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Review

# Research progress on wearable temperature sensors for human temperature monitoring based on biomechanics

**Xize Wang[1,2], Yaqiong Wu[1,2], Junzheng Yang[3], Yanhong Wu[1,2], Nan Shi[1,2,*], Haibin Wang[1,2,*]**

[1] College of Chemistry and Chemical Engineering, North University of China, Taiyuan 030051, China
[2] Dezhou Institute of Industrial Technology, North University of China, Dezhou 253000, China
[3] Guangdong nephrotic drug Engineering Technology Research Center, Institute of Consun Co. for Chinese Medicine in Kidney Diseases, Guangzhou 510530, China
*** Corresponding author:** Nan Shi, shinan115@nuc.edu.cn; Haibin Wang, whaibin@nuc.edu.cn

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**Abstract:** With the continuous development of science and technology, flexible wearable electronic products are flourishing in many fields, especially in the areas of health monitoring and medical improvement. In the realm of biomechanics, the human body is a complex mechanical system, and monitoring physiological parameters like body temperature has a unique connection to biomechanical research. Body temperature, as one of the most important physiological parameters of the human body, is not only important for health monitoring but also has implications in understanding the body's mechanical-thermal balance. Biomechanics studies how forces and mechanical stress affect the body's functions, and temperature can influence the mechanical properties of biological tissues. Researchers have extensively studied the various properties of wearable flexible temperature sensors, such as high precision, good biocompatibility, flexibility, agility, light weight, and high sensitivity, continuously improving real-time and sensitive detection of temperature in various parts of the human body. This article reviews the research progress of high-sensitivity flexible temperature sensors for monitoring body temperature changes. Firstly, the commonly used active materials for flexible temperature sensors were summarized. Secondly, the imaging manufacturing method and process of flexible temperature sensors were introduced. Then, the performance of flexible temperature sensing was comprehensively discussed, including temperature measurement range, sensitivity, response time, and temperature resolution. Additionally, the article explores the potential of flexible sensors in biomechanical applications, such as monitoring joint angles, muscle activation patterns, and pressure distribution during movement. Finally, the challenges faced by flexible temperature sensors in the future were summarized and discussed. By combining temperature sensing with biomechanical data collection, this study highlights the potential of flexible wearable technologies to revolutionize health monitoring and motion analysis.

**Keywords:** flexible wearable electronics; biomechanics; flexible temperature sensor; active materials; sensitivity

## 1. Introduction

Temperature is a fundamental physical parameter that plays a crucial role in all aspects of life, including health monitoring [1], artificial electronic skin [2], robotics, and the Internet of Things (IoT) [3]. Among various physiological parameters of the human body, body temperature is of great significance [4]. Many complex chemical reactions are involved in human life activities, most of which require the participation of enzymes [5]. Enzyme activity is affected by temperature and can be disrupted when body temperature deviates from the normal range [6]. Most temperature sensors operate based on the principle of detecting physical changes caused by temperature variations. Among them, resistive temperature sensors are the most commonly used due to their high response speed, precision, and stability [7]. In addition, thermistors [8], infrared temperature sensors [9], and mercury thermometers [10] have also been widely applied. However, these sensors have inherent limitations, such as inflexibility, large size, and fragility, as they are primarily made of ceramics, conventional metals, and metal oxides. These characteristics restrict their application, especially when attaching them to curved surfaces of objects, making measurement more challenging. In recent years, the demand for simple operation, flexibility, softness, and biocompatibility has been increasing. At the same time, temperature measurement requires high accuracy in many applications. As a result, the research on flexible temperature sensors has been rapidly evolving for body temperature monitoring, leading to numerous innovative breakthroughs [11].

Flexible wearable temperature sensors [12] mainly utilize thermosensitive materials that generate electrical signal variations in response to temperature changes, enabling real-time temperature monitoring. By leveraging the properties of flexible substrates, these sensors can adhere closely to the skin for enhanced functionality. As a result, wearable, flexible, lightweight, and highly sensitive patterned temperature sensors have become a research hotspot in recent years [13]. This review focuses on the selection of thermosensitive materials and novel manufacturing technologies for large-area production of flexible temperature sensors, aiming to achieve both high sensitivity and scalable fabrication.

The development of flexible temperature sensors is moving toward wearability, high sensitivity, portability, large-area applicability, precision, and real-time monitoring. This review summarizes recent research advancements in high-sensitivity flexible temperature sensors for human body temperature monitoring, covering thermosensitive materials, manufacturing strategies, and fundamental performance metrics. The first section discusses the materials used in flexible temperature sensors. The second section highlights recent literature on flexible temperature sensors, reviewing patterned fabrication methods and showcasing representative manufacturing processes. The third section presents key performance parameters of temperature sensors. Finally, we discuss the potential challenges and prospects of high-sensitivity flexible temperature sensors for human body temperature monitoring.

## 2. Material types

Flexible resistive temperature sensors typically utilize the inherent properties of thermosensitive materials, where the resistance of the material changes with temperature variations. These sensors are generally fabricated by depositing thermosensitive thin films onto flexible substrates. Common thermosensitive materials include carbon-based materials [14], metals [15], metal oxides [16], and conductive polymers [17].

### 2.1. Metal materials

Metal materials are generally conductive and are commonly used as electrodes and wiring for sensors. Metals such as gold (Au) [8,10], silver (Ag) [18], copper (Cu)

[19], platinum (Pt) [20], nickel (Ni) [21], and aluminum (Al) [22] are frequently utilized in flexible temperature sensors. Compared to traditional rigid metal temperature sensors, flexible metal temperature sensors offer superior mechanical flexibility, allowing them to conform to highly curved surfaces. This makes them particularly suitable for detecting minute temperature variations and localized temperature distributions.

In typical temperature sensors, platinum and gold are the most commonly used thermosensitive materials. Bin et al. proposed using microelectromechanical systems (MEMS) technology to deposit platinum as a sensing material onto a PI film through a lift-off process. After pattern formation via lamination, the sensor was used to monitor temperature variations in the range of 15 ℃–115 ℃, achieving a TCR of 0.0032 $℃^{-1}$. Although platinum is more expensive than gold, gold offers better conductivity and flexibility [23]. Feng et al. developed a sensor using the thin Cr/Au layer as the temperature-sensing element, integrated with a porous, semi-permeable membrane substrate. As shown in **Figure 1a**, this sensor exhibited excellent air permeability and superior waterproof performance. It was applied to the armpit and forearm for monitoring body temperature and skin surface temperature. Giovanni and his team investigated a temperature sensor composed of fully biodegradable magnesium material and a compostable flexible polymer, Ecoflex. The optical image of the sensing element is shown in **Figure 1b**. The sensor remained functional even under stretching and bending conditions [24]. Dankoco et al. employed silver ink to fabricate smooth and uniform silver wiring onto the film via inkjet printing, as illustrated in **Figure 1c**. This resulted in the sensor capable of measuring temperatures ranging from 10 ℃ to 70 ℃, with a sensitivity of $2.41 \times 10^3$ $℃^{-1}$ [25]. Bao et al. demonstrated a binary polymer temperature sensor filled with nickel microparticles. This sensor featured an adjustable temperature range, excellent thermal cycling stability, and an RFID wireless system, enabling wireless transmission of temperature data [21]. Ren et al. fabricate a high thermal resolution sensor based on a silver nanoparticle (NP)/pentacene thermistor integrated. The sensor covered a temperature detection range of 20 ℃–60 ℃, confirming the feasibility of using temperature-sensitive silver nanoparticle composite materials in thermistor applications [26]. Yu et al. prepared Ag NWs/PVDF temperature sensors, as shown in **Figure 1d**. The resistance of sensors is unchanged after 4000 bending cycles at a curvature radius of 3 mm, indicating excellent mechanical flexibility. The ultra-thin thickness (5 μm) allows the Ag NWs/PVDF temperature sensors to be intimately attached to human skin, guaranteeing the accuracy of the measurement [27]. Zhao et al. proposed an $Al_2O_3$@Cu NWs/PVDF composite temperature sensor. It has great potential for wearable, flexible electronics because of its extremely thin, stable properties as well as its special semi-embedded structure and the capacity to be precisely fitted to the skin [28]. Rogers et al. fabricate the sensor that relies on the TCR of the finely patterned serpentine gold wire adhered to the human epidermis for continuous and precise temperature measurement [9]. Metal and metal oxide-based flexible temperature sensors provide enhanced biocompatibility and environmental sustainability. Additionally, the integration of backend circuitry facilitates long-term and real-time temperature monitoring.

