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Research progress on key technologies of flexible wearable electronic devices

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Abstract: Flexible wearable device is an innovative technology product, using soft, lightweight material design, can fit the curve of the human body, providing a comfortable wearing experience. These devices typically integrate a variety of sensors, batteries, and connectivity technologies to enable biometric monitoring, motion tracking, communication, and other intelligent functions. Traditional electronic products tend to give a "stiff" impression that they cannot withstand bending, twisting and stretching. In recent years, under the background of the integration of electronic technology and modern material science technology, the emerging flexible electronic wearable device has become a research hotspot with its more flexible material, more sensitive and accurate signal transmission, and more extensive monitoring range. The development of flexible electronic technology has greatly improved the user's wearing experience and is more suitable for the free movement of the human body. This paper summarizes the basic principle and classification of key technologies of wearable electronic devices, and introduces the research progress and research trend.

Keywords: Wearable electronic devices; Flexible material; Key technologies.

1. Introduction

At present, the Internet of Things technology is closely integrated with people's lives. In this process, smart wearable devices, as an important entrance and application terminal of the Internet of Things, are experiencing unprecedented rapid popularity and development. Traditional wearable devices, including helmets, bracelets, watches, etc., these electronic devices themselves have some limitations, such as large size, heavy weight, etc., are not convenient to carry and wear. In the age of iot, many things can stay connected; However, biological systems, including those critical to human health, are unable to stay connected to the global Internet due to a lack of flexible conformal biosensors. The fundamental challenge is that electronics and biology are different and incompatible because they are based on different materials through different functional principles. In particular, the human body is soft and curvy, while electronic devices are usually rigid and flat. Recent advances in materials and material design offer tremendous opportunities for designing flexible wearable bioelectronic devices. The development of wearable devices in the future may develop in the direction of flexible electronic devices, and flexible electronic technology is applied to wearable systems, which can make wearable systems smaller, lighter, more convenient to carry and more comfortable to wear. Flexible wearable electronic devices generally refer to electronic devices with mechanical flexibility and can directly or indirectly fit closely with the skin, which has become a new generation of data traffic entry and a hot spot in the future mobile Internet era, and the wide application of flexible electronic technology may promote a big change in wearable systems. This paper reviews the latest research progress of key technologies for flexible wearable devices, and focuses on the application of flexible wearable devices in different fields.

2. Basic principles and key technologies of flexible wearable devices

2.1. Basic Principles

Wearable devices, also known as wearable computers, are computer devices that can be worn on the body and can transmit data. Wearable devices are widely used in the field of human condition monitoring, such as vital signs monitoring, body posture monitoring, motion monitoring, etc. [1] The core technologies used include sensing technology, cloud computing technology, etc. The sensor is a device that can detect and transmit information, and can convert the information to be measured into electrical signal output according to certain rules. The realization of various functions of wearable devices rely on sensors to record the state of the body. The core component of flexible wearable devices is flexible sensors, and the principle of flexible sensors is to convert external deformation signals into electrical signals. According to the signal conversion mode, the flexible wearable device can be divided into piezoresistive, capacitive and piezoelectric.

2.2. Key Technologies

2.2.1. Flexible display technology

At present, there are many display technologies for flexible display devices. Including traditional Liquid Crystal Display technology (LCD) [2], Bistable Liquid Crystal Display technology (BLCD) [3], Organic Light-emitting Diode (OLED) Display technology [4], Electrophoretic Display technology, (EPD), Electrochromism Display (ECD) and Electroluminescent Display (ELD) [5]. The display panel using OLED technology has the advantages of self-illumination, high contrast, thin thickness, wide viewing Angle, fast reaction speed, and can be manufactured on the flexible substrate, which is the representative of a new generation of flat display technology, and has become an important development direction and one of the most promising technologies in the field of flat panel display, and is respected by the industry. At present, the main innovation of flexible display is the innovation of display structure and the improvement of materials, which makes the flexible display screen thinner and more durable, and improves the degree of bending, so that the screen can present a good display effect even if it is bent. [6]

