Wearable Strain Sensors and Their Applications

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Abstract— Wearable and stretchable strain sensors have received much attention because of their easy interaction with the human body. They are widely used in many fields, such as healthcare monitoring and human motion detection. Recent advances in the design and implementation of wearable and stretchable strain sensors and their application prospects are summarized herein. The research on sensitive strain sensors will be introduced herein first, which mainly involves the application of nanomaterials in the strain sensor. The remarkable properties of nanomaterials enable the carbon nanotube sensor to be embedded in socks, gloves, bandages, and other items that can be attached to the human body to accurately monitor various movements of the human body, including training, breathing, typing, and speaking. And then, we will focus on the application prospects of wearable strain sensors. With the development of the Times and the progress of science and technology, wearable strain sensors are gradually applied to various fields, especially in intelligent medical treatment, sports and fitness, and entertainment. Although the research on wearable strain sensor has produced considerable progress so far, it is still in the prototype stage, and wearable strain sensor still faces significant challenges in manufacturing a multi-functional integrated strain sensor. The research of this paper will be of great value to the study and application of wearable strain sensors.

1 Introduction

Wearable electronic devices can monitor the human body for a long time and simply interact with the human body. The human body's physical, chemical, biological, and environmental state can be monitored with high efficiency and minimal discomfort by various flexible sensors, which can convert external mechanical stimulation into electrical signals. Wearable sensors on the skin can be installed on clothes or even directly on human skin to monitor real-time human activities. Besides high efficiency, they must also meet several simplest requirements, including low power consumption, biocompatibility, and portability. In recent years, with the great progress and development of science and technology, people put forward new application requirements for various devices in daily life. Wearable electronic products are widely used in wearable devices, such as electronic skin, pressure sensors, touch screens, human motion monitoring sensors, energy sources, etc. And so on, has aroused great concern of people. Among them, the right stretchable strain sensor that can monitor signals plays an important part in the field of smart wear. It has extensive prospects applying in human motion monitoring, body monitoring, human-computer interaction, agile robots, wearable electronic devices, electronic skin, and so on. With the progress of material science and micro-nano technology, these sensors have recently shown their possibilities as sensory skin in soft robots, ensuring that robots can easily react with the natural environment and humans. Regarding applications, strain sensors must have good tensile strength (more than 50%), perfect sensitivity, and excellent durability to adapt to several scales and dynamic deformation caused by human activities. In addition, they should be mechanically soft, compatible with curvilineal and soft surfaces (for example, human skin), chemically sweat-proofing, and adaptable to the atmospheric environment. For instance, changes in temperature and humidity. Compared with the traditional silicon-based sensor, which is more rigid and brittle, the agile tensile strain sensor can effectively capture high-quality mechanical signals on the curved surface and convert them into electrical signals because its good elasticity and flexibility make the agile tensile strain sensor has good sensing performance. The agile tensile strain sensor is usually composed of an elastic substrate and conductive material. Currently, elastic polymers such as polydimethylsiloxane (PDMS), polyurethane (PU), and Ecoflex or fabrics with good elasticity are usually used as elastic substrates. Elastic films and elastic fabrics have excellent tensile properties, which can make the agile stretchable strain sensor monitor signals in a wide strain range. One or a combination of several conductive polymers, carbon nanotubes, graphene, metal nanowires, and transition metal carbides/nitrides (MXene) are used as