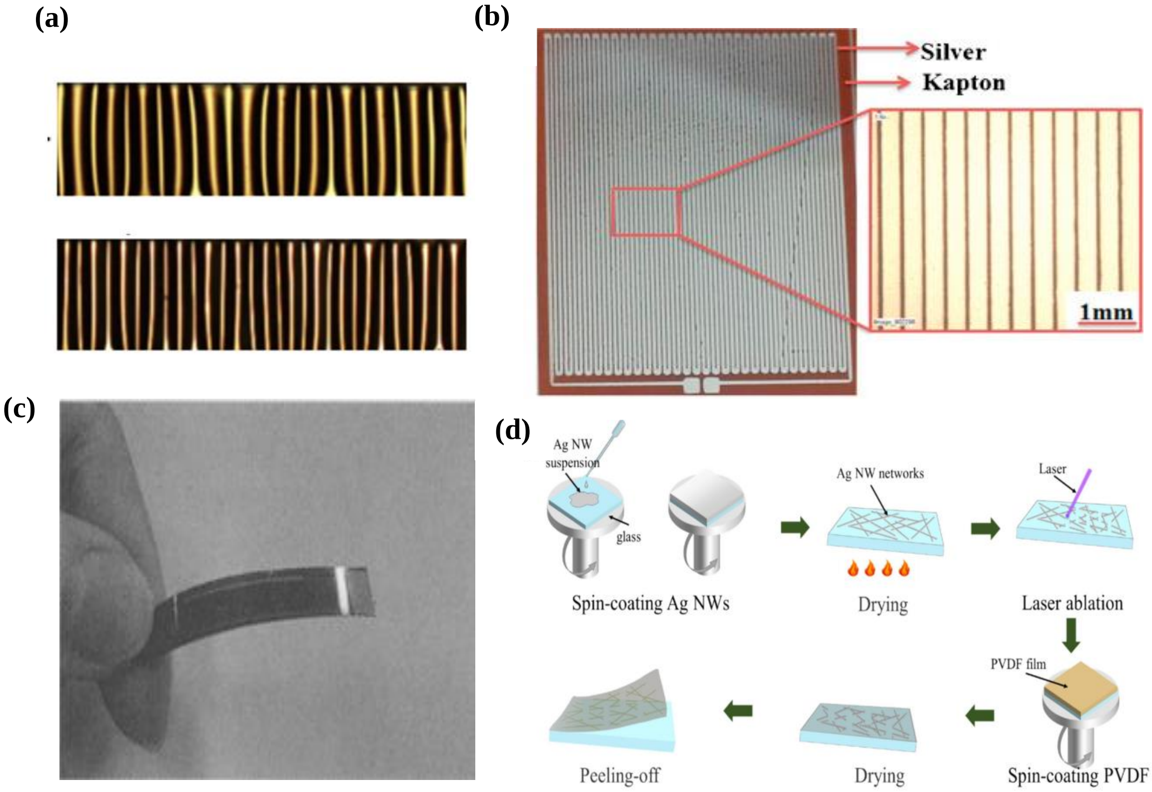

**Figure 1. (a)** Stretchable sensor with periodic buckling patterns on a PDMS substrate [23]; **(b)** photo of silver temperature sensor inkjet printed [24]; **(c)** temperature sensor image [25]; **(d)** the Ag NWs/PVDF temperature sensors [27].

Temperature sensors are also significantly affected by the use of metal oxides that are widely used. The performance of their temperature-sensing capabilities can be improved by utilizing the high-temperature coefficient of resistance found in metal oxide materials. When there are temperature changes, the thermosensitivity of metal oxide semiconductors means that the metal oxides are resistant to change. Liu et al. reported a high-sensitivity temperature sensor based on a multilayer structure of PET/vanadium dioxide ($VO_2$)/PDMS, fabricated using transfer printing technology, as shown in **Figure 2a**. This flexible sensor integrates an advanced manufacturing strategy inspired by spider-mimetic microstructures, demonstrating promising feasibility for simultaneously detecting both vibration and temperature. The high temperature coefficient of resistance of $VO_2$ enhances its temperature-sensing performance, achieving a resolution of 0.1 K [29]. Huang et al. used a printing technique for producing thermistor arrays. This process utilized nickel oxide (NiO), a material with a high temperature coefficient of resistance, to produce stable nanoparticle-based inks. As shown in **Figure 2b**, these printed thermistors feature sub-millimeter adjustable dimensions and operate over a wide temperature range from room temperature to 200 °C (*B*-value ~4300 K). They exhibit high sensitivity, minimal hysteresis, a certain degree of flexibility, and fast response times [18]. A solid foundation for the application of metallic materials in metal thermal characteristics-based flexible temperature sensors has been provided by a great deal of research on metals and metal oxides. When it comes to temperature sensor comparison to flexible metal, traditional rigid metal temperature sensors have a very high degree of flexibility. The introduction of conductive metal nano-inks, nano-fillers, nanowires, and patterned films to form the active temperature-sensing layer enables metal materials to conform to the surfaces of curved objects. However, this also increases manufacturing complexity, and the inherent weight of metal materials necessitates lightweight treatment.

In wearable temperature sensors, polymer materials (e.g., PDMS, PU) and carbon-based materials (e.g., graphene, rGO) are commonly used materials. They are highly flexible, lightweight, biocompatible, and low-cost, making them ideal for use in wearable devices. In addition, composites are able to provide better performance by combining the advantages of different materials, making them ideal for wearable sensors. In contrast, metal and metal oxide materials, although they have the advantages of high sensitivity and fast response, due to their rigidity and weight, are limited in their application in wearable devices.

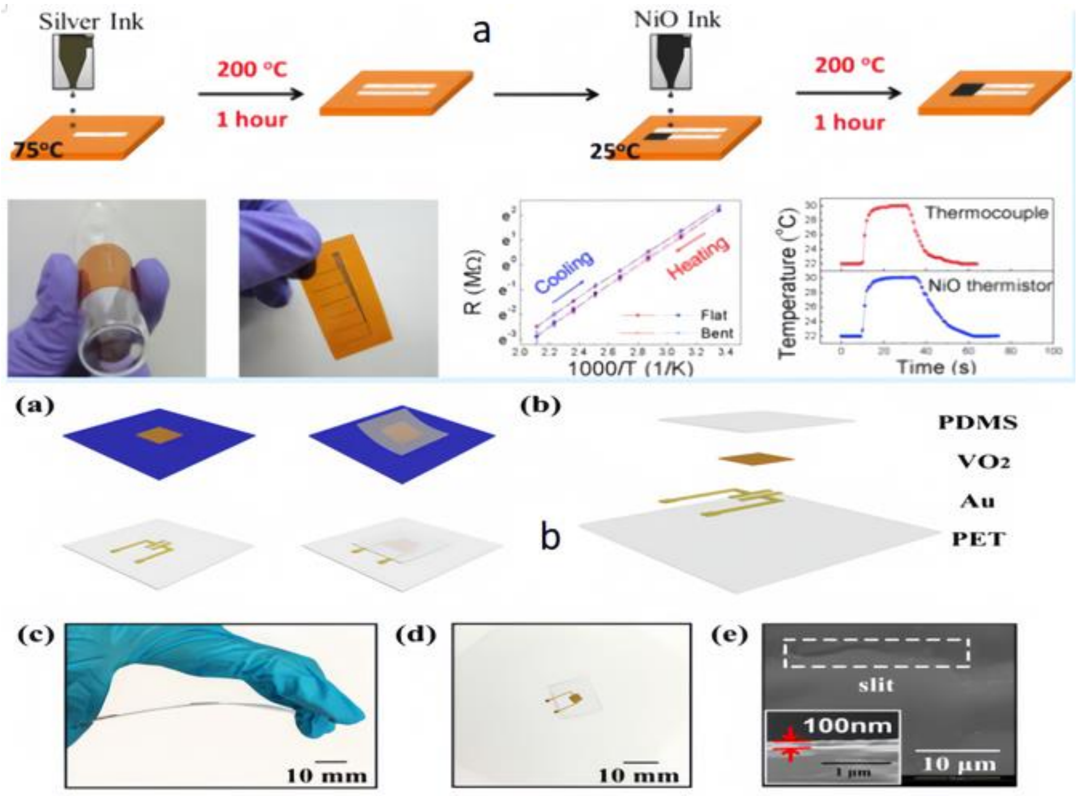

**Figure 2. (a)** Preparation of PET/vanadium dioxide/PDMS multilayer structure using $VO_2$ transfer printing technology [29]; **(b)** is a temperature sensor manufactured using inkjet printing [18].

## 2.2. Carbon-based materials

### 2.2.1. Carbon black and graphite

Carbon black because of their superior mechanical and electrical qualities, as well as their low cost, graphite, and carbon are frequently utilized as conductive fillers. When carbon black is mixed with polymers to form composites, it tends to form aggregates, and temperature variations can significantly affect its electrical properties [30]. Is caused by this stability, which increases the temperature coefficient of resistance [31]. With a low coefficient of thermal expansion [32], graphite is the typical allotrope of carbon with good electrical conductivity, thermal conductivity and chemical stability. Compared to carbon black, graphite powder is more sensitive to temperature changes when used as a sensor material. Shih et al. developed a flexible temperature sensor array using graphite powder as the thermosensitive material, fabricated on a PI film through a printing process. In comparison to a traditional platinum (Pt) thin-film temperature sensor (TCR = 0.0055 $K^{-1}$) tested within the same temperature range (20 °C–120 °C), reducing the graphite volume fraction to one-fourth resulted in a decrease in the composite material's TCR to 0.042 $K^{-1}$, demonstrating that Gr-PDMS composites displayed greater sensitivity [33].

