigid sensors are still being used in the monitoring of physiological signals clinically. Due to the poor strain sensing ability of conventional rigid sensors, it only suitable for flat surface measurement and unable to adapt to the curved surface of human skin, resulting in large errors during the measurement of human physiological signals and can be uncomfortable when wearing it for a long period of time. In addition,

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the bulk and weight of conventional rigid sensors limit the position and method for the measurement of physiological signals. Flexible pressure sensors have the characteristics of good flexibility, ductility, light, portability, able to be bent or even folded arbitrarily, and can adapt to complex curved surfaces during the measurement of physiological signals[2–4]. The light, portable, and flexible sensors are more convenient for people to monitor health, exercise, and other information at anytime and anywhere, and are conducive to the timely detection, prevention, or recovery of diseases.

At present, flexible wearable sensor technology has made significant progress, and a variety of flexible sensors have been widely used in the detection of pulse wave, movement, temperature, and biochemical parameters (such as glucose)[5–10]. However, there are still many problems to be solved for the development of flexible sensors. The conductive functional materials of flexible sensors can be divided into carbon-based nanomaterials, metal nanomaterials, liquid metals, conductive polymers, etc.[11] The preparation process of most conductive nanomaterials is complex, which increased the manufacturing cost of the sensors. Other than that, the production of high-performance sensors often involves complex and high-cost manufacturing processes, such as 3D printing, plasma metal deposition, silicon etching and other technologies, which made it difficult to achieve a production of large-scale, low-cost, and high-performance flexible sensors[12]. It is still an urgent problem to develop flexible pressure sensors with good mechanical compliance, light in weight, long life, high reliability, high sensitivity, rapid response, and low hysteresis that able to adapt to different applications.

The development of flexible pressure sensors in recent years is summarized from the working principle till the structural design of flexible stress sensors. The designation to build a high-performance flexible pressure sensors and the problems existing in current flexible pressure sensors are discussed, and the future development trend of flexible pressure sensors is prospected.

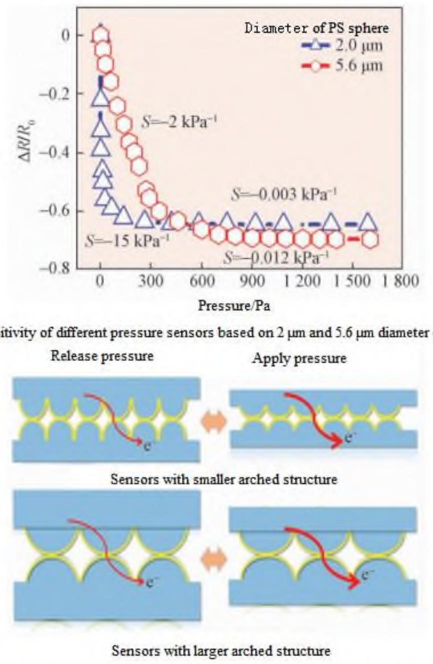
2. Classification of flexible pressure sensors

Generally, the working principle of flexible pressure sensors can be divided into flexible resistive sensors, flexible capacitive sensors, flexible piezoresistive sensors, and flexible field-effect transistors (FET) sensors.

2.1. Flexible resistive sensors

Flexible resistive sensors are flexible sensor which can convert the measurement into a measured resistive signal. Usually, the sensitivity of the sensors can be improved by changing the microstructure of the conductive layer. Through the designation of microstructure of the conductive layer, the changes in pressure to be measured causes the changes in the resistance of the sensor, thereby to achieve the design of high-sensitivity resistive sensor[13]. Zhang et al.[14] used a polystyrene (PS) microsphere-based template method to fabricate a double-layer resistive sensor with a microsphere array.