2.2.2. Flexible sensor technology

Traditional rigid or flexible sensors are difficult to accurately sense the contact interaction force and its dynamic distribution information between contact interfaces. With the development of flexible electronics, flexible sensing technology has become a new intelligent interaction technology. It plays a very important role in sensing the contact interaction force between the flexible contact interface, the curved surface and the irregular shape contact interface and the dynamic distribution information. According to the type of substrate material, the flexible strain sensor is mainly divided into elastomer based flexible strain sensor, paper based flexible strain sensor, fabric based flexible strain sensor and gel based flexible strain sensor. [7]

(1) Elastomeric flexible strain sensor

Elastomer substrates with good tensile properties, such as polydimethylsiloxane (PDMS), polyurethane (PU) sponges and silicone rubber, can improve the performance of elastomer based flexible strain sensors. The conductive filler is added to the flexible substrate by dipping, transferring, spraying and printing. Elastomer substrate with high ductility, excellent adhesion and mechanical properties has been widely used in the preparation of flexible strain sensors. However, elastomer based flexible strain sensors have problems of low sensitivity and low conductivity. Introducing conductive fillers into the cross-linked network of elastomer substrate can make up for these defects. A flexible sensor with high electrical conductivity and strong tensile property is prepared. [8]

(2) Paper-based flexible strain sensor

Paper based materials are usually prepared by electrospinning technology, surface coating technology and self-assembly technology. Paper-based flexible strain sensors have attracted much attention in flexible sensors because of their good degradability, high permeability, low cost and scalable production, but the strong water absorption of paper limits its application in strain sensors. Guan et al. Developed a paper-based wearable sensor with high permeability, degradability, and low cost through continuous dip coating, using MXene to enhance the detection performance of the composite material, while sizing agent (PMS) increases the hydrophobicity. This work provides a direction for developing practical and comfortable paper-based wearable sensors and improving the application of sensors in human motion monitoring and other fields.

(3) Fabric based flexible strain sensor

The fabric base flexible strain sensor has the characteristics of good flexibility and free bending, which can make the clothing obtain intelligence while maintaining its original comfortable performance. The flexible strain sensor based on fabric can realize the seamless integration with clothing to the maximum extent, and has high application value in the field of smart textiles.

(4) Gel based flexible strain sensor

Hydrogels can be prepared by incorporating various conductive materials into a polymer network. In recent years, conductive hydrogels have been developed and applied in the field of strain sensors because of their excellent conductivity, mechanical properties, self-healing and freeze-resistance. Kim prepared an ion gel-based strain sensor by using an ion permeating conductive polymer electrode with low contact resistance [9], which further improved the sensing performance of the ion sensor. The ion gel layer was patterned into a zigzag structure, which significantly increased the resistance response during stretching. Under external deformation, the sensitivity and effective detection range of the ion sensor can be controlled. Therefore, this study provides an effective strategy for developing highly sensitive, stretchable sensing systems for electronic skin sensors and soft robots.

2.3. Flexible battery technology

With the development of wearable devices, the demand for flexible energy storage devices is also increasing, and flexible batteries are the most typical example. Flexible batteries can withstand a certain amount of deformation and stretching without degrading their own performance. The existing flexible battery manufacturing methods can only obtain planar layered flexible electrodes or batteries, which not only limits the shape of the battery, but also hinders the improvement of energy density and power density, thus limiting its own development and application.

Compared to the composition of flexible lithium-ion batteries and traditional lithium batteries, the electrode materials of flexible batteries are thinner, lighter and flexible, using integrated electrode materials, such as carbon anode and lithium metal oxide cathode; No need for adhesives, conductors, collectors and battery diaphragms; [10] The electrolyte adopts a solid substance, such as a mixture of polymer and electrolyte salts, and the packaging material adopts a polymer package into a bag type. The electrolyte material of the flexible battery comprises a solid electrolyte material of the flexible battery and a flexible polymer electrolyte material; The flexible electrode materials include carbon nanotube-based composites and graphene composites. [11]