### 2.2.2. Carbon nanotubes (CNTs)

Carbon nanotubes (CNTs) are seamless cylindrical structures composed of graphene layers and exhibit extremely high aspect ratios [34]. CNTs are considered promising alternatives to traditional smart materials due to their excellent electrical conductivity, thermal conductivity, high modulus, and high strength [35]. The development of flexible sensors is made possible by their unheard-of potential because of their exceptional mechanical qualities. Their exceptional thermal conductivity and high aspect ratio enable them to be distributed along their length direction, making them highly effective for heat transfer. This has led to continuous innovations in their application in flexible temperature sensors. Kim et al. employed an additive printing technique to create a multilayer negative temperature coefficient (NTC) thermistor on a flexible polyethylene terephthalate (PET) substrate. By employing screen printing, two silver electrodes were printed onto an active layer containing CNTs, followed by gravure printing to deposit the silver electrodes. Using a screen-printed deposition process, the finished encapsulation was obtained. Experimental data showed that as the temperature climbed from −40 °C to 100 °C, the thermistor's resistance declined due to a TCR of −0.4%/°C, with an overall resistance variation of 53% [36]. Ray et al. fabricated a flexible tri-axial tactile and temperature sensor array using a printed composite material consisting of CNTs and poly(3,4-ethylenedioxythiophene) (PEDOT) copolymers with ethylenedithiothiophene [37]. Additionally, Karimov and his team successfully deposited CNTs onto a polymer tape substrate, developing a temperature sensor based on CNT materials. Experimental data showed that the sensor's resistance at 20 °C was 1.4 times its resistance at 70 °C, demonstrating a negative correlation with temperature [38].

### 2.2.3. Graphene

Graphene, due to its unique electrical, physical, thermal, and chemical properties, has emerged as one of the most influential elements in the development of efficient flexible sensors [39]. As a monolayer of carbon atoms, graphene possesses a large specific surface area [40], electrical conductivity, and biocompatibility [41]. When combined with graphene's exceptional thermal conductivity—exceeding that of metals and carbon nanotubes—along with its outstanding mechanical and electrical properties and unique temperature response characteristics [42]. Graphene oxide (GO), derived from graphene, exhibits a diverse range of properties due to its complex surface functional groups and unique two-dimensional structure [43]. It has demonstrated excellent performance in biosensing applications. Hou et al. proposed a dual strain-temperature sensor based on sodium alginate (SA) nanofibers, graphene oxide (GO), and polyacrylamide (PAM) nanocomposite hydrogels, referred to as

SNGP hydrogels [44]. The inclusion of GO as a reinforcement and thermal conductor improved both the mechanical properties and thermal sensitivity of the hydrogel. **Figure 3a** illustrates that the sensitivity was 2%/℃ at the temperature range of 25 ℃–65 ℃. another derivative, which is reduced graphene oxide, is produced by additional GO reduction. Sahatiya et al. utilized GO as a channel material, bridging electrodes fabricated on a PI substrate to create a highly sensitive temperature sensor, as illustrated in **Figure 3b** [45]. The TCR values for GO and graphene nanosheets were measured at 0.7429%/℃ and 0.413%/℃ within the temperature range of 35 ℃–45 ℃, respectively, both outperforming commercially available platinum-based temperature sensors (TCR = 0.39%/℃). Graphene nanoplatelets (GNPs) are composed of stacked graphene sheets, resembling the graphene layers found on the walls of carbon nanotubes (CNTs), but in a flat configuration. Using 3D printing technology, GNPs/PDMS ink was employed to develop stretchable and strain-insensitive nanocomposite sensors, as depicted in **Figure 3c** [46]. The sensor had a positive TCR of 0.8%/℃, which was greater than the sensitivity of typical commercial platinum-based sensors (TCR = 0.39%/℃). Graphene nanowalls (GNWs) are vertically aligned graphene sheets forming self-assembled networks on a substrate [47]. Wei et al. developed a wearable temperature sensor using GNWs and PDMS. The process began with synthesizing GNWs on copper foil using low-pressure RF PECVD [48]. When measured inside the 35 ℃–45 ℃ temperature range, the sensor had a TCR of 21.4%/℃, which is higher than that of commercial platinum-based sensors. It is a three-dimensional porous carbon nanomaterial with the ability to create a layer of interconnected multilayer graphene networks, which is called laser-induced graphene (LIG). Various carbon precursors (such as PI, PEG, wood, food, clothing, and paper) can be converted into LIG through laser irradiation in ambient conditions [49]. LIG preserves the electrochemical properties and high specific surface area of graphene, according to Marengo et al. They developed a flexible temperature sensor using LIG, as depicted in **Figure 3d** [50]. They optimized various laser parameters (including wavelength, power, speed, working distance, and pulse density per inch) to carbonize a PI substrate using a $CO_2$ laser. A TCR of 0.04145%/℃ was seen; the temperature response of the sensor was described in the 30 ℃–40 ℃ range. However, when compared to reduced graphene oxide (rGO) in terms of linearity, sensitivity, mechanical performance, and repeatability, it is found that temperature sensors using rGO as the active material exhibit the most balanced performance. The application of carbon materials in flexible temperature sensors enhances their potential in health monitoring, wearable devices, robotics, human-machine interfaces, artificial skin, and other fields.

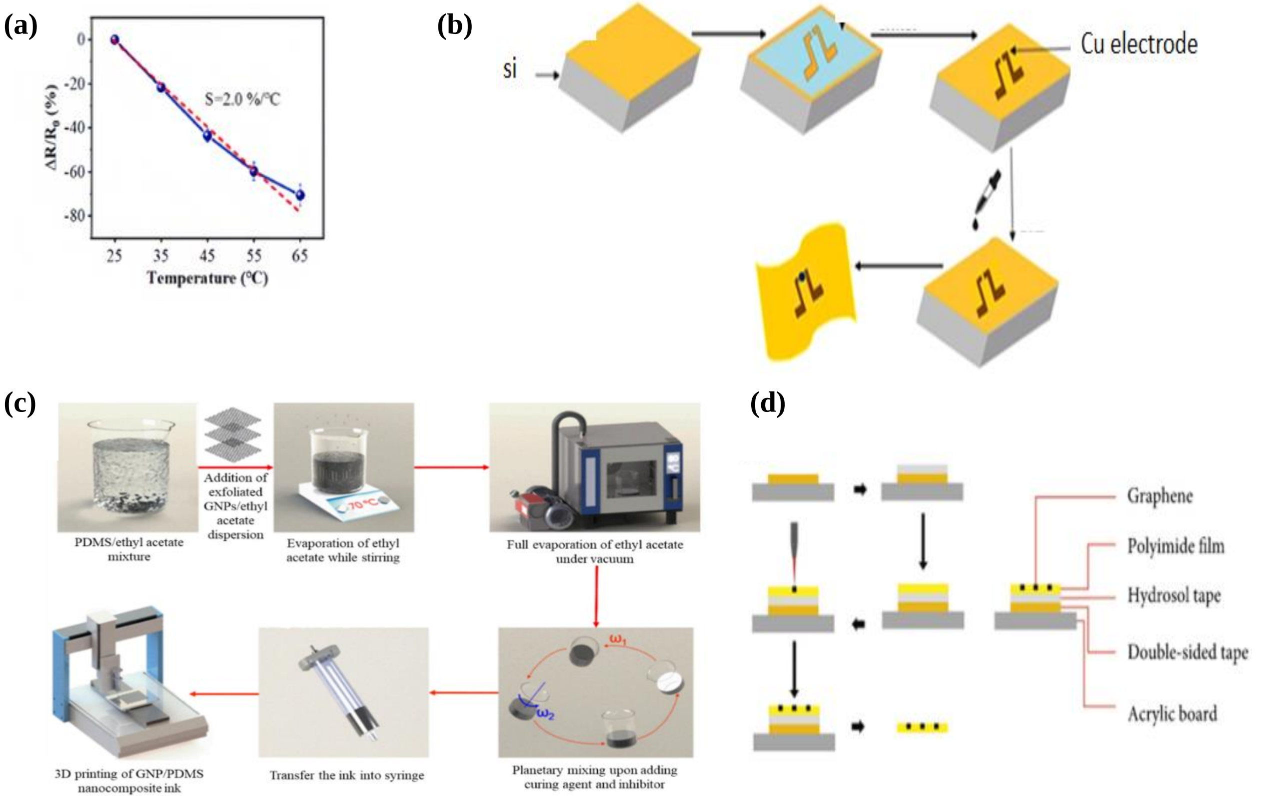

**Figure 3. (a)** shows the temperature dependent resistance curve of a temperature sensor based on graphene oxide [44]; **(b)** is a schematic diagram of a Cu electrode with rGO in the channel region of a flexible polyimide substrate [45]; **(c)** shows the preparation steps of nanocomposite ink [46]; **(d)** is the development of a laser temperature sensor [50].