As shown in **Figure 1**, when the external pressure caused deformation to the sensor, it will change the structure of electrical conductors with microsphere then changed the contact area, which convert the pressure into a change in electrical resistance. The sensitivity of the sensor can be adjusted by changing the size of the PS microspheres and the sensor able to detect the pulse waves at our neck. Pu et al.[15] developed an electronic skin with pressure sensing and electromagnetic shielding capabilities by mimicking the epidermal and dermal layers of human skin. They used sandpaper as a template to form a polydimethylsiloxane (PDMS) film with rough surfaces, then the silver nanowires were spin coated on the rough surface of PDSM film, a silver nanowire conductive sensing layer with micro/nanostructure was obtained by annealing. At the same time, they used the smooth surface of conductive PDMS film with the silver nanowires that prepared via transfer method will act as the protective layer. The multifunctional resistive sensor was composed of a silver nanowire sensing layer and a silver nanowire protective layer relatively encapsulated. The sensor can accurately detect the pressure, and notably that the sensor can also act as an electromagnetic shield. Designing the microstructure resistive sensing unit on conductive layer can improve the sensitivity of the sensor, but there are also some disadvantages. The pressure will cause direct contact with the microstructure of the sensing unit, and repeats contact friction will easily cause the instability of the device and lower the sensing performance, thereby reduced the service life of the sensor. Nie et al.[16] prepared a PDMS with micro-grid and filled the carbon nanotubes in the microgrids to produce flexible resistive strain sensors. The optical transparency of this strain sensor was as high as 87%, and the gauge factor (GF) can be up to 1,140, but the measurable strain range was only 8.75%. Currently, most flexible resistive sensors lack sufficient stretchability and exhibit a large hysteresis effect. During the measurement process, the hysteresis effect can cause large errors, which lead to inaccurate pressure measurement results. Chen et al.[17] produced a flexible pressure sensor by embedding the liquid metal eutectic Gallium-Indium (EGaIn) into a wave-shaped microchannel elastomeric matrix. The microfluidic sensor can withstand strains up to 320%, and its hysteresis performance is also improved from 6.79% to 1.02%. Sophisticated structural tuning can improve the elastic range while increasing the fabrication complexity. Another strategy to increase the detection range of the sensor was synthesizing novel conductive materials and tuning their microstructure to improve the detection performance of the sensor. Yu et al.[18] constructed a MXene nanoparticle-nanosheet hybrid conductive network with unique Ti3C2Tx, and the sensitivity in the whole wide range (53%) can reach GF>178.4. They ingeniously designed the structures of nanoparticles and nanosheets to form a synergistic conductive network that allowed the continuity of the conductive paths to be maintained in larger strained regions. Wang et al.[19] reported the combination of vertically aligned gold nanowire films and elastomers to construct a bilayer pressure sensor that can be stretched to about 800% deformation and able to maintain stable electrical conductivity at the same time. 1Dconductive materials such as silver nanowires (AgNW), gold nanowires (AuNW), carbon nanotubes (CNTs) or 2D nanomaterials such as graphene and other electroactive materials are embedded in elastic polymers to construct resistive sensors, but high contact resistance and relatively high hysteresis effects limit the application of resistive sensors.



(a) Sensitivity of different pressure sensors based on 2 μm and 5.6 μm diameter of PS sphere

(b) Schematic illustration of changes of sensor when same external pressure is applied to the PS sphere in different diameter

ΔR is resistance variation; R_0 is initial resistance; *S* is sensitivity

Figure 1. Response of the pressure sensor[14].

2.2. Flexible capacitive sensors

Capacitive sensors usually consist of a three-dimensional multilayer structure formed by a dielectric layer and two parallel electrode plates. When the sensor is subjected to pressure, the parameters of the capacitive sensor changed, such as the distance between the electrode plates, the dielectric layer, or the relative area of the electrode plates, which caused the capacitance of the sensor to change. The sensitivity of capacitive sensors is mainly determined by two key factors: (1) Compressible patterned and micro-structured dielectric layers; (2) Conductive material used in electrode plates. At present, changing the microstructure of the dielectric layer is the main strategy to improve the sensitivity of the sensor. Many complex dielectric layer models, such as micro-scale pyramids, micro-porous structures, micro-domes, micro-pillar arrays, rough surface structures, can improve the sensitivity of flexible capacitive sensors[20]. He et al.[21] fabricated a capacitive pressure sensor using low-cost elastic nylon mesh as dielectric layer (**Figure 2**) and formed a single electrode plate with a flexible sandwich structure of dielectric layer/conductive layer/base through nylon mesh/graphene thin layer/ PDMS. The sensitivity of the flexible capacitive sensors can be adjusted by changing the number of the nylon mesh which can change the thickness of the dielectric layer. The sensor can manage to perform a high-sensitivity detection to tiny pressure, with a simple, fast, and low-cost production. Kang et al.[22] developed a capacitive pressure sensor based on a biomimetic porous structure. PDMS thin films with regular and uniform porous structure were prepared using polystyrene (PS) as a template and used as a dielectric layer. A highly sensitive porous structure capacitive sensor was constructed by a porous PDMS layer/indium tin oxide (ITO) (electrode)/ polyethylene terephthalate (PET). The pore size of the porous structure affects the sensitivity of the sensor and the compressible thickness of the dielectric layer. Capacitive sensors have a simple structure and are easy to implement, but the signal output of capacitive sensing devices often requires complex signal conversion circuits.

