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Research progress of wearable temperature sensor based on electronic skin

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Abstract. The rapid development of science and technology has led to an increasing demand for new sensors, among which wearable temperature sensors based on electronic skin have played a particularly important role in artificial limbs and intelligent robots. This paper introduces the physical structure and working principle of wearable temperature sensor based on electronic skin. In this part, it focuses on two models of electrical signal changes caused by temperature changes. At the same time, the circuit structure and signal transmission and signal processing mode are also mentioned. This paper also introduces the characteristics of the material used in order to achieve direct contact with the human body. Some researchers' work is also introduced, including accurate and linear reflection of temperature changes, fast response, durable use, and resistance to external interference, etc. The researchers' research on the realization of the above functions is mentioned in the paper. Finally, the practical application and future prospect of this type of temperature sensor are introduced. In addition, some more mature technologies for the preparation of such wearable temperature sensors based on electronic skin are also described in this paper.

Keywords: Temperature, Biosensor, Thermal Resistance, Electronic Skin.

1. Introduction

With the development of science and technology, more and more various types of sensors have entered the public eye, and wearable biosensors are one of the most popular types.

Compared with traditional analytical methods, the new biosensor detection device is smaller and more targeted, It is easy to realization of automated analyzing and detecting, detecting results with high precision, highly sensitive, quick in detecting and analyzing, low detecting cost, and continuous on-line detection [1].

Biosensors are so powerful that they can be useful in many fields. For example, in order to help humans or replace humans to perform some dangerous, high-risk tasks (such as handling nuclear pollutants), intelligent robots are made, in order to adapt to the environment and respond to changes in the outside world, they need to be similar to human perception, biosensors can play a role in order to achieve the above functions. Similarly, for some people with physical defects, out of humanitarian considerations, they need to live like normal people, so some auxiliary devices are developed, such as artificial limbs, people equipped with artificial limbs need the same perception and control ability as ordinary people, biosensors can help realize these functions.

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The various types of devices mentioned above need to have the ability to accurately sense temperature. Temperature is an important indicator of the external environment, is also an important indicator of the state of the human body, people can judge whether it is suitable for some work at this time through the temperature, for the biosensor used in the human body, temperature measurement is more important. Body temperature can reflect many basic health conditions of the human body, such as the physiological activity of some tissues, organs and systems in the body, emotional changes and basic metabolism. Therefore, researchers have conducted a lot of exploration and research in order to design more advanced wearable temperature sensors, and they believe that temperature sensors based on electronic skin can play a good role. Therefore, they investigated many aspects of the design of the wearable temperature sensor based on the electronic skin, including the way how the electrical signal is generated by its temperature change, the way how the signal is transmitted and processed, and the appropriate materials used. In fact, some progress has been made in the above researches, which are briefly introduced in this paper.

2. Physical structure and working principle

When creating temperature-sensitive conductive Composites, conductive fillers travel through a soft polymer matrix to create a Complicated conducting net. The conductivity of this network is greatly influenced by the load level and uniform dispersion of the conductive fillings. The total Resistivity reduces gradually as filler content increases until it reaches the Seepage theory loading threshold, when it suddenly drops by many orders of Magnitude and then stabilizes. The electrical behavior of the conductive composite Material is mostly determined by the microstructure of the conductive network as temperature changes. The resistivity of the conducting compound Changes significantly with temperature because the microstructure of the Conductive network is altered by the difference in the coefficient of thermal Expansion of the matrix and filling. The distance between the two Adjacent fillers grows when the temperature rises as a result of the polymer Matrix's volume expansion, which raises resistance. The resistance of the Composite in this temperature range can alter by orders of magnitude as the Temperature rises, up until the polymer volume expansion hits the maximum melting point [2].