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conductive materials to construct conductive layers. Conductive polymers and conductive nanomaterials have good flexibility and conductivity, and agile tensile strain sensors made of them as conductive layers can have good flexibility and high sensitivity. The adjustable base gives the agile stretchable strain sensor good stretchability and flexibility to capture signals on curved surfaces and adapt to various bending actions. The conductive network constructed by conductive materials gives strain-specific conductivity and sensitivity. When the strain sensor is excited by a signal, the substrate generates strain, its structure changes, the position between conductive materials changes, and the resistance of the agile stretchable strain sensor changes, which makes the flexible, stretchable strain sensor have sensing performance and can effectively respond to the excitation signal. According to the difference between the elastic substrate and conductive material of flexible tensile strain sensors, this paper systematically summarizes the preparation, performance, and application of agile tensile strain sensors, comprehensively discusses the potential applications of wearable strain sensors and stretchable strain sensors, introduces the mechanical principle and application of wearable strain sensor, and expounds its different applications in different fields. The introduction sequence of this paper is as follows: Firstly, the common working mechanism of tensile strain sensor is introduced, and its manufacturing process is briefly introduced. Secondly, it expounds its application in different fields, including intelligent medical treatment, sports health, entertainment, etc. Thirdly, the performance parameters of the stretchable strain sensor are introduced, including stretchability, sensitivity, and linearity. Finally, the good application prospect and current challenges of wearable strain sensors are emphasized as their development prospects. The potential application scenarios and future development direction of flexible tensile strain sensors are discussed.

2 Mechanism of sensing

Generally speaking, strain sensors conduct transduction from external mechanical stimuli into electrical signals [1]. The primary mechanism of the capacitive and optical sensor is the size change during expansion. In addition to the internal resistance response of the material and the geometric effect, the stretchable resistance strain sensor is solved by not connecting micro/nanomaterials, tunneling effect, and generating controlled microcracks in the sensing film. The systems described above regulate the electromechanical response of highly stretchable tensile strain sensors relying on the type of material, as well as the surface interaction with the material and the manufacturing process. When it comes to wear-able items, strain sensors must maintain a high degree of tensile (>50%) and sensitivity, and excellent persistence to accommodate multi-scale and dynamic deformation caused by specific movements and activities is required. Stretchable strain sensors usually consist of an active sensing material integrated with a flexible and stretchable support substrate. Functional materials typically consist of conductive micro/nanomaterials, polymer composites, films, or conductive yarns/fabrics. Under applied voltage, the network of active substances acts as a resistor. When the material is stretched or compressed, the electrical resistance of the conductive network varies with the applied mechanical strain. The critical resistance changes in the tensile process come from the geometrical changes of the material, the internal resistance reaction of the material, the tunneling, and the disconnection mechanism. After releasing the strain sensor from tension or compression strain, the resistance will return to its initial value. Therefore, the distortion value can be accurately gauged by tracking the resistance movement of the resistive strain sensor. Wearable capacitive strain sensors are usually made by integrating an insulating film between two stretchable electrodes as a dielectric layer. Wearable optical strain sensors typically consist of a stretchable waveguide with a core-cladding structure, a light emitter, and a photodetector on two sides.

With the introduction of new electronic manufacturing technology, flexible polymer waveguides have been widely used in wearable strain sensors. The primary sensing mechanism is based on the deformation variations transmitted by the strain sensor. The optical power contrast between the light source and the photodetector gauges the deformation variations. Piezoelectric and triboelectric strain sensors are the two primary tensioning strain sensors. Piezoelectricity is a mechanism by which the electric dipole moment of piezoelectric material directly generates voltage under the action of external deformation. The strain sensor based on high piezoelectric coefficient material can sense mechanical deformation sensitively and quickly. The role of wearable triboelectric strain sensors is to convert external deformation into electricity through the combination of the triboelectric effect and electrostatic induction.

3 Highly sensitive strain sensors

Yamada et al. unveiled a flexible, wearable gadget constructed of novel electrical nanomaterials comprised of arrayed single-walled carbon nanotube (SWCNT) films [2]. Stretching the film causes it to distort, break into islets and interstices, and form bundles to span the gaps. By doing so, the authors looked at a novel kind of strain sensor that has a low creep (3.0% at 100% of strain), quick reactivity (latency time, 14ms), high endurance (10,000 cycles at 150% of music), and can measure and endure up to 280% strain (50 times more than metal parts strain gauges). These significant properties allow carbon nanotube sensors to be embedded in clothing such as stockings, gloves, and bandages to accurately monitor various human movements, including locomotion, respiration, typing, and talking. As a result, the widespread use of these humanized gadgets with realistic capabilities and skills will profoundly impact many industries in the future, including entertainment, virtual reality, robotics, and healthcare, which are not possible with traditional techniques.