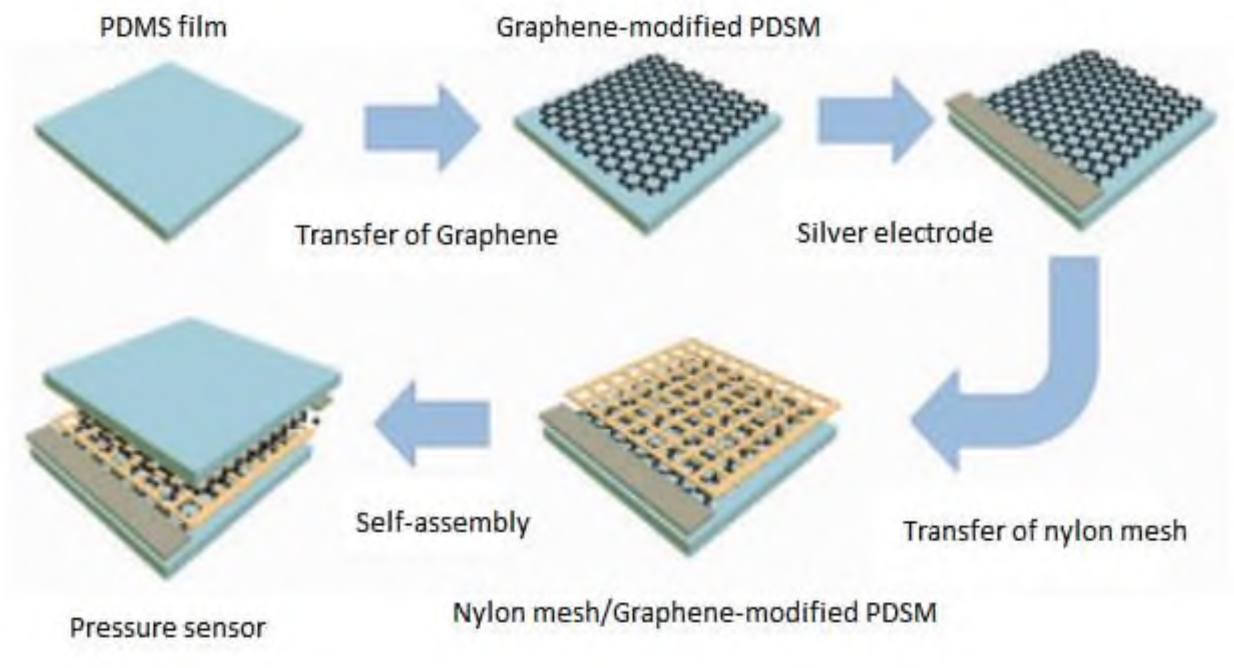


Figure 2. Fabrication steps of the sandwich-like pressure sensor based on low-cost nylon netting with numerous micro-sized square holes[21].