The reason why the resistance of composite Conductive materials changes has numerous causes. One example is that, as shown in figure 1, the CNFs (Carbon Nanofibers) that have been manufactured are mainly composed of disordered layered Graphite structure. While the lone electrons not involved in hybridization Overlap each other to form a delocalized bond, each carbon atom hybridizes with Three adjacent carbon atoms in sp2 mode to form a covalent bond. In the plane of in a carbon atom, those delocalized electrons can go around freely. Some of the Atom's previously bound electrons gain energy as the temperature increases, becoming free electrons that can move from the valence band to the conduction Band. The basic principle of temperature measurement in the sensing model is that the CNFs become more concentrated and mobile, Reduction of resistance [3].

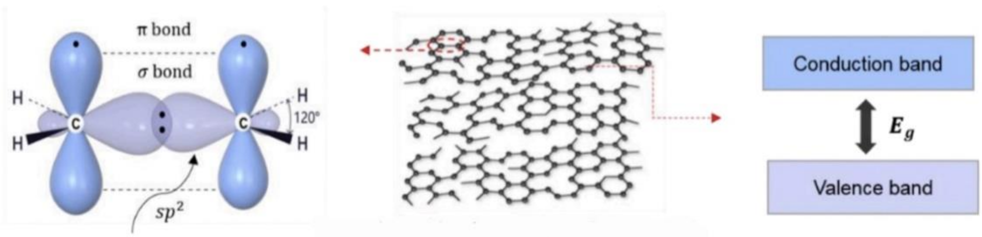

Figure 1. The structure of the layered graphite [3].

Several theories of conductive mechanisms have been proposed to reveal the thermo-mechanical and electromechanical effects of thermosensitive conductive composites, such as percolation, conduction pathway, hopping transport mechanism, tunnel effect and electric field emission theories.

What is discussed above can be regarded as the working principle of the thermal resistance temperature sensor. As a matter of fact, in addition to thermal resistance temperature sensors, common temperature sensors also include thermocouple. Fig 2 illustrates the basic mode of thermocouple temperature sensor.

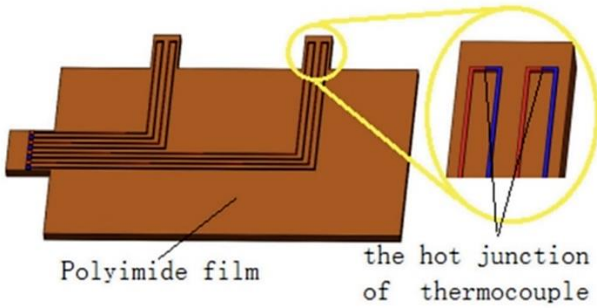

Figure 2. Physical mode of the flexible thermocouple file sensor [4].

Briefly, the working principle of thermocouple is based on a combination of the Seeback Effect and Heat Transfer Rule. Two different metal wires connected to two Nodes form a thermocouple. One of the nodes acts as a thermal junction, and the Temperature around it changes as the external environment changes. The free It acts as a cold junction and the temperature around it remains constant. Therefore, the temperature difference between the hot and cold junctions leads to create a heat potential. To explain this theory However, it may be assumed that the cold end and the hot end carrier Concentration are the same at the beginning, and with the change of Temperature, the average motion speed of the hot end carrier increases, the Energy increases, so does the chemical potential. As a result, carriers Move toward the cold end and accumulate, and these carriers create an electric Field that prevents other carriers from continuing to move toward the cold end, and eventually the two reach equilibrium, with the potential difference between The cold and hot ends called the Seeback voltage. Here's a simple explanation For the Seeback effect.

Thermocouple temperature sensors have some disadvantages in terms of accuracy and stability of temperature measurement. The "non-uniform potential" of thermocouple will directly affect the temperature result. The homogeneity of a thermocouple refers to the degree of homogeneity of the pole material of a thermocouple. Suppose the material of the two thermal electrodes is not uniform, and the thermal electrode is in a temperature gradient field. In that case, the thermocouple will produce an attached heating potential, that is, the "non-uniform potential", which will affect the total thermoelectric potential of the thermocouple circuit. Therefore, the existence of "non-uniform potential" will cause the thermoelectric characteristics of the thermocouple to change, thus reducing the temperature measurement accuracy. The contamination, oxidation reaction, reduction reaction, high temperature reaction and embrittlement reaction of the thermocouple thermal electrode will cause the measurement error of thermocouple temperature sensor [5].

