

REVIEW

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Material, structural design, and post-processing strategies for strain-insensitive stretchable temperature sensors

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Abstract

This review provides a comprehensive survey of contemporary strategies for minimizing signal crosstalk in resistive temperature sensors, with particular focus on engineering approaches that achieve strain insensitivity. The discussion is structured to parallel the central themes of material selection, geometric structural design, and post-fabrication processing. First, the review categorizes conductive materials, including carbon-based nanomaterials, metallic nanostructures, and conductive polymers, highlighting how their intrinsic properties and structural forms determine sensor performance in terms of conductivity, flexibility, and mechanical robustness. The role of geometry-inspired designs, such as serpentine, multipolygonal, and Kirigami architectures, in enhancing mechanical compliance and contributing to the decoupling of thermal and mechanical signals is examined. Additionally, recent advances in post-fabrication processes, including welding, soldering, and surface treatments, are evaluated for their roles in maintaining long-term electrical stability and device reliability. By systematically integrating these multidisciplinary engineering strategies, this review delineates practical design principles for the advancement of next-generation resistive temperature sensors and provides a foundation for the robust integration of flexible electronics into a broad spectrum of emerging application domains. These insights are expected to accelerate innovation in wearable technology and other emerging fields, paving the way for the development of reliable, high-performance, flexible sensing systems.

Keywords Temperature sensor, Signal crosstalk, Strain insensitivity, Flexible sensors, Wearable electronics, Carbon nanomaterials, Metallic nanostructures, Conductive polymers, Geometry-Inspired structural design, Post-Fabrication processing

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Introduction

With the rapid advancement of wearable technology, interest in human–machine interfaces has significantly increased. Consequently, the demand for flexible and reliable temperature sensors has increased significantly. For example, studies have actively pursued the fabrication of wearable sensors in array formats for attachment to the wrist [1, 2], and the integration of artificial skin with sensors for the precise measurement of biosignals [3–5]. For wearable applications, temperature sensors must offer capabilities beyond high accuracy. Specifically, they must be flexible and lightweight for attachment to the skin. Additionally, properties such as mechanical compliance for integration with clothing, wireless communication capability, and miniaturization are required. Wearable temperature sensors must simultaneously exhibit stretchability, sensitivity, and long-term stability [6, 7]. Particularly, sensors for measuring body temperature require precision in the range of tens of millikelvins. To maintain high precision, the sensor must remain well-adhered to the user during free movement or deformation, and the data obtained from the sensor must be error-free. However, conventional temperature sensors, such as thermocouples, resistance temperature detectors (RTD), thermistors, and infrared (IR) sensors, have limited flexibility, leading to low skin conformability, which degrades the accuracy of temperature sensor signals.

Nanomaterial-based temperature sensors have been developed to overcome the limitations of conventional sensors [15, 17–19]. Although temperature sensors incorporating nanomaterials exhibit markedly improved flexibility and stretchability, they are now limited by electrical signal changes (crosstalk) caused by deformation. Crosstalk refers to signal interference caused by various physical stimuli, which can significantly reduce sensor accuracy [20, 21]. Therefore, strategies to minimize the influence of deformation on temperature sensing signals are needed.

For these reasons, research on ‘strain-insensitive’ temperature sensors that can accurately measure only temperature without interference from external mechanical deformation has emerged as an important research area. From a material selection perspective, some studies have achieved high stretchability and low resistance variations using copper-based metal films or spring structures [16, 22]. Other studies have attempted to achieve both flexibility and sensitivity using carbon-based nanomaterials such as graphene and carbon nanotubes (CNTs) [23, 24]. Beyond material selection, researchers have also explored structural design strategies to achieve strain insensitivity. For instance, multilayer stacking and waveform geometries have proven effective in decoupling temperature signals from mechanical deformation [14]. Furthermore,

the development of scalable fabrication methods, such as printing technologies using conductive polymers (e.g., PEDOT: PSS), metal oxides, and carbon-based materials, has facilitated the commercialization of flexible temperature sensors [25].

Computational signal decoupling methods have also been explored to eliminate interference after electrical signals are acquired from the sensor [26]. These methods can be categorized into two primary strategies: advanced signal processing and multifunctional sensor integration with circuit design. In the case of advanced signal processing, ultrathin conformal devices for skin temperature measurement have employed signal processing techniques to remove strain-induced artifacts. Specifically, these approaches leverage the differences in characteristic frequencies between motion and temperature changes to filter out residual strain-related variations through frequency-based signal analysis [27]. Meanwhile, multifunctional sensor integration with circuit design has demonstrated diverse strategies for strain suppression. For instance, differential readout circuits have been developed to eliminate strain-induced signal interference in temperature sensing [11]. CNN-based algorithms have been applied to sensor arrays to distinguish signal features from different sliding trajectories, achieving 96.67% accuracy. Furthermore, printable bifunctional sensors have achieved fully decoupled signal detection for simultaneous pressure-temperature sensing, demonstrating the potential of integrated multifunctional sensing systems [26]. While computational signal decoupling methods have proven effective, they require additional post-acquisition signal processing steps, which can increase system complexity and power consumption. Moreover, these approaches do not address the origin of strain interference at the sensor level. To date, previously published review papers on flexible sensors have primarily focused on materials, operating mechanisms, fabrication processes, and computational signal decoupling strategies. However, there remains a critical need to systematically examine design approaches that achieve strain insensitivity by fundamentally engineering the intrinsic physical properties of the sensor itself, thereby eliminating the need for extensive post-processing.