2.3. Flexible piezoresistive sensors

Piezoelectric sensor is a device that uses the piezoelectric effect of materials to convert the physical quantity to be measured into electric charge. Piezoelectric materials can directly convert the mechanical energy into electrical energy. When deformation occurred due to an external force, the surface of the piezoelectric material will generate an amount of charge that proportional to the magnitude of the external force, and the change in electrical polarization inside the dielectric layer will cause the potential of the upper and lower surfaces of the piezoelectric material to change. The charges on the two electrodes that contact with the surface of the piezoelectric material will be readjusted to balance the surface potential of the piezoelectric material, lead to a flow of charge in the circuit. The piezoelectric materials that commonly used include inorganic piezoelectric materials [such as lead zirconate titanate (PZT), aluminum nitride (AlN), zinc oxide (ZnO), quartz, and the like], and organic piezoelectric materials (organic polymers), composite piezoelectric materials, etc. In inorganic piezoelectric crystals, the internal polarization of the material changed with the applied stress, resulting in an electric field at the material boundary. There are some disadvantages on inorganic piezoelectric ceramic materials, such as high temperature is needed to reorient the polarity of the material, high fabrication cost, and poor flexibility. In organic piezoelectric polymers, the piezoelectric effect is caused by the molecular structure and orientation of the polymer[23]. Piezoelectric polymer materials have excellent mechanical flexibility, good formability, biocompatibility, and environmental friendliness. Therefore, piezoelectric polymer materials are widely used in piezoelectric sensors. Polymer nanomaterials, especially polyvinylidene fluoride (PVDF), PVDF copolymers and PVDF nanocomposites, are currently the most promising piezoelectric materials[24], which can meet the demands of dynamic sensing in flexible wearable electronic devices. PVDF nanofibers offer good flexibility as well as piezoelectric properties. Park et al.[25] used the electrospun nanofibers [copolymer polyvinylidene fluoride-trifluoroethylene (PVDF-TrFE)] were sandwiched between two elastomer sheets with sputtered electrodes as the piezoelectric active layer, as shown in **Figure 3**. This piezoelectric sensor has the sensing ability to detect tiny stimuli (including deformations as small as 1 μm), enabling the detection of radial artery pulse waves. When the arrangement and orientation of PVDF fibers are more ordered, the piezoelectric properties of the material can be improved. PVDF nanocomposites prepared by electrospinning (such as PVDF/Ag[26], PVDF/carbon nanotubes[27], PVDF-TrFE[28]) have significantly improved piezoelectric properties. In addition, organic-inorganic composite materials can be used to improve the electromechanical properties of strain sensors, to overcome the brittleness of inorganic materials and the structural instability when compounded with organic materials, and the flexibility and conductivity of the device can be improved at the same time. Chen et al.[29] produced a flexible piezoelectric sensor (PVDF@ZnO) based on PVDF-TrFE fibers and ZnO nanowires. This device can withstand ultimate stretching with a stretch ratio up to 30% and exhibits excellent performance with high sensitivity (gauge factor of 4.59) and 150° change in bending.

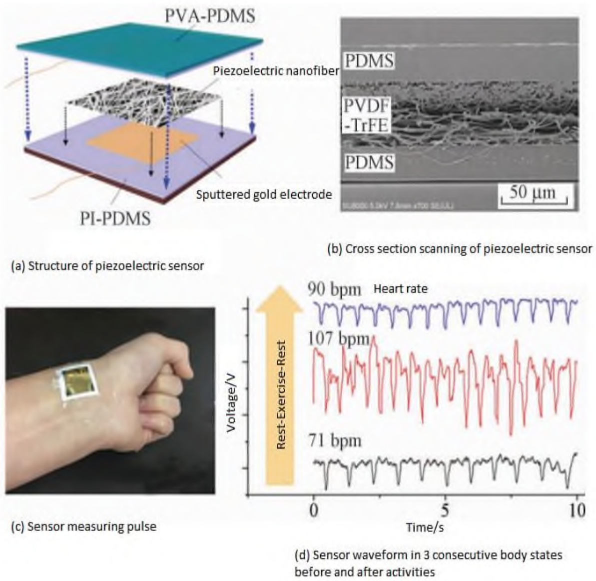


Figure 3. Structure and physiological signal measurement of the piezoelectric sensor[25].

Piezoelectric sensors have good stability, biocompatibility, low power consumption, fast response speed, simple device structure, and low-cost manufacturing process, and can directly convert mechanical energy into electrical energy without external circuit components. However, the limited stretchability constraints the application range.