Based on the above demonstration, it is generally believed that thermal resistance temperature sensors are more suitable.

Since the temperature of the human body is continuously changing, the resistance value of the thermistor will also change, if there is a voltage source in the circuit, the current generated will change with the resistance, the change of the electrical signal can reflect the temperature change, which is the basic principle of the thermal resistance temperature sensor can detect the temperature.

In order to allow users to easily understand the temperature situation, the man-machine display interface can be designed, which is based on the Bluetooth module, through which the current signal of the temperature sensor can be sorted out and transmitted to the hardware of the remote terminal. In fact, the Bluetooth module also includes ADC(Analog-to-Digital Converter), which can convert the Analog signal collected into a Digital signal for easy transmission. Fig 3 shows the circuit structure of this temperature sensor.

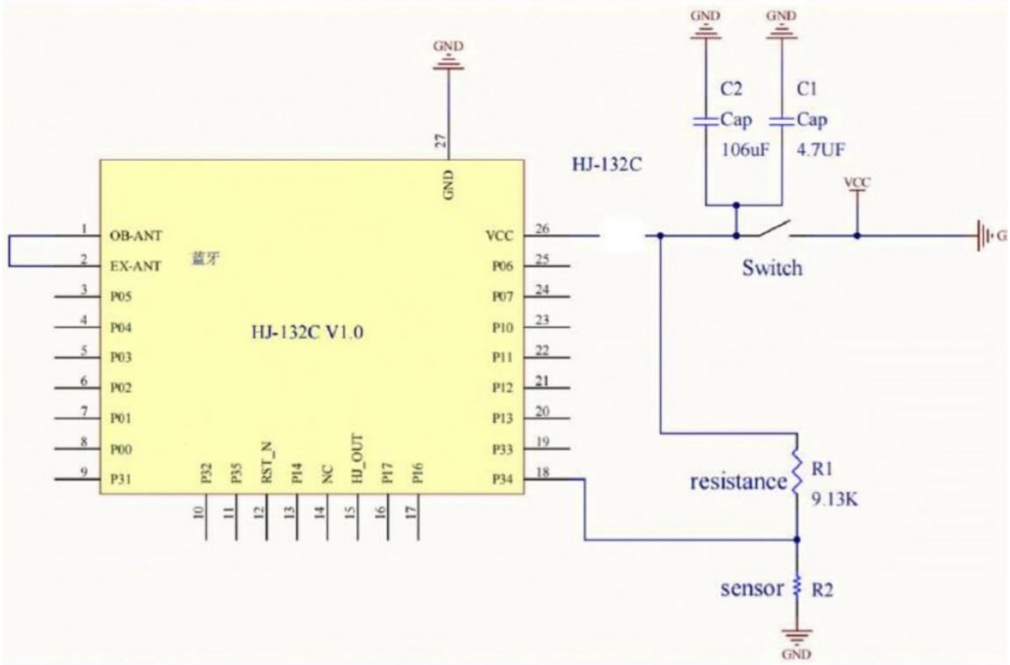

Figure 3. The circuit principle design of the wearable flexible temperature sensor [6].

The data of the wearable flexible temperature sensor system is initially generated by the flexible temperature sensor sensing the body temperature information, and finally displayed in the display interface, and the data is transmitted level by level. To summarize this roughly, it is roughly after three data transfers. The first data transfer is the ADC module on the Bluetooth module to collect the information of the flexible temperature sensor. The second data transfer is that the Bluetooth module transmits information from the flexible temperature sensor to the terminal hardware. The third data transmission is that the terminal hardware transmits information to the terminal software, that is, the display interface of the upper computer.