Cohen et al. proposed a highly elastomeric strain measurement relying on parallel-plate capacitance, which uses the Poisson effect to convert the uniaxial strain to a scaling distortion, pushing these two porous electrodes in closer proximity [3]. Using this strategy, they circumvent some of the traditional issues with the design of piezo resistors and porous nanotube electrodes, such as changing strain coefficients and hysteresis. Additionally, the device was made utilizing a process that involved hydrophobic silicone patterning and vacuum filtration of SWCNTs. This allowed for speedy (complete assembly 20 min), inexpensive ($1/sensor), and equipment-light fabrication.

Over 3000 cycles, the capacitance output of the sensor maintains stability within 3%, i.e., variability is less than 3%. The sensor has the most significant gauge factor of any strain gauge that can reversibly endure 100% or more strain (gauge factor = 0.99). In addition, its reliable linearity makes the sensor simple to calibrate and suitable for practical sensing applications. To illustrate how this kind of sensor may be used with a wide range of different joints and linkages, the authors replaced an angle encoder on a robotic platform with one of these sensors to convert changes in the robot's joint angles.

Luo et al. reported a thorough analysis of the piezoresistive properties of the SWCNT thin films [4]. The researchers designed the thin film piezoresistive sensors using the spraying methodology. They used various ultrasonic treatment periods to generate SWCNT aqueous dispersions with bundle lengths (L=447-5446 nm) and SWCNT diameters (D=2.4-22.6 nm). Quantitative characterization was then completed using dynamic light scattering techniques and the preparative ultracentrifugation method. Subsequently, utilizing the spraying process, the SWCNT thin film piezoresistive detectors of varying thickness are created from the dispersions defined by dynamic light scattering techniques and the preparative ultracentrifugation method. To support SWCNT sheets, they used two distinct materials: polyethylene terephthalate and polydimethylsiloxane. The authors examined the relationship between SWCNT thin-film sensors' structure, piezoresistive performance, and processing using cyclic tensile experiments and real-time resistance measurements as assessment criteria. They discovered that, within the small deformations range (0-2%), the dependency of the SWCNT film piezoresistive sensor's specification factor on the microstructure of the beam and the film thickness, i.e., beam length and diameter, can be negligible.

Nevertheless, the microstructure of SWCNT and the film thickness have a combined effect on the sensor's piezoresistive performance in the high strain range (20-30%). Combining smaller beam sizes and thicker thin films facilitates extensive deformation testing of more sensitive sensors. Therefore, the experimental methodology used in this research provides an approach for SWCNT integrated pressure sensor performance optimization.

4 Applications

With the changes of the times and the development of technology, wearable device technology has gradually been applied to various fields, mainly medicine, sports, and entertainment. So, this season explicitly describes the practical applications of the device.

4.1 Smart healthcare

Wearable device technology provides essential support for the application and expansion of intelligent healthcare. Wearable device intervention benefits physical and mental health, associated with better living situations. Stress, depression, and anxiety are some of modern office workers' most common mental health problems.

The real significance of wearable medical devices lies in implanting and binding the human body and identifying the physical characteristics and state of the human body. Continuously monitor our physical condition, exercise status, and metabolism status, but also let us dynamic, static life data. Its real value lies in the vital characteristic data; wearable medical equipment can real-time monitoring of blood sugar, blood pressure, heart rate, blood oxygen, body temperature, respiratory rate, and other human health indicators and essential human treatment [1]. Wearable healthcare devices can be divided into three categories: One is for the public’s health tracking equipment; the wearable monitoring devices on the market are mainly smart bracelets and smartwatches, with strong penetrability, ease to carry, and attractive appearance characteristics. The main functions are step counting, vital signs detection, blood glucose monitoring, energy consumption, and sleep monitoring. The second category is for a particular disease of the equipment, such as blood pressure monitor, blood glucose meter, and other equipment, such equipment is mainly used by patients with medical rehabilitation needs through the National Medical Products Administration medical device certification of equipment, its accuracy can be used as a clinical reference [3]; The third category is wearable devices with medical and health application scenarios, such as smart mirrors, intelligent crutches, smart watches, etc., which take medical and health applications as one of their application scenarios [5].