Therefore, this review comprehensively examines strategies for achieving strain-insensitive flexible temperature sensors through fundamental sensor design engineering. Existing approaches are categorized into three strategies: material selection, structural design, and post-fabrication processing. Representative cases demonstrating stable temperature sensing in wearable environments through these design strategies are illustrated in Fig. 1.

To provide a comprehensive overview, the representative studies corresponding to each design category are systematically summarized in Tables 1, 2 and 3. Table 1

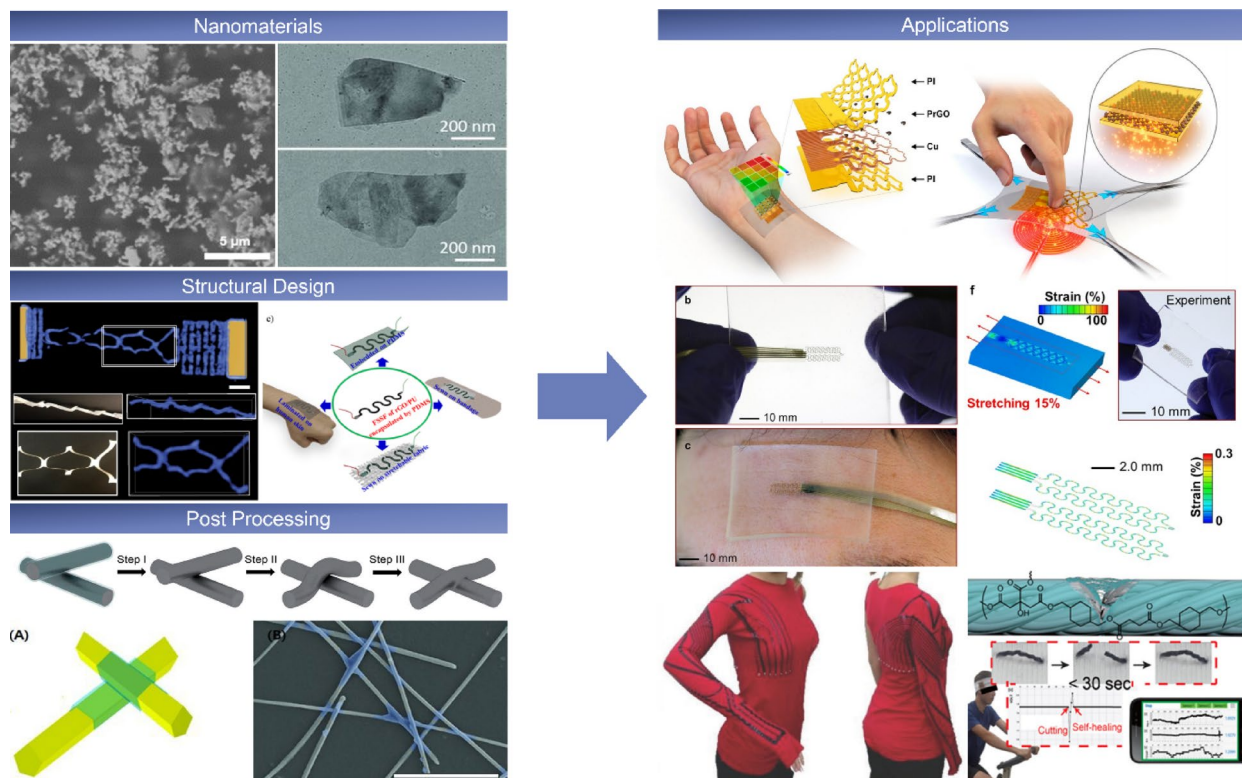


Fig. 1 Overview of strain-insensitive flexible temperature sensors: from nanomaterials to applications in wearable devices. Adapted with permission from [1, 8–16]. Reproduced with permission from [1], Copyright 2023 American Chemical Society (ACS). Reproduced with permission from [8], Copyright 2018 Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim. Reproduced with permission from [9], Copyright 2016 American Association for the Advancement of Science (AAAS). Reproduced with permission from [10], Copyright 2015 Springer Nature. Reproduced with permission from [11], Copyright 2018 American Chemical Society. Reproduced with permission from [12], Copyright 2013 Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim. Reproduced with permission from [13], Copyright 2014 Royal Society of Chemistry (RSC). Reproduced with permission from [14], Copyright 2016 Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim. Reproduced with permission from [15], Copyright 2019 American Chemical Society (ACS). Reproduced with permission from [16], Copyright 2007 Materials Research Society (MRS)

Table 1 Material selection-based strategies and summary of temperature sensing performance