### 2.3. Conductive polymer materials

Polymers are among the most commonly used materials in flexible sensors and have attracted significant attention in temperature sensor applications. Thermosensitive composite materials are widely used as substrates or active agents due to their mechanical flexibility, stable performance, ease of processing, and low manufacturing cost. poly(3,4-ethylenedioxythiophene)-poly(PEDOT:PSS) [51], poly(phenylene) [52], polypyrrole (PPy) [53], poly(vinylidene fluoride) (PVDF) [54], and poly(3-hexylthiophene) (P3HT) [55], common thermosensitive polymers used in temperature sensors include poly(N-isopropylacrylamide) (PIPAM) [56], poly(PEDOT:PSS) [51], and poly(3-hexylthiophene) (P3HT) [56].

Based on a strategy to enhance the accuracy of stretchable CNT temperature sensors, Yokota et al. proposed a semi-crystalline acrylate polymer/graphite composite material that enables multi-point measurement and can be fabricated via printing technology [7]. In this system, high sensitivity (20 mK) was shown, and the response time was very short (< 100 ms). In addition, it showed outstanding repeatability with a performance of more than 1800 cycles. Furthermore, the sensor's function remained largely unaffected when bent to a radius of less than 700 μm, making it suitable for conformal applications on living tissues. The detection temperature range can be adjusted from 25 ℃ to 50 ℃, accommodating variations in physiological temperatures. However, issues such as the lack of breathability and long-term wearability need to be addressed. Low-cost, environmentally friendly, readily available materials with excellent biocompatibility are essential for large-scale production [57]. Cellulose, which is abundantly available and possesses outstanding elasticity, plays a crucial role in flexible sensor devices, serving as a flexible substrate. Polypyrrole (PPy) has good biocompatibility and electrochemical stability. Mahadeva et al. utilized in-situ polymerization technology to integrate nano-scale PPy onto the cellulose surface without disrupting its structure [53]. After 16 h of polymerization, the cellulose-PPy nanocomposite-based flexible sensor exhibited good linearity, reversibility, and rapid response and recovery performance. Due to the material's unique sensitivity to humidity, the sensor's capacitance increased as temperature rose.

PEDOT:PSS is an emerging organic conductive polymer frequently featured in recent studies and is widely applied in flexible temperature sensors [58]. Overall, PEDOT:PSS offers high conductivity (~$10^3$ S/cm), excellent thermoelectric properties [59], strong stability [60], and transparent doping capability [61]. Conductive polymers are generally p-type semiconductors, and their conductivity can be significantly improved by adding solvents such as dimethyl sulfoxide (DMSO) [62] or polyhydroxy organic compounds such as ethylene glycol (EG) [63]. Harada et al. fabricate electronic whiskers composed of CNTs and PEDOT:PSS. The resulting composite thermosensitive films exhibited temperature sensitivities of 0.25–0.78%$℃^{-1}$ [64]. The use of flexible temperature sensors in wearable devices and medical care has increased due to a number of different fabrication techniques. Besides changing the composition ratio, structural changes can also improve the performance of the composite films. Oh et al. utilized photolithographic lift-off and spin-coating processes, drawing inspiration from the adhesive structure of octopus suckers to enhance sensor performance. They developed a resistive temperature sensor composed of PEDOT:PSS and CNTs, which exhibited high thermal sensitivity of 2.6%$℃^{-1}$ in the 25 ℃–40 ℃ range, enabling precise detection of skin temperature variations within 0.5 ℃ [55]. As a prospective option for continuous skin temperature monitoring, this sensor was shown to be durable, non-irritating to the skin, and have repeatable detection capabilities in a way that was both durable and reproducible. In addition to their mechanical flexibility and lightweight characteristics, composite materials also offer features such as transparency, stable performance, and excellent biocompatibility. However, some composite materials have complex preparation processes, and high-performance composites often come with higher costs.

## 3. Manufacturing processes

As the demand for flexible, multifunctional, simple-to-manufacture, and high-sensitivity electronic devices continues to grow, researchers have been actively exploring lightweight, cost-effective, and large-area manufacturing methods for flexible sensors. This section reviews recently reported and feasible manufacturing strategies for flexible temperature sensing devices and discusses key processes for improving their performance.

### 3.1. Thin-film deposition

Thin-film fabrication methods can be categorized based on the phase of the material used. Deposition techniques are categorized into vapor-phase deposition and solution-based deposition (e.g., spin-coating and inkjet printing). Vapor-phase deposition is further divided into physical vapor deposition (PVD) and chemical vapor deposition (CVD), based on whether a chemical reaction occurs during the process.

PVD is typically used to make electrodes or active metal layers [65]. This process includes the deposition of material in a vacuum environment using conventional methods such as ion plating, sputtering deposition, and vacuum evaporation. Among these, metal target ion sputtering involves ionizing residual gas molecules in a vacuum chamber under a high voltage (~1500 V), forming a plasma that accelerates cations toward a metal target. This bombardment causes metal atoms to be sputtered from the target, forming a conductive film on the sample surface [66]. Ahmed et al.'s substrate, which was created with the help of a polyimide, was used to create a flexible silicon temperature sensor [67]. In their study, undoped amorphous silicon was deposited between RF magnetron sputtered metal electrodes and encapsulated as the sensing material. The sensor structure consisted of a 35 μm-thick polyimide layer as the flexible substrate, with another 35–40 μm polyimide layer spin-coated on top to ensure the sensor remained at the zero-stress plane. Webb et al. developed an ultrathin, conformal, skin-like sensor system that provides continuous and precise thermal measurements [9]. As illustrated in **Figure 4a**, this system was fabricated using serpentine micro structured Cr/Au layers deposited onto a PI film via metal evaporation deposition, photolithography, and wet etching. and metal deposition methods were also used to finish the sensor array by means of reactive ion etching. Bin et al. presented a simplified MEMS method, in which sandwiched between PI layers as flexible substrates and platinum resistors as sensing materials [5]. The Pt layer was deposited onto an aluminum layer via evaporation and then spin-coated with PI. The Pt layer patterning was achieved using PI-based spin-coated sensing layers, followed by encapsulation processing. A frequency response of 160 kHz when it was operated with a 1 mA driving current. The physical vapor deposition (PVD) can precisely control the thickness and uniformity of thin films at the nanoscale with great precision, which makes it appropriate for the production of sensors that are extremely conductive and sensitive to heat. However, it has a high cost; PVD equipment is expensive and requires a vacuum environment, which increases the manufacturing cost, and the process is more complex. Therefore, PVD can be manufactured with high sensitivity and high resolution, but it is not suitable for large-scale production due to its high cost.

Compared to other thin-film fabrication techniques, CVD can produce thin films with high purity and superior quality. This method allows precise structural and atomic-level control [68]. A notable advancement in this field is radio-frequency plasma-enhanced CVD (RF-PECVD), which enables the synthesis of graphene nanowall (GNWs) films on copper foils. Yang et al. used GNWs-based structures integrated with PDMS (polydimethylsiloxane) to show an ultra-sensitive wearable temperature sensor; **Figure 4b** [48] illustrates the fabrication process. This device exhibited an exceptionally high positive TCR (0.214 $℃^{-1}$), three times that of conventional devices. The RF-PECVD process improved deposition rates and film quality compared to conventional CVD techniques. Zhou et al. employed the FCCVD technique [69] to produce highly conductive CNTs. By leveraging this superior base material, drop-casting was employed to fabricate flexible n-type thin films. As the demand for simpler, lower-cost, and scalable nanodevice manufacturing techniques continues to grow, complex and high-cost CVD processes are gradually being replaced by more efficient alternatives. High-quality, high-purity thin films can be obtained by chemical vapor deposition (CVD) of well temperature sensors. Ideal for large-scale production, CVD effectively deposits thin films uniformly across extensive substrate areas. However, it usually requires high temperatures, which limits its application on flexible substrates, and the process is complex, increasing the difficulty of manufacturing. Therefore, CVD can be manufactured as a high-performance temperature sensor, but due to the high temperature and complex process, its application in flexible electronic devices is limited.

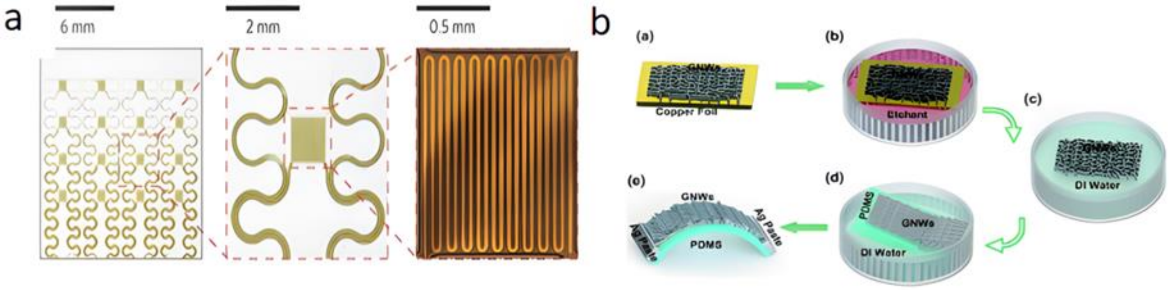

**Figure 4. (a)** shows the optical image of a 4 × 4 TCR sensor array integrated on a thin elastic substrate, with an enlarged view of a single sensor [9]; **(b)** is the schematic diagram for the production of GNWs/PDMS temperature sensors [48].