Since the emergence of wearable electronic devices, the development of flexible battery technology has always been implemented, flexible battery is an important research and development direction, but due to other objective reasons, flexible battery technology branch has not been more in-depth research, the general research is basically around the battery life and its structural substrate. For example, how to thin film flexible batteries and capacitors, so as to meet the needs of both storage capacity and thickness reduction of flexible batteries and capacitors; How to improve flexible electronic materials to ensure the safety of flexible batteries and capacitors without the use of rigid packaging materials; How to improve the use time of flexible batteries. [12]

3. Application progress of flexible wearable devices

3.1. Health Monitoring

Most of the patients in the rehabilitation medicine department are elderly and most of them are complicated with chronic metabolic diseases, such as hypertension, diabetes, hyperlipidemia and so on. So chronic disease management is very important for rehabilitation medicine. The most effective management means is to regularly monitor the body data and adjust the medication according to the monitoring results. The most traditional way of monitoring is in the community hospital, which is time-consuming and laborious, and is not conducive to patients' long-term persistence. In recent years, with the development and application of wearable devices, the easy-to-measure physiological indicators such as blood pressure, heart rate and blood oxygen have been able to be independently detected by patients anytime and anywhere, but the current wearable devices have problems such as poor wearing comfort and few measurement indicators. The development of flexible sensors is expected to allow wearable devices to monitor more physiological data while being more comfortable and lightweight.

At present, the measurement of vital signs by wearable devices mainly relies on photoelectric and photochemical conversion. Although these devices can achieve real-time mobile measurement, they are expensive and may cause discomfort when worn for a long time, and the accuracy and sensitivity are also lacking. At present, many literatures have reported that flexible wearable devices have better performance and comfort. For example, KIM et al. [13] Made flexible sensors by adding pleated gold film on the flexible substrate. Wearable devices based on this sensor can monitor radial artery blood pressure with sensitive response, and have the potential to be used for ambulate blood pressure monitoring. On this basis, Han et al. used reduced graphene as the main material to prepare a flexible multi-mode sensor. The wearable device based on the sensor can monitor respiration and pulse at the same time, realizing functional integration and simplifying the number of wearables. [14]

Measuring equipment for home use is often bulky and uncomfortable. This often leads to an unconscious stress response and may result in false blood pressure values. A team from Joanneum Research in Austria, in collaboration with Osaka University in Japan, has developed an ultra-thin sensor that can measure various vital signs and collect energy. The research took two years and focused on developing the wearable energy-harvesting sensor patch.

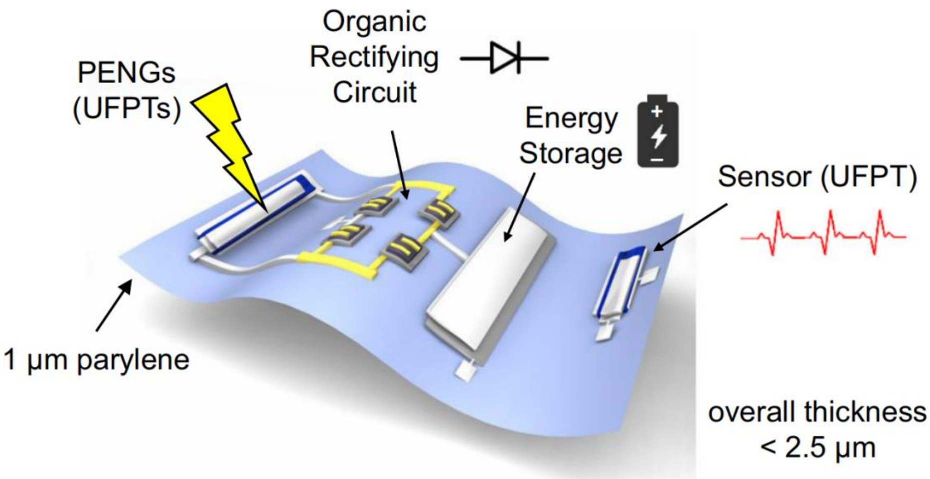

Figure 1. Ultraflexible piezoelectric energy harvesting and sensing [15]