Category	TCR (%/°C or %K ⁻¹)	Sensitivity ($\Delta R/R$ per °C)	Sensing range (°C)	Response/ recovery time	Linearity (R^2 or related)	Refs.
PEDOT: PSS/Graphene/PVA	1% /°C (0.01 K ⁻¹)	1.72% / °C (max)	20–75 °C	Response: 0.35 s	Good linearity (based on TCR)	[26]
CB/PVC Composite (6 wt%)	−0.148% K ⁻¹ (max)	(Same as TCR)	18–44 °C	Response: 0.7 s	Excellent linearity ($R^2 = 0.995$)	[28]
Au Thin Film (TCR sensor)	$1.7 \times 10^{-3} \sim 1.9 \times 10^{-3}$ K ⁻¹	-	25–50 °C	Response: ~5 ms (air blast test)	-	[29]

outlines material selection-based strategies, whereas Table 2 presents structural design strategies for strain-insensitive temperature sensing. Table 3 further summarizes post-processing strategies and their associated sensor performance improvements. Finally, this review provides an outlook on design principles and future research directions for developing highly reliable, deformation-insensitive temperature sensors.

Material-based approaches

This section examines cases wherein a material-based approach is employed to achieve flexible temperature sensors that are insensitive to mechanical deformation. Generally, flexible temperature sensors have structures wherein conductive particles are dispersed within a flexible polymer matrix. As the conductive particles come into contact with each other, a conductive pathway is formed, allowing current to flow and enabling the detection of temperature changes. Therefore, the shape and distribution of conductive particles, and their interaction with the polymer matrix, are key factors determining

Table 2 Structural design strategies and summary of temperature sensing performance

Category	TCR (%/°C or %K ⁻¹)	Sensi- tivity (ΔR/R per °C)	Re- sponse Time	Linearity	Refs.
Multipolygo- nal Structure (PEDOT: PSS/ Gra- phene/ PVA)	-	up to 1.6% /C;	0.35 s (20– 45 °C)	Excellent cy- cling stability (20– 75 °C; <0.5% sig- nal deviation)	[26]
Serpentine Metal Trace (Au, Si diode type)	0.1×10^{-3} – 1×10^{-3} K ⁻¹	-	~ 5 ms	High tempera- ture stability and mechanical reliability	[27]
Serpentine FSSF (R-GO/PU Fiber)	$-0.528\% \text{ K}^{-1}$ $\sim -1. \% \text{ K}^{-1}$	0.8% /°C	7 s	Linear ln(R) vs. 1/T relation	[11]

not only the overall performance of the sensor but also whether stable electrical responses can be maintained under mechanical deformation.

The shape of conductive particles greatly affects the ease of forming conductive pathways and their robustness against deformation. Some particle structures maintain stable pathways under deformation, while others break easily even under slight strain. Additionally, the interfacial properties between the particles and the polymer matrix, particularly dispersion and adhesion, are important factors determining the sensor's sensitivity to external deformation.

In this section, various conductive nanomaterials applied to flexible temperature sensors are classified according to the material type (carbon-based, metal-based, and conductive polymer-based materials) and geometric dimensions (0D, 1D, and 2D). The way in which the electrical responses to mechanical deformation vary depending on the specific shape is analyzed to provide practical criteria for material selection and structural optimization in future sensor designs.

Carbon

Carbon is a representative allotrope material that is widely used in the development of flexible electronic devices owing to its structural diversity and excellent electrical and mechanical properties [28, 29]. Particularly, carbon black (CB), fullerenes, CNTs, and graphene exhibit outstanding electrical conductivity, as the carbon atoms form sp² hybridized orbitals and engage in π-bonding. These π-electrons are delocalized, allowing free charge transport throughout the structure. Because of these characteristics, carbon-based materials have emerged as promising candidates for sensor applications that require both flexibility and high electrical responsiveness [30, 31].

According to their geometric structure, carbon-based materials can be classified into 0D fullerenes and CB, 1D CNT, and 2D graphene. This structural difference significantly affects the mechanical flexibility, stretchability, electrical properties, and response to deformation. For example, 0D CB is advantageous in terms of dispersibility and processability but may be less favorable for forming conductive pathways. 1D CNTs have high flexibility and resilience to tensile deformation, whereas 2D graphene provides a uniform electrical response over a large area but may suffer from conductivity loss when wrinkles or cracks occur.

This section compares and analyzes how various forms of carbon-based materials have been applied to flexible temperature sensors, and how their mechanical and electrical properties change depending on their structural dimensions. On this basis, an attempt is made to identify the most suitable form and application strategy of carbon materials for flexible sensor design.