2.4. Flexible FET sensors

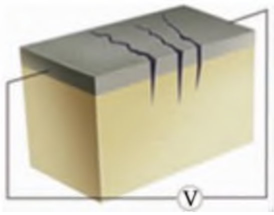
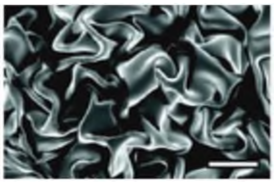
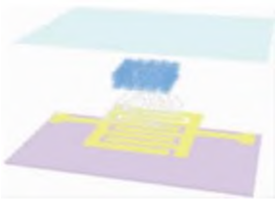
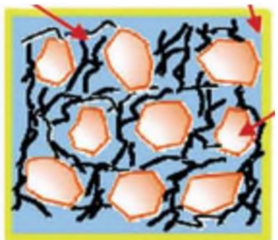
FET-based pressure sensors have received extensive attention in recent years due to their excellent signal amplification, high array uniformity, excellent stress monitoring, high spatial contrast, and convenience. FET is a voltage-controlled semiconductor device, metal oxide semiconductor field effect transistors (MOS-FETs) and organic field effect transistors (OFETs) are commonly seen in the field of FET sensors. There are several advantages of organic semiconductors properties, such as diversity in molecular design, low cost, light in weight, good flexibility, low operating voltage, and can be mass produced through low temperature inkjet printing. Due to its unique three-terminal structure, optimizing any single component of FET (e.g. gate electrodes, source and drain electrodes, dielectric layers, or semiconductor active layers) can significantly improve the sensing performance of FET devices. Liu et al.[30] proposed a new concept of the piezoelectric effect by replacing the gate voltage of FET with the piezoelectric potential energy generated by the mechanical response of the piezoelectric material, and the piezoelectric sensor perfectly combines the piezoelectric effect with the FET device. Wang et al.[31] developed a flexible piezoelectric sensor that can convert external mechanical force into voltage through PVDF nanowire arrays to drive OFET devices, which in turn can amplify the piezoelectric voltages, thereby can significantly improve the performance of piezoelectric sensors. Generally, FET-type flexible pressure/strain sensors are more sensitive than resistive and capacitive-type sensors due to their ability to adjust the conductance of the semiconductor channel material by controlling the gate voltage. Dai et al.[32] used the hydrogel "stamp" as a biometric module and graphene FET as a sensor module to form a module of FET biosensor. The sensor enables real-time, label-free detection of penicillin and urea using penicillinase and urease-encoded PEG hydrogels as biometric modules respectively. FET devices are widely used in the field of biosensing. At present, FET biosensors[33] have made progress in the detection of different biomolecules such as glucose, cholesterol, uric acid, urea, hormones, proteins, nucleotides, and biomarkers. In addition, related papers also reported its application in the detection of weak neuronal action potential[34]. However, high operating gate voltages limit their application in wearable electrical systems. Moreover, the toxicological properties of organic semiconductors restrict their application in invasive medical examinations.

3. Typical structure of a flexible pressure sensor

Scientific research on flexible sensors has shown that wide detection range, high sensitivity, rapid response, good durability, flexibility, and excellent stability are necessary conditions for high-performance flexible sensors. When the flexible sensor deformed by an external force, its conductive mesh structure also forced to deform at the same time, thereby generating an electrical signal output. Other than using advanced sensing materials with excellent intrinsic electromechanical properties, unique microstructures are also an effective strategy to fabricate high-performance flexible wearable sensors[35–36]. The conductive network can enhance the ductility and stability of the sensor, and effectively improve the sensitivity, response speed and detection range of the flexible sensor[37].

Table 1[38–43] summarizes several sensors with different conductive network structures. Commonly used conductive network structures including serpentine structures, porous structures, microcrack structures, and wrinkled structures. Various conductive network structures are used to improve the performance of flexible sensors[44]. Different conductive network structures produce different sensor performances[45,46]. The idea of the microcrack structure comes from the slit organ of spiders[39]. Yang et al.[47] fabricated a gold thin film flexible sensor with channel cracks for ultrasensitive strain sensing. The sensor has high sensitivity, good cyclicity and rapid dynamic response. Introducing weak interfacial interactions between metals and polymers can simultaneously achieve fracture geometry and reversible electrical responses. The sensor can reach a GF of 2 000 for 2% strain and can detect an amplitude of about 10 nm. However, due to the microstructure of sensor is easily damaged when a large deformation occurs, therefore problems such as limited detection range and easy peeling of the conductive layer on the surface can be occurred.