## 3.2. Patterned printing fabrication

Thin-film patterning is at the core of flexible sensor manufacturing. It follows the fundamental principles of material removal (top-down) or material addition (bottom-up) during fabrication. Key processes include thin-film deposition, imaging, transfer, replication, and fidelity control. Flexible electronics require highly precise molding techniques, low processing temperatures, and cost-effective fabrication methods. Currently, patterned printing techniques used for flexible temperature sensors include screen printing, soft etching, nanoimprinting, inkjet printing, laser sintering, transfer printing, and nano direct writing [70].

### 3.2.1. Screen printing

Screen printing has a long history and has evolved into a widely used technique in electronic industries, such as integrated circuits and piezoelectric components. As shown in **Figure 5a**, the main components of a screen printing station include a printing platform, substrate, screen mask, squeegee, and screen material. Screen printing has the following benefits: high speed, cheap, large-scale production capacity, and the advantages of screen printing include small-scale and large-scale manufacturing capacity. It is widely used in sensor circuit fabrication, electrode printing, and sensor element manufacturing. However, its pattern resolution is limited, making it unsuitable for complex geometric structures. Yokota et al. developed a highly sensitive (20 mK), fast-response (< 100 ms) printable flexible thermal sensor using semi-crystalline acrylate polymer/graphite composite materials for body temperature detection [57]. With mask printing technology and the use of thermocompression molding, which was used to fabricate the ultra-flexible temperature sensor, a copolymer filled with graphite particles was placed between two digitated gold electrodes that were placed on a PI film. Complex and costly procedures, including deposition and photolithography, were prevented by Harada et al. Ricexial force and temperature sensors were created on flexible substrates by stress/strain engineering, which was instead employed by printing methods [64]. The PEDOT:PSS/CNT composite ink was printed onto a PET substrate through shadow mask screen printing, forming circuit structures. After laser scribing (LS), the perforations enabled strong adhesion between the printed layers and the lower PDMS substrate. The fingerprint-like structure, shown in **Figure 5b**, was combined with screen-printed strain sensor layers to form a flexible sensor array. By optimizing masks, inks, and printing conditions (e.g., pressure, speed, and squeegee angle), high-resolution electronic skin could be created in the future, at least 10 μm resolution and 5 μm alignment precision. In another study utilizing a fully printed approach, Kanao et al. proposed a multifunctional flexible sensor array based on a cantilever structure, as shown in **Figure 5c** [1]. On both sides of a PET substrate, patterned shadow mask printing was used to fabricate PEDOT:PSS/CNT composite-based flexible temperature sensors. The electrodes were printed on screen-printed electrodes with electrical contacts in the form of these patterns. When the cantilever structure was strained, the heat source moved closer to the bottom-mounted temperature sensor, improving temperature monitoring accuracy. Screen printing technology is suitable for manufacturing low-cost printing technology that can manufacture sensors on flexible substrates, suitable for wearable devices, and can be manufactured quickly, but due to low resolution, as well as high requirements for ink viscosity and surface tension, the choice of materials is limited, which may affect the sensitivity and accuracy of the sensor.

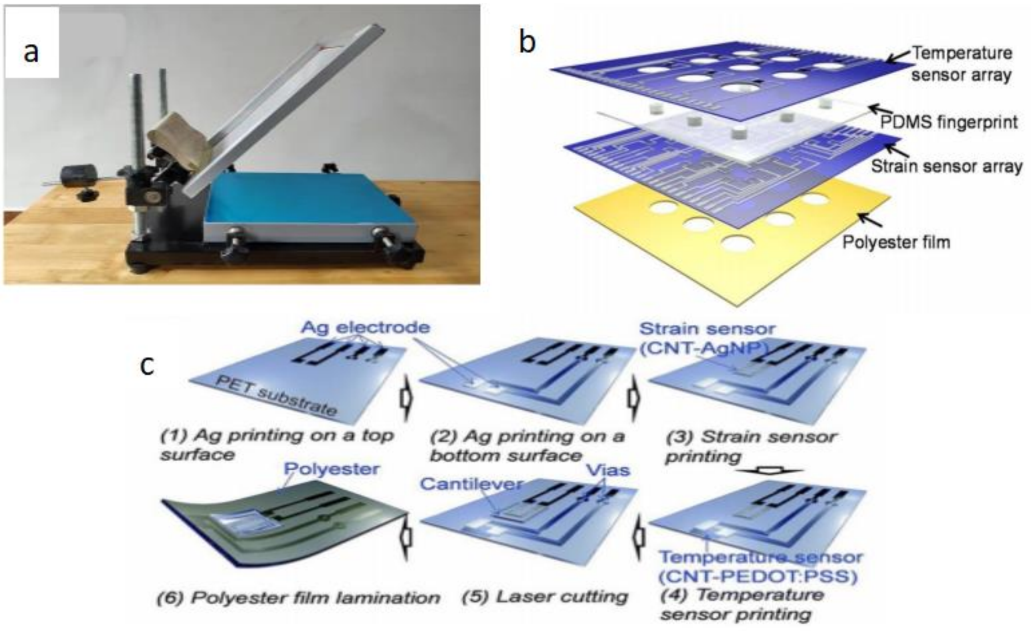

**Figure 5. (a)** shows a common screen printing instrument; **(b)** is a schematic diagram of each layer of the electronic skin device [64]; **(c)** is a schematic diagram of the process of manufacturing electronic skin on PET substrate using printing methods [1].

### 3.2.2. Inkjet printing

Screen printing operates in a non-contact manner, using digitally controlled microdroplets to print sensitive films onto substrates with high precision. While screen printing lacks high resolution, inkjet printing offers better accuracy, resolution, and flexibility. Compared to photolithography, which is complex and expensive, inkjet printing is low-cost, environmentally friendly, and easy to operate. It also provides better uniformity and continuity than other printing techniques, such as soft printing and nanoimprinting, making it suitable for large-area, high-precision patterning.

A crucial element in inkjet printing is conductive ink. In order to meet the strict requirements of performance, the ink must be optimized for its solubility, viscosity, and surface tension. Dankoco et al. developed a bendable temperature sensor by depositing silver-based conductive ink onto a PET film using inkjet printing [25]. The optimal inkjet printing parameters produced a smooth, uniform silver layer, forming a highly flexible sensor. At 38.5 ℃, which spans 20 ℃–60 ℃, the sensor had a nominal resistance of 2.032 kΩ and a temperature sensitivity of 2.19 × 10 ℃. Oh et al. developed a temperature sensor using PNIPAM thermosensitive hydrogel, PEDOT:PSS, and carbon nanotubes (CNTs). This sensor demonstrated high thermal sensitivity (2.6%$℃^{-1}$) in the 25 ℃–40 ℃ range, enabling the detection of 0.5 ℃ variations in skin temperature [51]. Inkjet printing was used to pattern graphene oxide (GO) and rGO onto a PDMS substrate, followed by CVD processing to create sensor circuits, as shown in **Figure 6a**. The sensor adhered well to the skin, causing no irritation, and maintained stable and repeatable temperature detection, even after multiple attachment/removal cycles. The conductivity of inkjet-printed graphene was seven magnitudes greater than that of CVD-grown graphene. Both screen printing and injet have shown to be successful in the large-scale creation of flexible sensors at low cost. Zirkl et al. combined both techniques to create a fully printed flexible sensor array using multiple screen printing layers, as illustrated in **Figure 6b** [71]. This system integrated multiple functional electronic components, including pressure and temperature sensors, electrochromic displays, and organic transistors, using only five types of functional inks on the same flexible substrate. Vuorinen et al. developed a temperature sensor using two mixed inks. This skin-conformable sensor adhered well to the skin-forming substrate, maintaining good wearability and flexibility [72]. Unlike conventional photolithography, which requires multiple steps and generates more waste, this method directly monitors skin temperature in the 35 ℃–45 ℃ range, with a TCR greater than 0.06%/℃ [73]. While inkjet printing is advancing in the flexible electronics field, challenges remain in printhead and ink control technology. Unlike the fast fabrication process of screen printing, inkjet printing requires extensive calibration and has a lower printing speed. The huge failure rate of inkjet nozzles and the restricted number of printheads are currently limiting their capacity to produce large amounts of data. Because inkjet printing equipment is reasonably cheap, it can produce sensors on flexible substrates that are appropriate for wearable devices; however, because of its low resolution, it may have a significant impact on the sensitivity and accuracy of the sensor; additionally, because of the high requirements for ink viscosity, surface tension, and other characteristics, it might restrict the selection of materials.