3.2. Electronic skin for interaction

The human skin is a delicate and complex biological tissue with a keen sense of perception. It can quickly and accurately perceive various stimuli from the outside world, and transmit these information to the brain through the nervous system, so that the brain can accurately identify the location, nature and intensity of the stimulus. [16]

Electronic skin is a flexible electronic technology, combining the principles of electronics, biology, materials and other disciplines, developed electromagnetic detection device. As the largest organ in the human body, the skin has the function of blocking germs and sensing external temperature. The structure of the electronic skin is simple, can be processed into a variety of shapes, similar to clothing attached to the surface of the device. This innovative technology allows the robot to sense information such as the position, orientation and hardness of objects. The electronic skin has the ability to sense pressure and touch by covering it with numerous pressure and temperature sensors. This technology allows electronic devices to simulate the perception mechanism of human skin, making it sensitive to external stimuli, providing a more detailed and authentic touch experience for human-computer interaction, virtual reality and other fields.

Electronic skin products for interaction can achieve a tight fit with the human body, so that more accurate and stable collection of human data. These include wearable EMG collectors, made of innovative materials such as ultra-thin transparent nanomaterials and piezoelectric polymer flexible substrates, with excellent flexibility and transparency. This device can efficiently collect the human EMG signal and pass it to the processing terminal for further analysis. By fitting with human skin, such electronic skin products can not only provide a more comfortable wearing experience, but also provide advanced hardware support for the development of interactive technology. Electronic skin has a wide range of potential applications in the field of human body, can help the human body to feel some extremely weak signals, such as light and sound. By incorporating into the human body, electronic skin can extend the range of human perception and provide real-time feedback on changes in the environment, offering new possibilities for enhancing human perception and interaction. [17]

3.3. Voice Signal Collection

With the rapid rise of human-computer interaction and Internet of Things technologies, the need to develop mechanically flexible, magical wearable functional sensors is becoming more and more urgent. In this context, the emergence of new materials and devices is crucial to the design and development of technologies. Graphene is particularly compelling as a material with atomic thickness, mechanical flexibility, light weight, high electrical conductivity and transparency. Its unique large specific surface area makes it highly sensitive to the perception of external stimuli, so it is expected to be widely used in flexible sensor technology, which provides strong support for the development of wearable devices. [18]

A research and development team at Tsinghua University has successfully applied graphene to wearable intelligent artificial throat devices for the first time, creating a "graphene artificial throat" the size of a coin, providing an innovative solution to regain a new voice for people with speech disabilities. Graphene has a high sensitivity to low-frequency muscle movement, mid-frequency esophageal vibration and high-frequency acoustic information, while also having anti-noise speech perception. The graphene intelligent artificial throat developed by Professor Ren Tianling of the School of Integrated Circuits of Tsinghua University can not only emit a certain frequency of sound through thermoacoustic effect, but also identify different movements of users, such as crooning, screaming, coughing, swallowing, nodding, etc., and convert these "meaningless sounds" into meaningful sounds with controllable frequency and intensity. After several upgrades, a new generation of graphene artificial larynx successfully recognized the daily words vaguely spoken by a laryngectomy patient with an accuracy of more than 90%, basically restoring the patient's language communication ability.