Table 1. Sensors with different conductive networks and their performance[38-43]

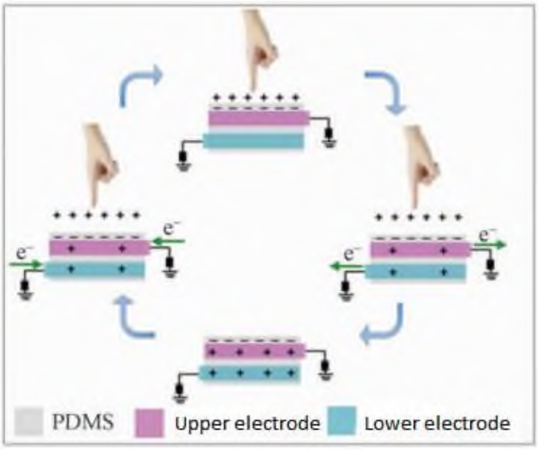
Structure	Structure	Image	Performance	Reference
Serpentine structure	Mixture of polyimide and 1-methyl-2-pyrrolidinone/Metal nanowires		Can measure up to 80% of the deformation, Electrocardiogram (ECG) and Electromyography (EMG)	[38]
Crack structure	Polyurethaneacrylate (PUA)/ Platinum film		GF = 2 000 (deformation ε <2%) Can detects tiny deformations up to 10 nm	[39]
Wrinkle structure	Ecoflex/Platinum/Gold film		GF = 42 (deformation ε <185%)	[40]
Kirigami structure	Silver nanowires/Ultrathin colorless transparent polyimide (PI)		0 to 400% tensile strain range, optical transparency greater than 80%, can measures EMG, ECG and EOG signals	[41]
Porous structure	Metal carbodes and nitrides (MXenes) sponge/Polyvinyl alcohol Porous structure (PVA) nanowires/Interdigitated electrodes		147 kPa^{-1} (pressure p <5.37 kPa) 442 kPa^{-1} (5. 37 < p <18. 56 kPa)	[42]
Isolation structure	PDMS/Electrically conductiveMulti-walled carbon nanotubes		GF = 142 (deformation ε <30%)	[43]

Liu et al.[48] fabricated a highly adhesive stretchable electrode using a novel nanostacks interlocking strategy. Nanofibers can significantly enhance the adhesion and redistribute strain in the film, enabling high stretchability. Nanostack electrodes can simultaneously monitor EMG signals and mechanical deformation. The wrinkle structure has a relatively broad detection range by using a pre-stretched flexible substrate, but the detection sensitivity was not as high as the microcrack structure. Other microstructures, such as three-dimensional porous structures and isolation structures enhanced the ductility of the conductive layer to a certain extent and expanded the detection range. However, its transparency and conductivity are limited. The design of these conductive structures enables the sensor to exhibit a dependence of external resistance force, which is mainly due to the change in the geometry of the sensitive element upon the application of external force. The kirigami structure shows good resistance to huge deformation[41]. Reference[48] proposed a novel fabrication method by using the art of kirigami to obtain highly stretchable electronic devices for various shapes, which have high electrical conductivity and high optical transparency (80%) and can be adapted to different curved surfaces of human body. The kirigami structure endows the electrode with adjustable elasticity, which can be adjusted in the range of 0-400% tensile strain and possess constant electrical properties.The design of the structure of highly conductive network is crucial to produce a sensor with high ductile and high-sensitivity.In practical applications, more suitable conductive structures can be designed according to the requirements of different application.