### 3.2.3. Transfer printing

Transfer printing involves moving patterns from a donor substrate to a target substrate by leveraging adhesion differences. It includes direct transfer (patterned material moves directly) and indirect transfer (pattern is first transferred to an intermediate film). For flexible temperature sensors, indirect transfer is commonly used. Liao et al. used VO-based multilayer PDMS structures to create a flexible temperature-mechanical dual-parameter sensor that was created by moving them onto a flexible substrate. This sensor used bio-inspired microstructures (spider-inspired design), demonstrating the ability to detect both vibrations and temperature changes. The high TCR of $VO_2$ allowed temperature resolution as fine as 0.1 K, enabling precise real-time wrist pulse and temperature monitoring [29]. At the same time, the mechanical and thermal signals were decoupling, which made it possible to monitor at the same time. However, transfer-printed sensors often lack sufficient stretchability. To address this, Yu et al. developed a flexible device capable of 30% stretching and compression without performance degradation [74]. As shown in **Figure 6c**, the sensor was initially fabricated on a silicon wafer and later transferred onto a pre-stretched PDMS elastomer substrate. Upon releasing the pre-strain, the sensor self-formed micro-scale, periodic wavy geometries, enhancing flexibility and stretchability. The thin-film sensor could withstand up to 30% strain without damage or performance loss. Compared with screen printing, transfer printing can manufacture high-precision and high-performance temperature sensors, but due to the complex process and the need to accurately control adhesion and peeling force, as well as the high transfer printing equipment and technical requirements, it is not suitable for large-scale production.

### 3.2.4. Laser direct writing (LDW)

Laser direct writing (LDW) is a mask-free, vacuum-free fabrication technique that uses laser beams to directly pattern materials on a substrate. Unlike traditional lithography, LDW allows selective material ablation and modification, offering high spatial selectivity, fast processing speeds, high precision, and minimal material waste. Compared to traditional thermal activation techniques, where thermistors require high temperatures and complex processing, LDW enables low-temperature, high-precision sensor fabrication. Shin et al. introduced a monolithic laser-induced reduction sintering strategy, creating a seamless, high-sensitivity artificial skin sensor [75]. Unlike traditional multi-step lithography or vacuum deposition, LDW enables direct patterning without heterogeneous integration challenges. Harada et al. proposed a direct batch fabrication method for flexible temperature sensors, further advancing previous research [76]. The process involved printing a thermosensitive composite ink on a substrate and using laser etching to remove unwanted material, forming precise sensor arrays. The resulting high-sensitivity artificial electronic whisker sensor array, shown in **Figure 6d**, was capable of 3D object scanning and sensing. As fabrication methods continue evolving, the rapid expansion of flexible electronics research suggests that fully functional, wearable flexible devices will soon be realized. Laser direct writing can fabricate temperature sensors with high precision and high sensitivity for fabricating complex patterns on the micron scale, but it is not suitable for mass production due to high cost and high requirements for material absorption characteristics. Different manufacturing methods have a significant impact on the performance, cost, and suitability of flexible temperature sensors. High-precision manufacturing methods (e.g., photolithography, laser direct writing) can produce high-performance sensors, but they are costly and complex, making them unsuitable for mass production. Low-cost manufacturing methods (e.g., printing, inkjet printing) are suitable for mass production but have lower resolution and accuracy, which can affect the performance of the sensor. As a result, choosing the right manufacturing method requires trade-offs between performance, cost, and manufacturing complexity.

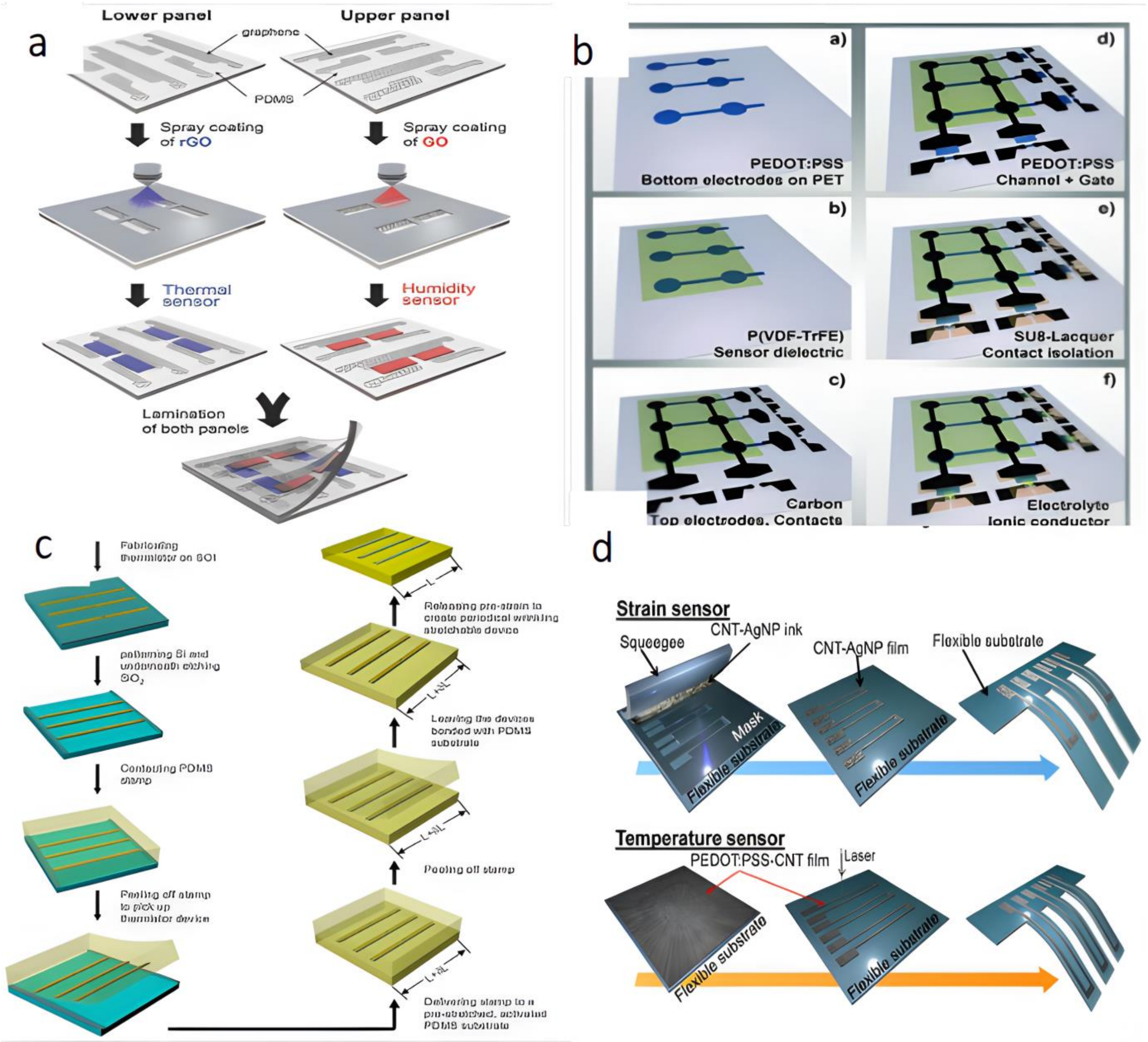

**Figure 6. (a)** Preparation of stretchable multimodal all-graphene E-skin sensor matrix [55]; **(b)** is the manufacturing process of printed ferroelectric active matrix sensor arrays [71]; **(c)** is the manufacturing process of the temperature sensor [75]; **(d)** is a multifunctional electronic device that needs to be manufactured [76].

## 4. Key parameters of flexible temperature sensors

### 4.1. Sensitivity

Sensor sensitivity refers to the ratio of the system response variation to the corresponding input variation under static conditions, which is the dimensional ratio of output to input. Temperature sensors have the following expression for the TCR: $r/r_0 = s(t)t_0$, which is a function of temperature change ($r/r_0$) in relation to relative resistance, where s stands for TCR. TCR is considered the most critical parameter because it represents the resistance characteristics of the component as a function of temperature. The higher the TCR, the higher the sensitivity. A positive TCR indicates that resistance changes in the same direction as temperature, while a negative TCR indicates that resistance changes in the opposite direction. Flexible sensors used for body temperature monitoring mostly focus on temperature variations within a 10 ℃ range, so capturing small temperature changes requires high sensitivity.