Carbon black

CB is a 0D carbon nanomaterial composed of amorphous nanoparticles produced from the incomplete combustion of hydrocarbon gas. These nanoparticles, typically ranging from 10 to 100 nm exist as agglomerates

Table 3 Post processing strategies and summary of temperature sensing performance

Category	Material/sensor Type	TCR/Sensitivity change	Linearity/hysteresis improvement	Stability enhancement	Refs.
Photonic Sintering (IPL)	Ag Flakes / Ag NCs composite	Electrical conductivity increased from 1444.8 S·cm ⁻¹ to 2345.2 S·cm ⁻¹ ; Gauge factor (GF) improved from 4.9 to 7.1.	-	Maintained high mechanical stability over 10,000 cycles at 50% strain.	[30]
Thermal Annealing / Curing	Pentacene / Ag NPs (active matrix)	Activation energy(E _a) increased from 157 meV (pure pentacene) to 613 meV after annealing with 5 nm Ag NPs.	Very low hysteresis; stable with s < 0.002 during continuous measurement (25–40 °C).	Stable under continuous static operation for 10 min.	[29]
Chemical Reduction (Reduction Time Control)	Chemical Reduction (Reduction Time Control)	Chemical Reduction (Reduction Time Control)	Maintained linear ln(R)–1/T relationship.	Maintained linear ln(R)–1/T relationship.	[11]

and have large specific surface areas, making them suitable for the formation of conductive networks within a polymer matrix [33].

Because CB exhibits a percolation threshold, when a certain concentration is exceeded, tunneling occurs between the particles, resulting in a sharp increase in conductivity. Therefore, even a small amount of CB can control the composite's electrical properties. Composites based on CB exhibit a negative temperature coefficient (NTC), indicating that conductivity increases with temperature. This is because the polymer matrix expands slightly when heated, which changes the distance between the CB particles. As the particles move, the probability of electron tunneling increases, leading to an increase in the measured current.

The size and distribution of CB particles, and the interfacial interactions between the polymer matrix and CB, affect the composite's thermal stability. For example, CB introduced into ethylene propylene diene monomer (EPDM) rubber maintains thermal stability up to approximately 300 °C, ensuring stable sensor performance even in high-temperature environments.

Owing to its low processing cost and ease of patterning onto flexible substrates via screen printing, CB offers a significant advantage. For example, a temperature sensor fabricated by mixing polyvinyl chloride (PVC) and CB inks and screen printing exhibited a fast response time of 0.7 s, excellent repeatability, and high linearity [32]. Notably, polydimethylsiloxane (PDMS)/CB composites can be micropatterned using soft lithography, and adjusting the CB concentration enables an optimal balance between conductivity and mechanical flexibility [33].

When conductive polymers such as polyaniline (PANI) or polypyrrole are introduced onto the CB surface via *in situ* polymerization, the electrical connections between the particles are strengthened, enhancing the composite's overall conductivity and processability. Particularly, when applied to an EPDM matrix, this method results in a lower percolation threshold compared with pure CB, more uniform particle dispersion, and improved mechanical properties. Functionally modified CB can optimize interactions with polymers by regulating the inherent charge distribution on the particle surface, and also addresses the issue of the composite's increased viscosity. Consequently, thermal stability is improved, allowing the sensor to maintain its performance even during repeated operations [33].

Composites based on CB have been used in various flexible sensors. For example, NTC temperature sensors based on PVC/CB composites have been fabricated using printing-based processes. Wearable sensors fabricated from this material have also proven effective for the real-time monitoring of biosignals, such as respiration or skin temperature. Figure 2 illustrates the formation of

conductive pathways and the sensitivity characteristics in response to temperature changes. Additionally, sensors using PDMS/CB-based composites have exhibited properties suitable to dynamic signal detection, maintaining stable electrical characteristics even under repeated deformation owing to the agglomerated structure of CB, thereby enabling rapid recovery after mechanical stress.

Overall, owing to its superior electrical performance, processability, and functionalization ability, CB is well suited as a conductive component in flexible sensors. Particularly, its low percolation threshold, NTC properties based on electron tunneling, and ability to be functionalized with conductive polymers contribute significantly to the development of high-sensitivity sensors. Combining CB with various polymer matrices and integrating it with new processing technologies is expected to enable the development of flexible electronic devices with enhanced performance.

Carbon nanotubes (CNTs), classified as representative 1D carbon nanomaterials, exhibit unique electronic structures that possess both metallic and semiconducting properties. In metallic regions, electron mobility is significantly enhanced, while in the semiconducting regions—particularly at nanotube junctions—electron tunneling becomes a critical factor governing overall electrical conductivity. These characteristics serve as key mechanisms that determine the response of the conductive network formed by CNTs to mechanical deformation.

Multi-walled carbon nanotubes (MWCNTs) are nanomaterials comprising multiple concentric graphene cylinders, typically tens of nanometers in diameter and several micrometers in length. Their high aspect ratio, exceptional tensile strength, and excellent electrical conductivity render them ideal one-dimensional nanofillers [35]. When dispersed in a silicone rubber matrix, MWCNTs spontaneously self-assemble into an interconnected electrical percolation network, forming continuous conductive pathways even at low filler loadings [36]. By combining metallic charge transport through nanotubes with electron tunneling across adjacent tubes, the resulting composite exhibits heightened sensitivity to both temperature changes and mechanical deformation [37].