As mentioned above, the human-machine display interface receives the electrical signal transmitted by the terminal hardware, even if it is converted into a change in the sensor thermistor resistance value through the background, but this is still not the change in human body temperature that we need to measure, so the human-machine display interface needs to be told what kind of resistance change corresponds to what kind of temperature value, then we need to provide a benchmark for the human-machine display interface. It is convenient for it to determine the relationship between the change of resistance value and the change of temperature. The solution is to conduct many experiments, use the data obtained from these experiments to fit a functional curve, and use this fitted curve as the above reference.

Due to the inevitable data loss and error in data transmission, there will always be some accidental data in the fitting process, and these data fluctuate greatly, which will affect the accuracy and credibility of the fitting. To deal with this problem, filtering algorithms filter through these random data [6].

3. Material

The material for a wearable temperature sensor based on electronic skin is also important. This sensor is directly worn on the body, for reasons such as portability, traditional bulky batteries and some materials will no longer be suitable.

Traditional electronics typically use traditional materials such as silicon and metal, which have a surface elastic modulus of 140 to 600kPa, and are so bulky that they cannot be widely used in wearable devices that require large deformation. The excellent ductility of the material allows for high temporal and spatial resolution of the contact between the device and the skin with its complex dynamic structure, making the measurement more accurate and also enhancing the signal collected from the skin interface [7].

Polymers are the most promising intrinsically stretchable materials for substrate materials because of their superior elasticity and stability, such as Polydimethilsiloxane (PDMS), PU (PU) and Ecoflex (EP). Azide cross-linking chemistry is used for semiconductor polymers to make intrinsically stretchable semiconductor polymer. The energy caused by strain can be dissipated by reversible breaking and recombining of weak hydrogen bond and electrostatic interactions in the polymer. To further improve the tensile properties of the dynamic non-covalent crosslinks of flexible polymeric chains can be added. Plasticizers and nanoconfinement effects have been shown to improve the inherent ductility of conjugated polymers and can be used to design stretchability.

Specifically, the selection of the flexible substrate in the wearable flexible temperature sensor needs to meet the following points: 1. Raw object compatibility, wearable flexible temperature sensors are mostly in direct contact with the human skin surface, so the selection of flexible substrates needs to be harmless to the human body. 2. With good flexibility and extensibility, wearable flexible temperature sensors can continuously measure human surface temperature at multiple points to better communicate with human skin [8].

Surface contact, flexible substrate needs to have a certain degree of flexibility and extensibility. 3. Manufacture of flexible devices Manufacturing involves different process steps and requires high temperatures above at least 300 ° C, therefore, excellent heat resistance performance is the key requirement of flexible substrate. The flexible substrate should also have a traditional thermistor sensor base Some characteristics of the plate include insulation, hydrophobicity, etc.

A common and practical method is as follows: The pre-cleaned Capton substrate supports the device. Horizontally, the ZnO nanowire array is the core material of the device. Manufacturing processes (deposition of digital interelectrode patterns), including lithography and electron beam evaporation processes. ZnO nanowires (length :12 μm) can pass through the electrode pair (distance :5 μm). The distance between adjacent electrode pairs is 20 μm, ensuring that all ZnO nanowires' C-axis direction is the same [9].

The above is a common process for making flexible electronic skin, which enables the electronic skin to have the characteristics of low mass and breathability, while not affecting its function.

4. Specific research work introduction

Due to the increasing demand for highly sensitive and flexible temperature sensor systems. A fully flexible NiO temperature sensor system was previously investigated using a single-step, monolithic laser reduction sintering (m-LRS). Figure 4 shows the resistance of three Ni Electrodes in the 25-70 ° C temperature range. The antenna Ni electrode produced by m-LRS method has the same thermal resistance ratio (TCR) in comparison to standard Ni. The TCR properties of Ni-NiO-Ni structure is remarkably high as − 9.2% ° C − 1. Over the entire measurement range (25-70 ° C), the material constant of the resulting thermistor is calculated to be 7350 K. In particular, very high values of 8162 K are obtained at ambient temperature. Their results are believed to be the highest sensitivity ever reported for a thermistor [10].