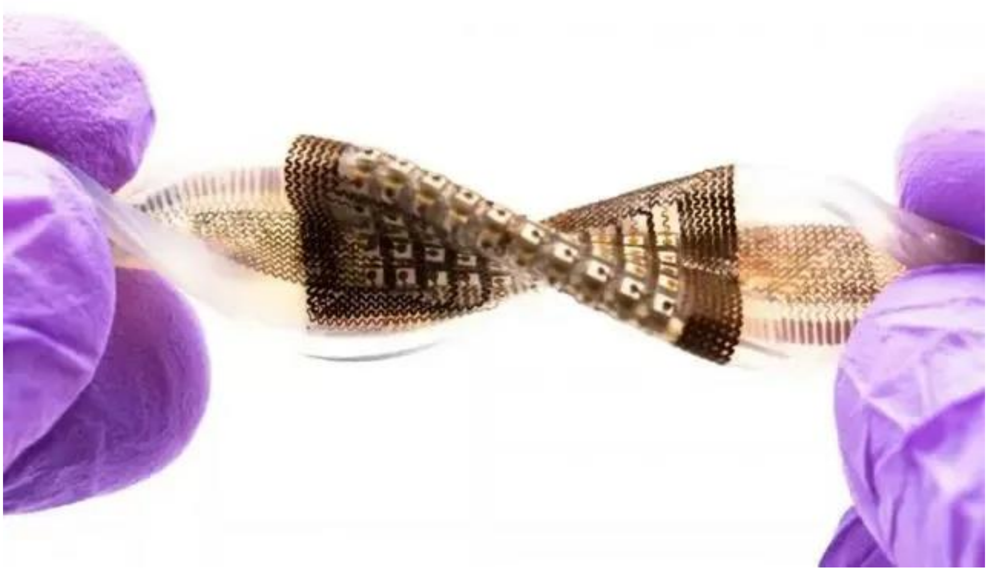

Figure 2. Electronic skin for interaction

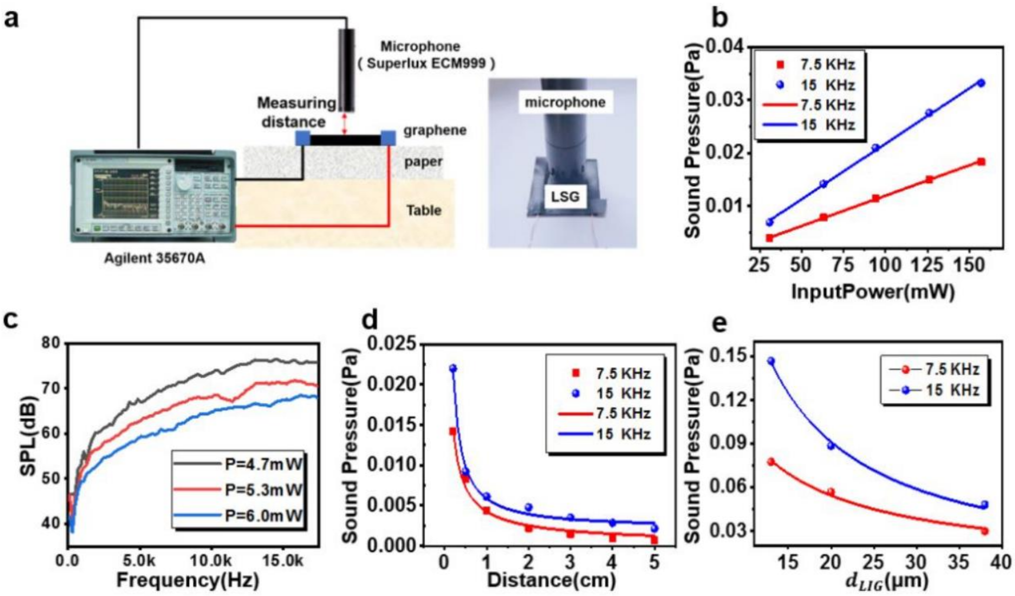

Figure 3. Phonation performance test diagram and simulation test of graphene artificial larynx [19]

4. Challenges and future prospects of flexible wearable electronics

Powerful and flexible wearable electronic devices bring broad prospects for health monitoring. The ability to design these products to withstand the changes in mechanical, temperature, and hydration conditions that humans face is critical to enabling next-generation applications. [20] A series of innovations in material development and structural innovation have contributed to the successful design of devices. Electronic devices that work stably in a variety of mechanical, temperature and hydration environments, from normal to extreme, have found widespread use in multiple aspects of wearable health monitoring. Despite these impressive achievements, challenges remain in collecting sample sources and screening analyte targets, material and structural design of components, human-machine adhesion, and adaptation to more complex extreme conditions (see figure 4). The future development prospects of flexible wearable electronic devices for these problems need to be clarified.