A cross-stacked CNT film is a structure wherein CNTs are arranged in an intersecting pattern in two directions. This configuration imparts isotropic electrical properties to the film, enabling it to maintain consistent conductivity under deformation in various directions. Notably, even under tensile strains up to 35%, the relative change in resistance remains as low as 3%–6%, indicating remarkable stability. Furthermore, the cross-stacked arrangement ensures that the external mechanical deformation is uniformly distributed across the entire conductive network, allowing the preservation of conductive

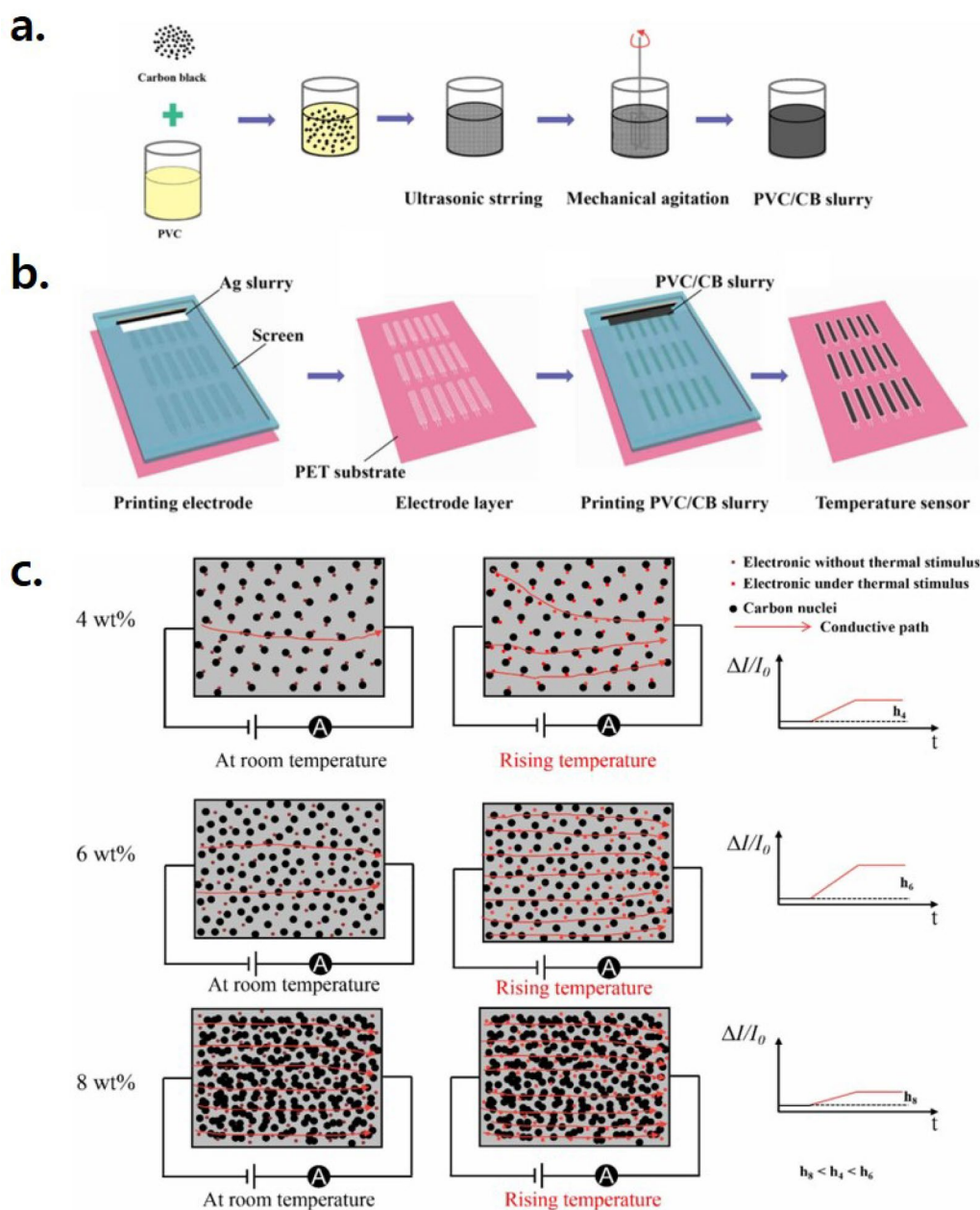


Fig. 2 Fabrication process and operating mechanism of temperature sensors based on PVC/CB composites. (a) Schematic diagram of process steps involved in producing temperature-responsive functional PVC/CB slurry [32]. (b) Preparation of Ag electrode on polyethylene terephthalate (PET) substrate followed by sequential formation of functional PVC/CB layer [32]. Reproduced with permission from [32], Copyright 2021 IOP Publishing Ltd. (c) Various electrical conduction behaviors and proposed temperature-responsive mechanism in PVC/CB films [24]. Reproduced with permission from [24], Copyright 2018 Multidisciplinary Digital Publishing Institute (MDPI)

pathways even when the sensor shape changes. Particularly, composite materials fabricated by incorporating cross-stacked CNTs into PDMS exhibit stable electrical resistance characteristics under repeated tensile loading, making them suitable for application in wearable electronic devices [38].