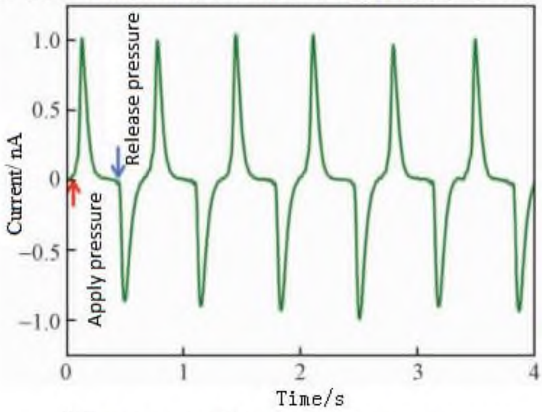
4. Challenges and development trends

4.1. Self-powered sensors

Suitable energy devices are important for the normal operation of flexible sensors. Conventional power supply modules are usually bulky and rigid, which are not compatible with emerging multifunctional electronic skin systems. Flexible self-powered systems are a promising alternative strategy, enabling self-driven sensor systems by harvesting ubiquitous energy from the environment or human movement[49–51]. With the continuous development of stretchable energy-harvesting active materials (carbon nanotubes, AgNWs, and graphene, etc.), and the emergence of various stretchable strategies (serpentine or self-similar), piezoelectric, triboelectric, and pyroelectric effects of dielectric elastomer-based energy harvesting devices have made some progress in wearable and stretchable electronics[52]. Frictional Electron Nanogenerator (TENG) have been shown to be a cost-effective and reliable method for the harvesting of environmental mechanical energy. The working principle of TENG is based on the periodic contact and separation of two materials with opposite triboelectric polarities. During the motion of contact and separation, a potential difference is created, which will help electrons to flow between the conductive electrodes and produce an electrical output. Although the operating principle of TENG is simple, but there are still some challenges exist in the development of TENG. Conventional TENGs usually work in contact or sliding mode, which mainly rely on unidirectional triggering. This would limit the application of TENGs in harvesting energy only from specific directions. Yang et al.[53] proposed a TENG device composed of paper-based substrate, polytetrafluoroethylene (PTFE) film and aluminum foil. The device fully utilizes the origami 3D structures to harvest mechanical energy generated by various human movement, such as stretching, lifting, and twisting. Ma et al.[54] reported a triboelectric pressure sensor composed of PDMS layers and carbon fiber electrodes (**Figure 4**). The device can be mounted on a finger or beetle and can achieve self-powered pressure sensing without an external power source, with a sensitivity of 0.055 nA/kPa and a strain detection limit of the sensor of 0.8 kPa. It had been reported that there are still some problems in the assembly and integration of the energy collection device currently, and the consistency, scalability, flexibility, long-term stability, comfort and energy conversion efficiency of the whole system still need to be improved.



(a) The working principle of the triboelectric pressure sensor



(b) Response of the triboelectric pressure sensor

Figure 4. Working principle of triboelectric pressure sensor[54].

4.2. Biocompatibility

The good biocompatibility of wearable sensors to human body is thekey to prevent any adverse reactions[55]. Issues of safety and long-term stability must be considered during the designation of implantable flexible devices. Reference[56] designed and fabricated an implantable pressure and strain sensor that completely made of biodegradable materials, which showed excellent biocompatibility and good pressure and strain detection in a rat model, in which the healing in tendon can be monitored under real time condition.

Biocompatibility of flexible wearable devices requires consideration not only of the sensing elements but also other modules of the device. High-performance flexible nanogenerator with biocompatibility is an important part for flexible wearable devices, which can supply the required energy for the operation of wearable devices. Zhu et al.[57] proposed a flexible and biocompatible triboelectric nanogenerator with simple fabrication process and adjustable internal resistance. This nanogenerator exhibits good flexibility and biocompatibility for the applications of wearable devices. Li et al.[58] fabricated a nanogenerators based on polypropylene ferroelectrics (FENG), which is light in weight, flexible, foldable, and biocompatible as a power source for flexible wearable devices. FENG require some advantages such as of light in weight, flexibility, foldable, biocompatibility, scalability, low in cost, and strong flexibility, which make FENG as a promising alternative in the field of mechanical energy harvesting for various autonomous electronic devices. Due to the high impedance of FENG, the short-circuit current of the devices limits their applications.

Although scientists have now developed a variety of biocompatible and degradable sensors[59–60], they are still facing various problems. For example, there are some sensors without good sensing performance, or used materials with unproven biocompatibility.