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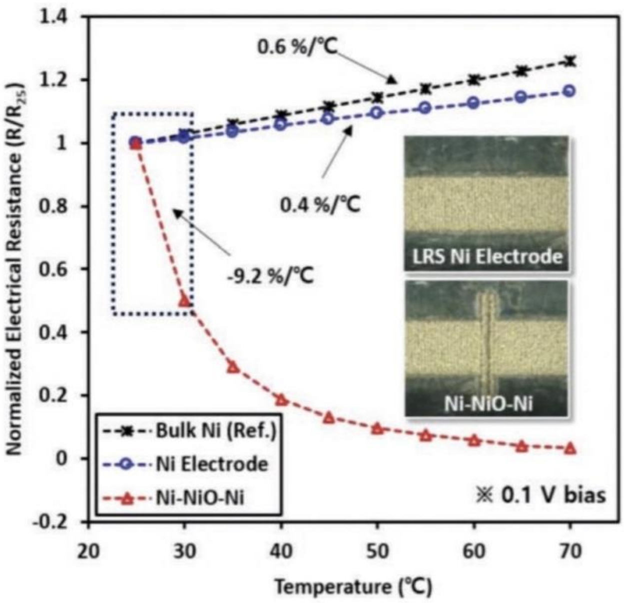

Figure 4. Test results of electrodes of different materials [10].

At the same time, a good wearable temperature sensor needs to be able to accurately and sensitively reflect temperature changes, but also needs to be able to quickly respond to temperature changes, but also needs to be able to remain stable after multiple measurements.

In order to achieve the above functions, researchers have conducted a number of tests on the wearable temperature sensor based on electronic skin prepared by it. To test its linearity and stability, they heated the sensor gradiently, The results show that in the measuring range of 20~100 °C, the experimental data points basically coincide with the fitting line, the linearity error is 1.5%, and the sensitivity is 3.2×10 -3 °C-1; To test its response time, they measured the temperature gradient signal on the sensor by adding drops of water, The result is that the nickel film is only separated from the water drop by a 25 μm thick PI film, so the response time is only 1.5 s. After the droplet is gradually cooled to room temperature by air, the relative change in resistance is also reduced to 1.5×10-2; To test its cyclic stability, they cycled the sensor repeatedly on a hot table, The result shows that the resistance varies from 623.2 to 717.8Ω at the initial stage. After cyclic temperature loading, the resistance value corresponding to 40 °C increases by 0.85Ω and the drift rate is 0.14% Finally, they got a wearable temperature sensor that can better meet the above three requirements [11].

Another important factor to measure the performance of a wearable temperature sensor is its ability to resist external interference, and strain is a common external interference, which can not be ignored. For this reason, researchers designed and tested a sensor, fixed on a ring with different curvations (corresponding to different degrees of strain). At 20~50°C, the designed flexible temperature sensor is installed on a ring with a curvature of 0~0.5. The bending degree of the flexible temperature sensor can be precisely controlled by rings with different curvatures, and then the strain can be quantitatively controlled. The output resistance values of 5 groups of sensors were compared with the output resistance of horizontally placed flexible temperature sensors to verify the ability of sensors to resist strain interference. The average value of each group of sensors recorded 100 times of data showed that the flexible temperature sensor displayed consistent signal output on the surface of rings with different curvations. The result is that the biosensor they designed has better resistance to strain interference than traditional flexible temperature sensors [8].

The above is the design and research of some researchers on wearable temperature sensors, which has reference significance.

5. Practical Application

Electronic skin based biosensors can have many functions and can detect temperature, humidity, gas, strain, etc.