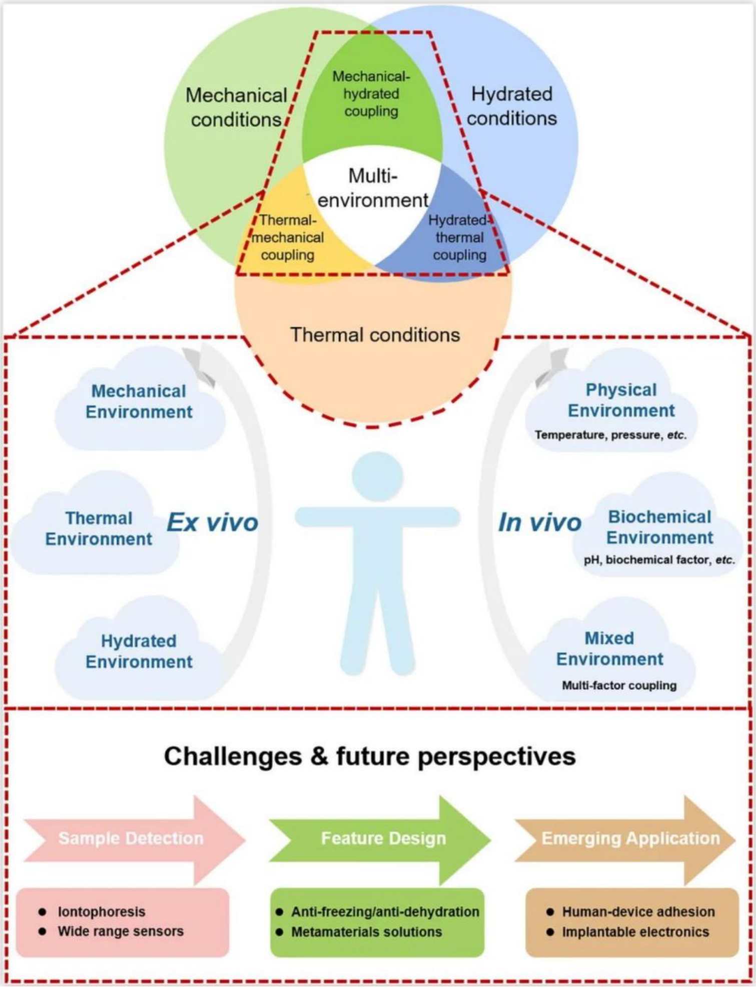

Figure 4. Challenges and future prospects of flexible wearable electronics

First, biochemical information related to bodily fluid health is difficult to obtain in some practical situations. In addition, the concentration of the analyte target may change in a changing environment.

Second, due to the limited bonding in the polymer network under freezing conditions, the cross-linking of the polymer chains is hindered, resulting in a reduction in the performance of the flexible material (such as poor self-healing properties and short service life).

Third, strong human-machine adhesion is required for flexible wearable electronics in changing environments during long-term health monitoring.

Fourth, there are challenges with flexible wearable electronics in various applications, not only in vitro, but also in vivo. Therefore, interdisciplinary research is needed in the future to integrate engineering, materials science, chemistry and biology in order to promote the advanced capabilities of implantable bioelectronics with cutting-edge scientific and technological achievements to adapt to complex microenvironments in vivo and in vitro and to provide potential solutions for clinical diagnosis and prognosis of unsolved medical problems.

Finally, in the practical application of flexible wearable electronics, there will inevitably be a mixed changing environment. Multifactor coupling can be seen in real-world scenarios, and it is considered a key future perspective outlining the development of next-generation wearable electronics.

With the development of new materials and technologies, the next generation of flexible wearable electronics is expected to achieve environmentally compatible performance. These improvements will further extend the application range of flexible wearable electronics from normal conditions to extreme conditions, thereby facilitating healthcare for people who work and live in different environments.

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