4.3. Integration and multi-functionalization of devices

The human body is a complex living body, and it is difficult to determine the pathology by relying on only one or two physiological parameters. It is necessary to systematically and comprehensively collect a number of relevant physiological indicators of human body, such as blood pressure, blood sugar, blood oxygen, pulse, body temperature, ECG, etc. for accurate diagnosis. The development of multi-parameter and multi-function sensing technology has created favorable conditions for smart wearable medical devices. Sensor arrays or integrated platforms that simultaneously detect multiple physical signals are of great significance for personalized medicine. Reference[61] developed and designed a wireless, battery-free vital signs monitoring system for neonatal vital signs monitoring (**Figure 5**). The system consists of ultra-thin, lower modulus measurement modules, ECG, photoplethysmography (PPG), skin temperature, and wireless battery-free modules, which can accurately and non-invasively measure neonatal vital signs, such as heart rate, blood oxygen, temperature, respiratory rate and pulse wave. However, there are some problems occurred in the system, such as short wireless communication distance and brittle connection between modules. Reference[62] further improved and optimized the system to measure not only the physiological parameters such as heart rate, respiration rate, temperature, and blood oxygen, but also able to monitor the variability in heart rate, which can be used to predict changes in the clinical condition of infants before the apparent signs of disease. Wang et al.[63] fabricated a flexible temperature-pressure electronic skin sensor, using flexible and transparent silk nanofiber-derived carbon fiber membranes as electroactive materials, and integrated silk-based temperature and pressure sensors through a lamination strategy, to produce a sensor with high temperature sensitivity of 0.81%. The strain sensor shows extremely high sensitivity with a gage factor of 8,350 at 50% strain. The temperature and pressure sensors do not interfere with each other. Gui et al.[64] developed a sandwich-like sensing system capable of simultaneously monitoring temperature, light, and pressure signals without mutual interference of signals. The system employs skin-like epidermis, dermis, and subcutaneous structures to achieve multi-signal sensing properties, including ambient temperature, body temperature, pressure, and near-infrared light. Yamamoto et al.[65] integrated a skin temperature sensor, an ECG sensor, and an ambient ultraviolet (UV) light sensor with a printed triaxial accelerometer to demonstrate a multifunctional wearable health monitor. For sure there will be challenges in the future, and the reliability and overall performance of the functional circuit structure still need to be improved[66]. A complete wearable sensing system includes sensing unit, power supply unit, signal transmission, etc. How to integrate these excellent functional circuits into a single flexible system for flexible, high-sensitivity, multi-parameter, high-stability, real-time, and durable detection are the problems that needed to be solved.

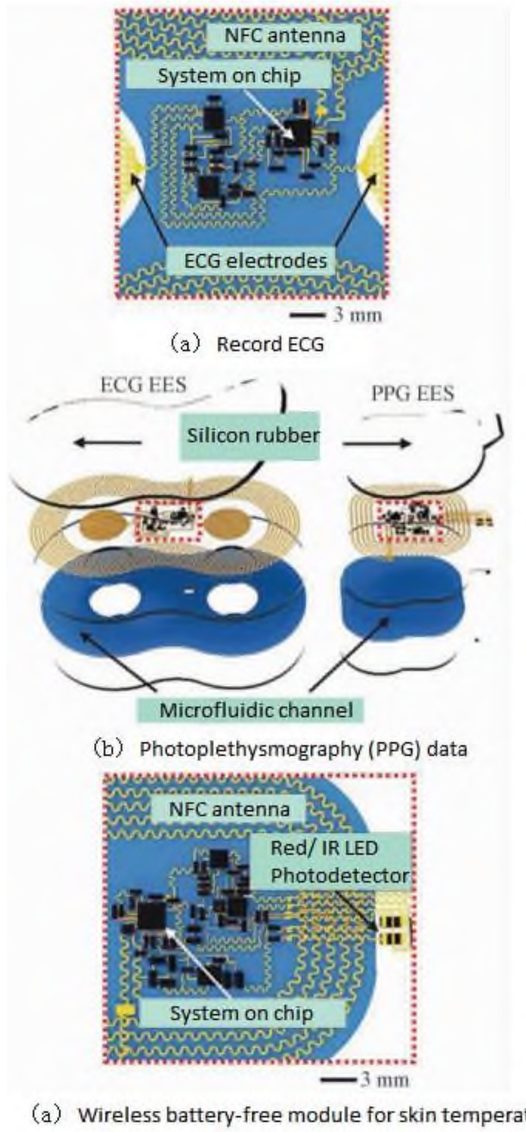


Figure 5. Flexible sensor for neonatal multi-sign monitoring[61].

5. Conclusions

The research progress of flexible wearable stress sensors in recent years is summarized in this review paper. According to the classification of working principles, the progress of resistive, capacitive, piezoelectric, and FET flexible sensors is analyzed and discussed, and the strategies for constructing corresponding types of sensors are discussed. In addition, a detailed analysis is made on how to improve the performance of the sensor from the aspect of structural design. Building highly integrated, high-performance, and muti-functionally flexible sensors is still the direction for future development. Although there are still many challenges in this field currently, flexible wearable stress sensors have shown excellent development potential and application prospects in the fields of biomedicine, robotics and entertainment technology.

Conflict of interest

The authors declare no conflict of interest.

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