Upon temperature stimulation, the internal conductive network undergoes structural changes, which affect temperature sensitivity. To enhance the temperature sensitivity of active materials, a strategy of converting temperature fluctuations into mechanical deformation has been employed to amplify the conductive network's response to temperature changes. By binding thermosensitive materials to a substrate with a high positive thermal expansion coefficient, thermal strain is increased, increasing sensitivity. This method has been applied in graphite- and graphene-based sensors, particularly in graphene nanowall (GNW)-based sensors. Another way to increase the sensitivity of flexible temperature sensors is the use of special structural designs. Researchers have worked to increase temperature sensing performance by optimizing sensor structures in recent years. Yu et al. recently developed a wearable temperature sensor with high sensitivity, linearity, and flexibility, based on a microcrack morphology strategy [77] shown in **Figure 7a**. The average length and density of microcracks determine the temperature sensitivity of the sensor, which is further optimized by three key process parameters: pre-stretching strain, sulfuric acid treatment time, substrate surface roughness. This high-performance PEDOT:PSS-PDMS sensor demonstrated a TCR of 0.042 $℃^{-1}$, with an exceptional linearity coefficient (0.998) in the 30 ℃–55 ℃ range. This microcrack-based sensor offers high transparency, superior temperature sensitivity, excellent linearity, and flexibility, making it a promising candidate for wearable thermal sensing applications. The creation process of flexible electronic equipment is essential to increasing the sensitivity of the sensor. Shin et al. developed a Ni/NiO-based flexible temperature sensor using a monolithic laser-induced reduction sintering (M-LRS) method. During laser irradiation, the M-LRS process simultaneously reduced NiO nanoparticles (NiO NPs) while annealing and consolidating adjacent NiO NPs. This process significantly enhanced the performance of non-ceramic NTC thermistor materials [75] shown in **Figure 7b**. The resulting NiO-based temperature sensor demonstrated superior temperature sensitivity compared to other thermistor-based sensors. Analysis and Raman spectroscopy showed that the novel thermal activation mechanism that the suggested monolithic LRS procedure introduced was responsible for this high sensitivity. Since flexible temperature sensors are often touch-sensitive, it can be inferred that the thickness of the sensing film influences sensitivity. Lee et al. developed a highly flexible, wearable paper-based temperature sensor using printed PEDOT:PSS conductive polymer ink [78], shown in **Figure 7c**. By employing a hydrophilic and flexible paper substrate, the sensor achieved remarkable sensitivity and simplified fabrication compared to polymer-based substrates. The electrical conductivity of the paper-based sensor at room temperature was 0.48 S/cm, with a high linearity coefficient of 99.86%. The sensor exhibited a sensitivity of 658.5/℃. Therefore, while increasing sensitivity is crucial, improving stability and accuracy remains equally important. **Table 1** presents the applications and key parameters of flexible temperature sensors.

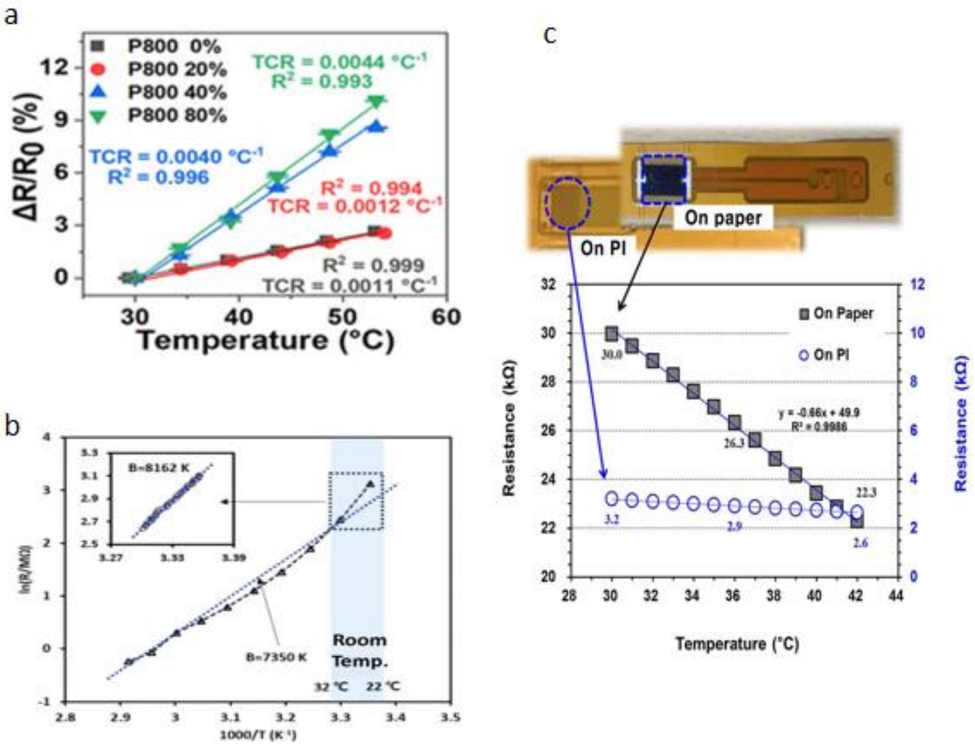

**Figure 7. (a)** is calculated crack parameters, including average crack length and crack density from optical images of PEDOT:PSS–PDMS sensors fabricated with various substrates [77]; **(b)** is PTC and NTC characteristics of the m-LRS processed Ni electrode and Ni-NiO-Ni structure. Remarkably high TCR of −9.2% $℃^{-1}$ for the Ni-NiO-Ni structure [75]; **(c)** Resistance to temperature, R(T), of the flexible temperature sensors in a specific span of 30 ℃–42 ℃, which is the range of human-body temperature [78].

**Table 1.** Flexible temperature sensors application and key parameter.

| Material | Fabrication Method | Sensitivity | Temperature Range (℃) | Response Time | Application | Reference |
|---|---|---|---|---|---|---|
| Gr | Coating Technology | | 25–42 | 26 s | Medical diagnostic temperature detection | 20 |
| MWCNT | Printing Technology | −1730% $K^{-1}$ | 35–75 | | Thermal sensors and distance sensors | 34 |
| Graphene | Lithography | 1.05% $K^{-1}$ | 30–100 | | Wearable temperature sensing applications | 41 |
| rGO | Printing Technology | 0.635% $K^{-1}$ | 30–100 | 1.2 s | Robotic skin; Internet of Things | 43 |
| rGO | Casting Technology | | 25–80 | | Wearable devices | 47 |
| rGO | Coating Technology | 1.34% $℃^{-1}$ | 30–80 | | Wearable skin electronics | 49 |
| GNWs | Polymer-Assisted Transfer Method | 0.214% $℃^{-1}$ | 25–120 | 1.6 s | Human health monitoring | 48 |
| Pt | MEMS Technology | 0.32% $℃^{-1}$ | 20–120 | | Biomedical applications | 23 |

**Table 1.** (*Continued*).

| Material | Fabrication Method | Sensitivity | Temperature Range (℃) | Response Time | Application | Reference |
|---|---|---|---|---|---|---|
| Au/Cr | Lithography | 2.5% $℃^{-1}$ | 25–45 | 3.7 ms | Stretchable electronics | 75 |
| Ag | Printing Technology | 0.223% $℃^{-1}$ | 20–60 | | Printed medical applications | 43 |
| Ni | Liquid Phase Mixing | 0.3 V $℃^{-1}$ | 35–42 | | Medical diagnostics | 22 |
| OA/BA/Graphite | Printing Technology | 20 mK | 25–50 | < 100 ms | Health diagnostics; Wearable devices | 57 |
| TE-nanowires | Drop Casting | 0.15 K | | 17 s | Triboelectric nanogenerator | 52 |
| pNIPAM/PEDOT:PSS/CNTs | Coating Technology & Lithography | 2.6% $℃^{-1}$ | 25–40 | 139 s | Disease diagnosis; Electronic skin | 55 |
| rGO/P(VDFTrFE) | Coating Technology | | 30–80 | | Electronic skin; Human-machine interface | 47 |
| PEDOT:PSS | Dipping Method | 0.1 K | 25–75 | < 2 s | Robotics and health monitoring products | 51 |
| $CaCl_2$ | Liquid Phase Mixing | 10 mK | 8–39 | | Biomedical applications | 54 |
| $VO_2$ | Printing Technology | −1.12% $K^{-1}$ | 3.15–46.85 | < 2 s | Wearable AI elements | 29 |
| MWCNT | Dip Coating Technology | 0.13% $K^{-1}$ | 30–45 | | Smart textiles | 56 |
| PEDOT:PSS | Dip Coating Technology | 658.5 Ω $℃^{-1}$ | 30–42 | | Medical diagnostics | 78 |
| PEDOT:PSS/CNTs | Printing Technology | 0.85% $℃^{-1}$ | 30–55 | < 50 ms | Health monitoring | 75 |