Furthermore, enhancements in conductivity and sensing performance have been achieved through the development of silver/multiwalled-CNT (Ag/MWCNT)

composites that integrate silver nanoparticles (AgNPs) and flakes with MWCNTs to form a hybrid film [39]. These composites exhibit a combination of high electrical conductivity, excellent printability, and outstanding mechanical stretchability. The CNT network imparts significant mechanical flexibility and ensures resilience to external mechanical deformation. Moreover, the integration of AgNPs introduces temperature-sensitive characteristics, thereby rendering the composite materials

particularly advantageous for use in high-sensitivity temperature sensor applications. The Ag/MWCNT composite maintains conductivities of up to 20 S/cm at strains exceeding 140%, exhibiting stable electrical performance under repeated stretching and recovery cycles.

Another notable approach involves the fabrication of strain-programmable CNT sensors [34]. These sensors have been produced by spray coating single-walled CNT (SWCNT) films onto a PDMS substrate, followed by pre-straining and releasing the substrate to produce a wave-shaped buckled structure. This process establishes a “strain-programmed” state wherein the sensor does not exhibit further change in resistance within a predetermined deformation range. Strain programmability arises from the alignment and wave memory acquired by CNT bundles subjected to strain. Consequently, it is possible to fabricate sensors that are insensitive to mechanical strain and exhibit resistance changes exclusively in response to temperature [37].

Figure 3 shows the fabrication process, structure, and characterization of the SWCNT-based strain-programmable sensors. Figure 3a illustrates a structure wherein the SWCNT film was oxidized, laminated onto a PDMS substrate, and finally covered with another PDMS layer to form the composite. Figure 3b shows a photograph of the sensor fabricated using this process, demonstrating

its flexibility under bending and twisting conditions. Figure 3c shows that the relative resistance change ($\Delta R/R_0$) remains constant within a certain strain range, confirming that the sensor exhibits strain-insensitive characteristics within that range.

For the reasons stated above, CNTs have attracted attention as key materials for flexible sensors because of their excellent electrical and mechanical properties. Through various design strategies, such as cross-stacked structures, Ag/MWCNT composites, and strain-programmable architectures, it is possible to eliminate noise signals caused by strain and achieve response characteristics that are sensitive only to temperature. Sensors based on CNTs are expected to become core technologies in fields requiring precise measurements, such as wearables, biofeedback, and artificial skin.

Graphene

Graphene, a typical 2D carbon nanomaterial, comprises a honeycomb-shaped planar array of carbon atoms with sp^2 bonds. It has excellent thermal conductivity (~ 3000 W/m·K), mechanical strength (1 TPa), and high electron mobility. The high aspect ratio of graphene enables it to achieve electrical conductivity above the percolation threshold, even at low filler concentrations.

