Wearable Flexible Temperature Sensors and Their Applications

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Abstract. Wearable flexible temperature sensors, as a new type of sensor technology, have the ability to monitor the surface temperature of human skin in real-time. Compared with traditional temperature sensors, wearable and flexible temperature sensors have the advantages of comfort, wearability, and strong adaptability, which can provide new solutions for medical monitoring, health monitoring, and sports training. The basic principle is based on the thermoelectric effect or thermistor effect. Specifically, temperature sensors convert thermal energy into electrical signals by measuring the temperature changes of an object. Based on the magnitude of electrical signals caused by temperature changes, the temperature of an object can be inferred. Using flexible materials as the substrate for sensors, temperature measurement is achieved by measuring the material's resistance, capacitance, or thermal conductivity. The preparation methods mainly include the selection of flexible materials, the preparation of sensing elements, and the integration of sensors. Common flexible materials include polymers, nanomaterials, and conductive fibers. This article reviews the research progress of wearable temperature sensors in recent years, including wearable optical temperature sensors, wearable temperature sensors for clinical detection, integrated wireless sensors, multi-mode force and temperature tactile sensors based on high sensitivity short channels, and other advanced temperature sensors. Finally, the challenges and future development directions of flexible wearable temperature sensors were proposed. Sensors, as one of the most important core components, will affect the functional design and future development direction of wearable devices. That's why it has been highly anticipated in recent years.

Keywords: Wearable sensors, temperature sensors, human detection.

1. Introduction

In recent years, research in biomedical engineering has tended towards highly flexible materials and electronic systems. In fact, new methods such as flexibility and epidermal electronics have opened up various avenues for studying wearable devices for monitoring different types of biological signals, and significant progress has been made in the research of high-performance passive and active materials, as well as in areas such as muscle artificial biosimulation, soft nerve implants, and intelligent or minimally invasive surgical tools [1]. Especially in remote sensing and biological detection [2]. Compared to traditional rigid silicon-based electronic technology, flexible electronic technology allows for the manufacturing of systems using polymer materials that can improve the sensitivity of machinery [3]. And it can provide highly effective assistance to researchers dedicated to challenging fields such as biomedical engineering, as these areas typically require high sensitivity and appropriate spatial resolution, such as electronic skin systems, which refer to a series of devices on the surface of the skin that simulate the function of human skin by converting various parameters and temperature sensors for flexible wearable and electronic skin applications [4]. Especially important in the touch field, as it requires highly flexible machinery, force/pressure, and temperature sensors, some interesting methods and solutions have emerged [5, 6].

2. Research and Development of Temperature Sensors

Temperature sensors are important sensors widely used in industries, healthcare, environmental monitoring, and other fields. In recent years, A wearable optical temperature sensor is made of dual wavelength (530/650nm) emitting material Li_2ZnSiO_4 excited by manganese ion manganese ion superexchange interaction has been developed. Figure 1a shows that compound Li_2ZnSiO_4 has a monoclinic structure. The Mn K edge X-ray absorption near-edge spectral spectra $Li_2Zn_{0.95}SiO_{4:0.05}Mn_{2+}$ and $Li_2Zn_{0.85}SiO_{4:\,0.15}Mn_{2+}$ are more similar to MnO than Mn_2O_3 or MnO_2 (see Figure 1b). This observation indicates that the valence state of Mn in these samples is +2, which is consistent with the synthesis conditions of the reducing atmosphere in these samples.

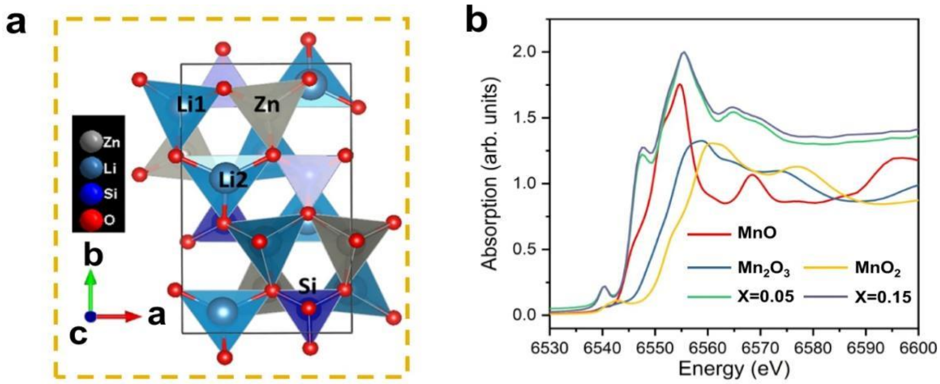

Figure 1. Structural analyses of Mn doping in Li2ZnSiO4. (a) The Crystal Structure of Li2ZnSiO4. (b) spectrum [1]

Mn2+ is achieved by easily increasing the concentration of Mn2+, where the two emission bands show different emission related behaviors but have very similar excitation spectra. A wearable optical temperature sensor has been developed with combining Li2ZnSiO4: Mn2+ in stretchable elastomer based optical fibers, which can provide wavelength thermal emission, achieve stable temperature sensing, and have good sensitivity and repeatability [7]. Dual wavelength emitting materials have calibration function, providing fluorescence intensity ratio technology for various applications, which has attracted increasing research interest [8]. Especially for temperature sensors made using the first technology [9]. The sensing platform for this flexible optical sensing fiber and compact all fiber device is shown in Figure 2.