### 4.2. Response time, resolution, and accuracy

The response time refers to the time required for a sensor to stabilize its output signal after being subjected to a temperature stimulus, making it another critical performance parameter. It is closely related to the thermal response of the active material and reflects the sensor's sensitivity to temperature variations. In practical applications, such as wearable health monitoring devices and real-time artificial intelligence components, a shorter response time is highly desirable. Many flexible temperature sensors exhibit fast response times, able to react to temperature changes within a few milliseconds, and the Au/Cr/PVA sensor developed by Yu et al. [74]. exhibits an extremely high response speed with a response time of 3.7 ms in the range of 25 ℃–45 ℃. Fast response in a narrow temperature range means that the response time of the sensor can be further shortened in a narrow temperature range, and the semi-crystalline polymer/graphite composite sensor developed by Yokota et al. [7]. has a response time of less than 100 ms in the range of 25 ℃–50 ℃, which is suitable for monitoring human physiological temperature changes. The response time in a wide temperature range requires some sensors to maintain a fast response time even in a wide temperature range, and the response time in a wide range is about 1 s, showing a fast response speed. The balance between response time and reset time means that the response time and reset time of the sensor need to be balanced to improve the monitoring efficiency, and the GNWs/PDMS sensor developed by Yang et al. [48]. has a response time of 1.6 s and a reset time of 8.52 s in the range of 25 ℃–120 ℃, showing good response and reset performance. The combination of high sensitivity and fast response is important, and the combination of high sensitivity and fast response is an important goal of sensor design, and the Ni/NiO sensor developed by Shin et al. [75]. achieves the combination of high sensitivity and fast response through integral laser-induced reductive sintering (m-LRS) technology, with a response time of several seconds. Influence of environmental factors on response time. Often environmental factors such as humidity and mechanical strain can affect the response time of a sensor. For example, the cellulose/polypyrrole composite sensor developed by Mahadeva et al. exhibits good response time stability under humidity and temperature variations The sensor exhibits a fast response time over a narrow temperature range while maintaining a fast response time over a wide temperature range. The combination of high sensitivity and fast response is an important goal in sensor design. The balance between response time and reset time and the influence of environmental factors on response time are also important considerations for sensor performance optimization. These advances provide a solid foundation for real-time monitoring applications of sensors in medical, industrial, and everyday life. The resolution of a sensor is defined as its ability to detect the smallest measurable change in input. It is determined by whether a small input variation results in a significant output change—the greater the output difference, the higher the resolution. Typically, it is given as the ratio of three standard deviations from the actual value in a certain range. For temperature measurement instruments, precision is usually a qualitative concept rather than a numerical value. High resolution and accuracy are crucial in body temperature monitoring, where natural temperature fluctuations are minimal. As a result, high-performance sensors with exceptional resolution and precision are essential.

### 4.3. Measurement range and durability

The measurement range of a flexible temperature sensor is a crucial factor, referring to the minimum and maximum temperature limits the sensor can detect. In this study, we focus only on sensors suitable for body temperature monitoring, specifically within the 30 ℃–45 ℃ range. Repeatability is the degree of variation in multiple measurements taken under identical conditions, with the same excitation, across at least three repeated full-range measurements in the same direction. The high sensitivity of the narrow temperature range is that many flexible temperature sensors show high sensitivity in a narrow temperature range (such as 25 ℃–42 ℃). For example, the Gr/PEO/PVDF composite sensor developed by Huang et al. [18] has high resolution (0.1 ℃) and high cycling stability (2000 cycles) in the range of 25 ℃–42 ℃. One application involving a broad temperature range is the ability of certain sensors to function effectively across a wider span of temperatures. Yang et al. [48], for example, developed GNWs/PDMS sensors, which are GNW/PDMS. Have an accuracy of 0.1 ℃ and a fast response time. There are also application-specific temperature ranges, e.g., for specific applications, such as medical diagnostics and industrial monitoring, where the measuring range of the sensor can be further extended. For example, the $VO_2$/PDMS sensor developed by Liao et al. is capable of detecting temperature changes in the range of 270–320 K (about −3.15 to 46.85 ℃) with a resolution of 0.1 K. In flexible temperature sensors, durability refers to the ability to maintain stable sensing performance and structural integrity under extended use. High durability and repeatability are essential for sensors to meet the requirements of long-term stable operation. Linearity is typically expressed as a percentage deviation between the actual response curve and the ideal fitted curve—higher linearity generally indicates greater reliability. High cyclic stability for durability generally means that many sensors exhibit high cyclic stability and are able to maintain stable performance after multiple uses. For instance, the rGO/PU sensor created by Trung et al. maintained a steady temperature response after 10,000 stretch cycles. The fact that certain sensors have good stability when used in the long run is referred to as long-term stability. For example, the Gr/PEO/PVDF sensor developed by Huang et al. [18]. maintained stable temperature monitoring performance for 1 month. Mechanical durability is important to the mechanical durability of a sensor for its application in complicated settings. Yang et al. [48], for example, developed GNWs/PDMS sensors, which are GNW/PDMS. They may nevertheless work normally under 70% strain, demonstrating outstanding mechanical endurance. Advantageous Environmental Adaptability Usually the sensor needs to adjust to different environmental situations, such as humidity, temperature changes, etc. For example, the cellulose/polypyrrole composite sensor developed by Mahadeva et al. [53]. exhibits good stability under humidity and temperature changes. Self-healing ability Through the introduction of self-healing materials, the durability of the sensor can be improved, and the dual-network ion-conductive hydrogel sensor has a self-healing ability, which can restore function after damage and improve the service life of the sensor.

## 5. Challenges and future prospects for the development of wearable temperature sensors

In recent years, wearable temperature sensors have been unprecedentedly developed, but some new challenges have emerged in the process of development. Our skin temperature is easily affected by the surrounding environment, resulting in inaccurate measurement results, and how to reduce the interference of environmental factors on temperature sensors is an important challenge. Although the response time of the current temperature sensor can be several milliseconds, the long reset time affects the monitoring efficiency and ability of the sensor. How to shorten the time difference between response time and reset time will directly affect the efficiency and ability of sensor monitoring. With the continuous advancement of technology, when multi-function sensors monitor multiple parameters at the same time, the signals are easy to interfere with each other, and how to achieve independent response and accurate output of signals is an urgent problem to be solved. How to maintain the stability and accuracy of the sensor while improving the sensitivity is a challenge, and the flexible sensor needs to have good flexibility and durability to adapt to long-term wear and use in complex environments. For implantable sensors, the development of biocompatible and biodegradable materials to reduce harm and rejection to the human body remains an important challenge.

The development of flexible temperature sensors shows us a foreseeable future. First of all, in this future, it is necessary to develop temperature sensors in the direction of higher sensitivity. At the same time, the sensors of the future will integrate a variety of functions, such as the monitoring of temperature, pressure, humidity, and other parameters, and realize the independent response and accurate output of the signal. The improvement of self-energy supply technology and wireless transmission technology will make sensors more portable and independent, reduce dependence on external power sources, and realize real-time wireless transmission of data, which will be a huge advance in intelligent monitoring systems. Future implantable sensors will make more use of biocompatible and degradable materials to reduce harm and rejection to the human body and achieve the natural absorption of the sensor to meet the needs of a wider range of people, becoming a flexible application device that everyone can use. Integrate sensor-collected temperature data into a health big data platform to provide the best assistance and data support for future medical diagnosis. In conclusion, future wearable temperature sensors will make important progress in sensitivity, multi-functional integration, self-supply, visualization, biocompatibility, large-scale manufacturing, etc., providing more accurate and convenient tools for human health monitoring and medical diagnosis.

Design principles for wearable temperature sensors include high sensitivity and accuracy, wide measurement range and fast response, flexibility and stretchability, durability and stability, environmental adaptability, versatile integration, self-powered and wireless transmission, biocompatibility and comfort, and large-scale, low-cost manufacturing. These principles provide comprehensive guidance for the design and optimization of sensors, helping to drive their widespread use in the field of health monitoring and medical diagnostics.

## 6. Conclusion

In this paper, we highlight the progress of the research work of high-sensitivity flexible temperature sensors for monitoring body temperature changes by combining the selection of active materials and patterned manufacturing processes, hoping to provide a reference for the application and future research and development direction of flexible electronic technology in the field of health monitoring and medical diagnosis. We review the research progress of high-sensitivity flexible temperature sensors and emphasize their potential for real-time and accurate monitoring of body temperature. In the future, flexible temperature sensors are expected to achieve large-area, low-cost fabrication; high sensitivity; self-powered operation; visualization; self-healing; biodegradability; and wireless remote sensing capabilities. Additionally, integrating multiple functionalities into these sensors will enable practical deployment in various applications. The collected temperature data can be integrated into health big data platforms, providing valuable support for future medical diagnostics. Furthermore, micro/nanopatterning fabrication techniques pave the way for low-cost, large-scale sensor production. With mature printing processes, the realization of multifunctional, large-area flexible devices is within reach. While current flexible temperature sensors have achieved high sensitivity, some remain susceptible to environmental interference. Future developments in flexible sensors for body temperature monitoring should focus on minimizing environmental impact. With further optimization of signal acquisition methods, real-time wireless visual data transmission under self-powered conditions could soon be realized—a major breakthrough for intelligent monitoring systems. The exploration of high-performance, easy-to-manufacture, low-cost, and widely applicable flexible temperature sensors will continue to drive innovation in this field.

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