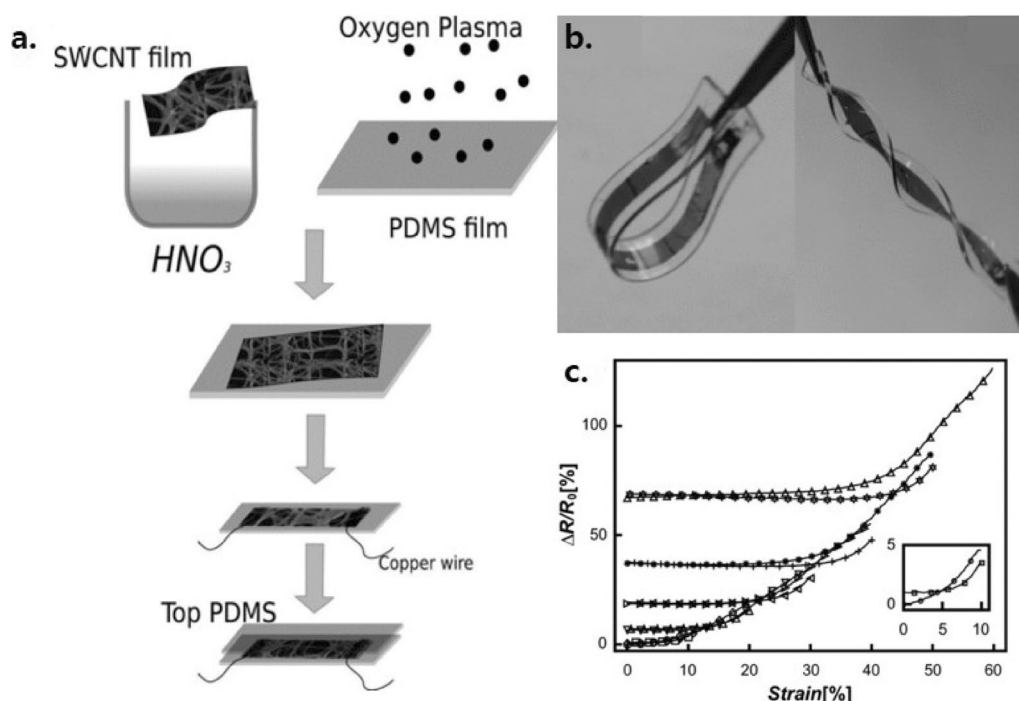


Fig. 3 Design of strain-programmable sensors based on SWCNT/PDMS Composites. (a) Illustration of preparation process for SWCNT/PDMS stretchable conductors [34]. (b) Photographs of bent and twisted SWCNT/PDMS stretchable conductors illustrating their flexibility. The opacity is attributed to the relatively thick SWCNT films used [34]. (c) Representative $\Delta R/R_0$ –strain curves from six successive loading–unloading cycles, illustrating influence of strain history on $\Delta R/R_0$. The inset provides a close-up of the initial loading–unloading cycle [34]. Reproduced with permission from [34], Copyright 2012 Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim

Graphene oxide (GO) undergoes an oxidation process that introduces hydrophilic functional groups, such as hydroxyl, epoxy, and carboxyl groups, onto the carbon framework. Consequently, GO exhibits excellent dispersibility in aqueous solutions. However, the electrical conductivity can be partially restored by reducing GO, a process that partially recovers the sp^2 bonding structure [41].

Graphene can be processed into polymer composites through various fabrication methods. When GO is functionalized with agents such as phenyl isocyanate, and then mixed with a polymer in a dispersion medium and reduced, a graphene-polymer composite with excellent dispersibility is formed. This composite exhibits a very low percolation threshold of 0.1 vol%, achieving a conductivity of approximately 0.1 S/m at 1 vol%.

The versatility of graphene-based composites is further exemplified by their application to flexible sensors. A notable approach involves the development of ‘G-putty,’ which is produced by integrating graphene with low-viscosity and highly elastic silicone (Silly Putty) [9]. In this system, graphene particles possess mobility within the matrix, in contrast to the fixed conductive fillers found in conventional composites. This unique property enables the formation of self-healing conductive networks that can re-establish electrical pathways even after repeated deformation. Despite this advantageous self-healing capability, a drawback arises from the progressive increase in resistance under continuous strain. Nonetheless, G-putty exhibits exceptional sensitivity, with a gauge factor surpassing 500, enabling the detection of minute

pressure variations, such as those generated by heartbeats or the footsteps of small insects.

Another representative example is the use of three-dimensional (3D) graphene foam (GF) fabricated via chemical vapor deposition (CVD) [40]. When this highly conductive foam is incorporated into a PDMS matrix, the resulting composite exhibits outstanding electrical conductivity of approximately 10 S/cm, even at low graphene loadings of 0.5 wt%. Furthermore, it maintains excellent mechanical stability with the electrical properties remaining essentially unchanged after 10,000 bending cycles and up to 95% strain.

Figure 4 illustrates the fabrication process and characterization of the GF composite. Figure 4a shows the photographs and scanning electron microscopy (SEM) images of the GF, revealing its highly interconnected porous structure. This 3D connectivity allows GF to withstand large deformations without structural damage, ensuring stable conductive pathways and offering a significant advantage over traditional 2D conductive particle-based composites.

As shown in Fig. 4b, the fabrication steps are as follows: GF growth on Ni substrate, polymethyl methacrylate (PMMA) coating, metal etching, and PDMS composite formation. Figure 4c shows the results of cyclic tensile–release testing at 50% strain, where the normalized resistance change ($\Delta R/R_0$) remains stable even after repeated stretching. Figure 4d shows the relationship between the conductivity and graphene content based on the average number of graphene layers, providing insights for optimizing structural conditions.