This wearable temperature sensor based on electronic skin has great potential in building better human–machine interaction, to exemplify, for intelligent humanoid robots, when they perform tasks such as picking up a glass of water, or performing high-risk tasks in place of humans, they need to have the same temperature perception as humans so that they can react to the temperature in a timely manner to avoid being damaged by extreme heat or cold.

In addition, when building an artificial limb, we need to consider its ability to sense temperature, and it needs to be able to accurately detect temperature, so that the disabled person using it can perform like a normal person.

For wearable temperature sensors, their function is even more important. Accurately detecting local temperature variations in real time in biological tissues, without considering large deformations, is essential for understanding the thermal principles of homeostasis, assessing complex health conditions, and further opening up possibilities for building smart healthcare and health systems [2].

At the same time, as an important indicator of human health, body temperature carries psychological information of health and can reflect the health status of the human body, such as physiological movement, emotion, and metabolism. It can also be used to determine wound healing, wound inflammation status, and for the early diagnosis of cardiovascular and pulmonary diseases. Taking the metabolic condition of body temperature response as an example, if the body temperature drops by 1 Celsius, activates a core of the body, causing primary metabolism to fall by six percent. 7%. The body's metabolism is accelerated as the outside temperature falls. The production of more hormones (for example, thyroid, adrenal, and so on), allowing the body to generate more energy. When the outside temperature rises, the opposite is true. The body adjusts its metabolism to maintain a normal body temperature. Therefore, body temperature can reflect whether the metabolism of the body is healthy, and this can assist in assessing physical health [12].

A variety of wearable temperature sensors have been developed at present, However, since humans wear this kind of sensor and it will touch people's skin directly, a lot of questions cannot be neglected, Such as some sensors are too heavy, some sensors will always attract people's attention to it, in addition, after wearing this sensor for a long time, people can feel itchy and humid heat because of air permeability problems. Because the materials used to make these temperature sensors are lightweight, breathable, and have excellent sensing capabilities, they can meet all these situations' needs, whether for humanoid, robotic and artificial limbs, or directly for real People. In short, the Wearable Temperature Sensor Based on Flexible Electronic Skin can precisely detect temperature. With excellent sensing ability, it can realize multiple functions such as environmental temperature detection and Expiration Temperature Monitoring Electronic skin can simulate the multi-dimensional information and perception function of human skin, and has been widely concerned in human-computer interaction, intelligent prosthetics, Intelligent robots, health monitoring, medical diagnosis and other aspects, so it has a wide range of uses [3].

6. Conclusion

Wearable temperature sensors based on electronic skin play an important role in the realization of human-computer interaction, engineering perception and humanoid perception due to their powerful functions. Since body temperature is an important physiological index of the human body, accurate measurement of body temperature is the main function of this kind of biosensor. In order to improve its performance and usability as much as possible, researchers have carried out many experiments, their purpose is to make their designed sensor can accurately and linearly measure temperature, but also to be able to respond quickly to temperature changes, while to ensure its durability but also improve its cycle stability, in order to adapt to different environments, but also to ensure that its measurement accuracy is not affected by external conditions. In addition, in order to make users more comfortable, they also need to explore lightweight, flexible and malleable materials, while not harmful

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to the human body and can ensure the full realization of its function. In order to achieve the above goals, they went deep into the principle level, understood the reasons why temperature causes changes in electrical signals, and analyzed the advantages and disadvantages of thermal resistance and thermocouple temperature sensors. For the electrical signal, they have taken a suitable way to collect, transmit and filter the data so that it can accurately reflect the temperature change, and for this, they have designed elaborate circuits. For the choice of materials, they start from the micro scale, using nano-components to manufacture flexible substrates, making their sensors portable, lightweight, flexible and malleable, and fully functional. In order to achieve the desired goal, they conducted many experiments on the designed biosensor. In the future, researchers should be committed to exploring more advanced materials, which will greatly improve the water resistance, air permeability, and ductility, in addition, more sophisticated circuit structures and components will make temperature measurement more accurate, and measurement errors caused by external conditions will be further reduced.

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