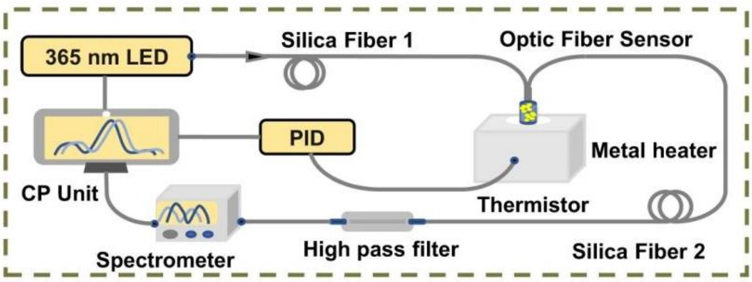

Figure 2. Sensor schematic diagram. Control and processing unit [9]

Their unique advantages, such as no need for contact, fast detection speed, easy portability, resistance to electromagnetic interference, and resistance to harsh environments, make them more widely used than traditional thermometers [10] Another research progress indicates that wearable masks integrated with this stretchable fiber sensor have been proven to detect physiological thermal changes, demonstrating enormous potential as wearable health monitors [11]. In addition, the mask can be fixed to the sensor, which can detect the corresponding temperature changes of exhaled and inhaled air due to its position near the lips (Figure 3a), indicating the application of the sensor in measuring body temperature. The temperature response of fiber optic sensors and in-situ placed thermistors in metal heaters was tested, as shown in Figure 3b.

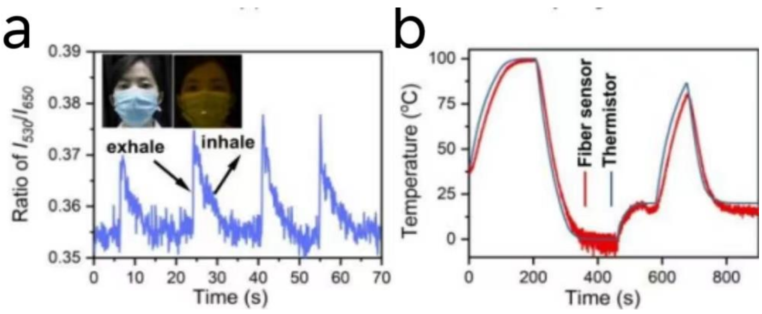

Figure 3. Performance testing [1]. (a) Monitoring the temperature change of the exhale and inhale with time by using the as-fabricated optical sensor. (b) Tracking the response time of a commercial thermistor and the fabricated optical fibre sensor [11]

However, finding more cost-effective dual wave emission materials remains a challenge. In recent years, the implementation of dual wave emission often involves doping rare earth ions or transition metal ions [12]. Temperature sensors with good absolute temperature sensitivity can be manufactured using this material; these sensors usually have lower relative temperature sensitivity, which affects the stability of related temperature sensors [13]. Therefore, it is urgent to design suitable dual wave emission materials for stable temperature sensors. There is also an integrated wireless sensor that can be implanted simultaneously in the heart or blood vessels for real-time measurement of pressure, flow, and temperature. This sensor is remotely controlled through a Bluetooth low-energy system that is implanted subcutaneously and wirelessly driven on a chip. This sensor can be transported through minimally invasive catheterization surgery or installed on passive medical devices such as stents. This device can effectively assist doctors in monitoring blood flow, blood pressure, and temperature. Without the need for batteries and wireless devices, such as devices with integrated flow, pressure, and temperature sensing functions, it provides the possibility for continuous monitoring of patient hemodynamics research [14]. For example, a highly repetitive, concise, and effective method is used to prepare a flexible multi peak transmission temperature and force sensor based on organic transistors, which is combined with a thermal/piezoelectric polymer polyvinylidene fluoride (PVdf). This method utilizes low resolution and scalability to obtain submicron vertical channel OMOFT with high sensitivity and linear response to various temperature and force changes, while reducing its overall size [14]. Developed by LEE and his colleagues, they studied various sensors based on organic multimodal transport transistors, including infrared, strain, temperature, and pressure sensors [15]. The main component is high crystalline copolymer P (VDF-TIFE), which is directly integrated on OFET as a multifunctional gate dielectric layer with piezoelectric and pyroelectric properties [16].