Just in recent years of COVID-19, wearable has also played a significant role; by combining basic vital signs with clinical symptoms, wearable devices can play an essential role in early warning of COVID-19 infection to identify people who might be most likely to be tested, to detect a sudden decline in isolated, isolated, or isolated people. In subdivisions, predominantly asymptomatic, remotely monitor non-COVID-19-related patients to prioritize resource use and allocation and reduce cross-contamination [6].

4.2 Sports and fitness

With the increased social pressure, more people exercise to relieve their stress, which also helps us become more muscular. To better help us understand the physical condition or formulate a training goal, wearable devices appeared.

Most sports wearables have acceleration sensors that can record people's movements. If they are closely carried, they can accurately perceive the user's movements through sensors and algorithms, and heart rate and blood oxygen sensors can also help monitor sleep quality. When these movements and heart rate blood oxygen data are confirmed, the smart bracelet can send the data to the mobile phone through Bluetooth, and then through the personal data provided by the user, through the analysis of various data, and finally give the user a relatively accurate monitoring data, the user can formulate corresponding countermeasures according to these data.

4.3 Entertainment

Entertainment has always been one of our lives, and wearable will subvert our perception of entertainment methods such as playing games and watching movies. We can experience movies and games more realistically in terms of somatosensory sensations, postures, sounds, and ideas rather than sitting in a movie theatre or using a mouse and keyboard. Japan's Telepathy has launched a wearable device that can create real-time access to social networks and cloud service environments, equipped with cameras, projection units, wireless communication modules, etc., which wearers can use to broadcast the scenery they see.

5 Discussion

Strain sensors typically translate mechanical impulses from the outside world into electrical output. It responds to the applied strain using various methods based on the interaction of the supporting material surfaces, i.e., micro/nanostructures, the manufacturing process, and the kind of sensing material [7]. The strain resistance response of conventional strain gauges stems from the material's inherent piezo resistivity and geometric effects.

When optical and capacitive sensors are stretched, their dimensions vary, which serves as the primary sensing mechanism. This led Cohen et al. to propose a highly elastic strain gauge for capacitive sensing depending on parallel carbon nanotube permeable electrodes [3]. The sensor is simple to calibrate and suitable for real sensing applications, such as replacing encoders in mechanical linkages, thanks to its consistent linearity and almost zero hystereses, although its sensitivity is relatively modest.

By utilizing the tunneling effect, the creation of controllable microcracks inside the sensing film, and the separation of micro/nanomaterials, stretchy resistive strain sensors have already been successfully manufactured [1]. For example, Yamada et al. investigated a class of wearable and scalable devices consisting of arrayed SWCNT films that can be used to build user-friendly gadgets with realistic features and capabilities that are not possible with conventional devices alone [2]. In addition, Luo et al. fabricated SWCNT thin-film piezoresistive sensors by spraying technique and investigated the structure-piezoresistive performance-processing relationship [4]. This experimental methodology also provides a solution to achieve further the best potential property of this type of sensor.

With the improvement of society and quality of life, people are becoming more concerned about their health [5]. According to the research above, these wearable strain sensor devices can be connected to clothing or human skin and use innovative nanomaterial technologies to monitor more private and individualized data. For instance, they can precisely track various human behaviors, such as speaking, typing, and breathing, as well as the bending and straightening of joints in the body [7]. As a result, we believe these gadgets will someday be widely employed in industries including innovative medicine, virtual reality, sports, healthcare, and robotics.

6 Conclusion

This mini-review summarized the basic situation of wearable strain sensors; it describes the primary sensing mechanism of this type of sensor. And it explains the device structure design and final device performance. Practical applications of the devices are also introduced in turn. Presently, wearable sensor technology is not popular and is only used in some aspects of life. But with the development of the times, some technologies will be improved.

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