3. The Application of Wearable Flexible Temperature Sensors

Wearable flexible temperature sensors have broad application prospects in fields such as medical monitoring, health monitoring, and exercise training. They can monitor patient temperature changes in real time, provide accurate data support for medical personnel, help detect and treat diseases early, and also monitor skin temperature changes in the human body, providing important data for health management. By monitoring temperature changes, an evaluation of the human body's condition can be achieved, which helps to prevent and intervene in health problems in advance. The wearable temperature sensors used for clinical testing have recently made significant technological progress, and they are expected to help medical researchers make significant contributions in research projects such as healthcare. In recent years, a wearable, wireless, continuous, multi-point sensor has been designed to monitor tissue circulation [16]. This system helps doctors evaluate by measuring pulse waves, skin color, and tissue temperature. Information is transmitted to the tablet via Bluetooth and can be displayed and analyzed on the tablet. It creates a smartphone/tablet application for storing and visualizing data collected by sensors to improve device versatility. This will enable some doctors to receive alerts and notifications when suspecting a patient's temperature issue. In addition, they can access data at any time by installing applications on their own devices. Flexibility supports the operability of sensors. As shown in Figure 4a, this unit consists of three sensors that continuously monitor pulse waveform, tissue color, and tissue temperature. This probe is a unit array with four channels and can be configured according to the size of the transplant. Figure 4b shows the adjustment of the sensor. This sensor has sufficient flexibility to adapt to different curved surfaces of the body. And use Fast Fourier Transform (FFT) to analyze pulse wave signals and estimate real-time fluctuations in body temperature changes. Analyze color and temperature signals through curve fitting to estimate the changes in these parameters when the cycle is affected, and independently calculate the risk rate using algorithms.

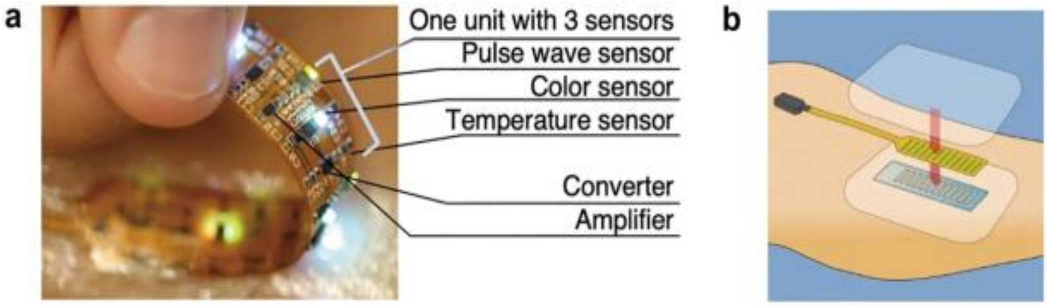

Figure 4. System overview [16]. (a) Details of sensor detectors [16, 17]. This probe is a four channel unit array that can be configured according to the size of the transplant. (b) Adjust the sensor

4. Conclusion

This article aims to summarize the research conducted this year on wearable flexible temperature sensors for real-time monitoring of human body temperature. By designing and preparing flexible sensors, utilizing micro nano technology and material engineering methods, a wearable flexible temperature sensor with high sensitivity and stability has been successfully developed. It can be observed that the sensor has excellent performance. Firstly, the sensor has a very fast response time and can accurately detect changes in human body temperature in real-time. Secondly, sensors have high temperature measurement accuracy and small errors. However, as an advanced temperature sensor, wearable flexible temperature sensors still face some challenges that need to be addressed. Firstly, accuracy and stability. Wearable flexible temperature sensors need to have high precision and stability to ensure the accuracy of measurement results. Secondly, further research is needed in material selection, sensor component design, and sensor integration. Next is comfort and wearability, and wearable flexible temperature sensors need to have good comfort and wear resistance in order to be worn for a long time and continuously monitored. Finally, data processing and privacy protection require effective processing and analysis of the large amount of data generated by wearable flexible temperature sensors. At the same time, it is also necessary to protect user privacy, use and store data reasonably. Therefore, as a new type of sensor technology, wearable flexible temperature sensors have the ability to monitor human body temperature in real-time on the surface of the skin, and can monitor changes in human body temperature in real time. However, future research should focus on improving accuracy and stability, comfort and wearability to meet the needs of different application scenarios, as well as solutions for data processing and privacy protection. At the same time, it is necessary to strengthen cooperation with the medical, health, and sports fields, and promote and apply wearable flexible temperature sensors in practical applications. It can be expanded from the following aspects. Firstly, this sensor can be combined with other wearable devices, such as smart bracelets, smart clothing, etc., to achieve more comprehensive health monitoring and data collection. Secondly, it is possible to further explore the application areas of sensors, such as medical diagnosis, sports training, etc., to meet the needs of different fields. Finally, further research can be conducted on the preparation process and materials of sensors to improve their performance and reliability.

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