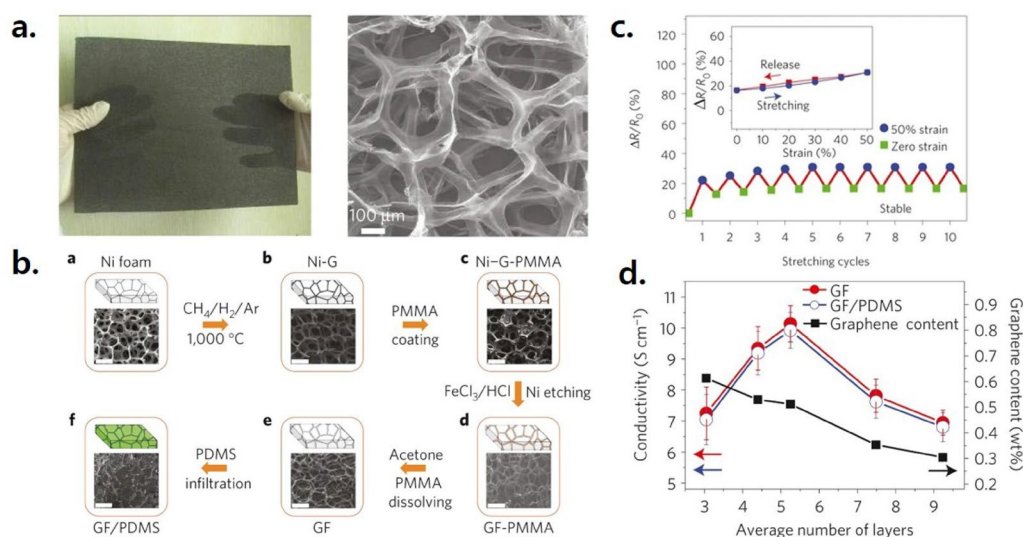


Fig. 4 Fabrication process and characterization of graphene foam (GF). (a) Actual photographs and scanning electron microscopy images of GF [40]. (b) Schematic of GF/PDMS composite fabrication process based on chemical vapor deposition [40]. (c) Results of cyclic tensile–release testing on GF/PDMS composite sensors [40]. (d) Conductivity versus graphene content relationship [40]. Reproduced with permission from [40], Copyright 2011 Springer Nature

Graphene is a highly promising material for flexible electronics owing to its structural, electrical, and processing advantages. Moreover, its high aspect ratio, surface area, electrical resilience, and 3D structural compatibility outperform those of conventional carbon-based composites. Self-healing composites such as G-putty (leveraging viscoelasticity) and CVD-based GF composites excel in sensor sensitivity and durability. The optimal combination of these properties is expected to play a vital role in the development of high-performance and reliable flexible sensors.

Metal

Metals are widely used owing to their superior electrical and thermal conductivities. However, their conventional bulk forms are inherently rigid, limiting their suitability for flexible or wearable electronic applications. To overcome this problem, metals have been processed into nanostructures. The conductivity, flexibility, and thermal stability of the resulting composite materials differ depending on whether the nanostructure is a 0D particle, 1D nanowire, or 2D nanosheet. For example, 0D particles offer excellent flowability and adaptability to deformation. 1D nanowires are advantageous for forming long conductive pathways, whereas 2D nanosheets provide a large conduction area and are well-suited for conformal integration with substrates. Recently, hybrid conductive networks combining various structures have attracted considerable attention.

This section compares and analyzes the electrical properties, thermal responsiveness, and structural advantages and disadvantages of various shapes (nanoparticles, nanowires, nanosheets, and flakes) based on gold (Au) and silver (Ag), suggesting directions for designing metal-based flexible sensors with maximum resistance to deformation.

Au nanosheets and Au nanoparticles

Because of its excellent electrical conductivity and chemical stability, Au is widely used in flexible sensors. Particularly, when Au is processed into nanostructures, such as 0D particle-shaped nanoparticles or 2D sheet shapes nanosheets, these nanostructures exhibit distinct differences in conductivity and mechanical stability depending on their shape.

Composites based on Au nanoparticles (AuNP), which are 0D nanomaterials, are fabricated using polyurethane (PU) and layer-by-layer (LBL) or vacuum-assisted flocculation (VAF) processes. These composites exploit the inherent dynamic rearrangement ability of 0D particles, allowing the nanoparticles to reorganize within the matrix and contribute to the formation of functional networks. Initially, the conductive network is unstable;

however, when external deformation is applied, the nanoparticles spontaneously align along the stretching direction through self-organization. After alignment, the newly formed conductive pathway exhibits higher resistance compared with the initial pathway. However, after a certain number of repetitions, the resistance change stabilizes. This is a notable example of achieving both higher deformation resistance and flexibility compared with composites fabricated using the VAF method [44].

Particularly, AuNP-based composites form an internal 1–5 μm cellular network when stretched, resulting in behavior similar to the fluid conductive pathways of liquid metals. After the tensile force is removed, the structure is rearranged back to its original shape, enhancing durability under repeated deformation.

Because Au nanosheets have a thin and wide 2D plate structure, flexible electrodes can be fabricated by stacking multiple layers and transferring them onto elastic substrates such as Ecoflex or PDMS. This structure forms a strain-memory zone where there is almost no change in resistance, even at high strains of up to 100%. In this zone, the initial resistance is almost perfectly restored, even after repeated stretching [45]. Conductivity tends to increase with the number of stacked layers, and the resistance can be lowered to approximately $2.5 \times 10^{-6} \Omega\cdot\text{m}$ through annealing. Additionally, sliding and wrinkling between nanosheets allows local absorption of stress, contributing to long-term electrical stability.

In summary, Au-based nanostructures offer multiple benefits for flexible temperature-sensing applications. Au nanosheets exhibit excellent mechanical strength and electrical stability, whereas Au nanoparticles exhibit superior fluidity and adaptability owing to their self-organizing capabilities. These features make Au an attractive material for the development of flexible temperature sensors.

Ag nanowires, ag nanoparticles, and ag flakes

Among all metals, Ag has the highest electrical conductivity. When Ag is nanostructured as nanowires, nanoparticles, or flakes, each form exhibits unique electrical and mechanical properties. These forms are used alone or in hybrid structures to fabricate flexible sensors with high sensitivity and stretchability.

Among 0D nanomaterials, Ag nanoparticles (AgNP) represent one of the most widely utilized forms of nanostructured silver. AgNPs are typically dispersed within polymer matrices to fabricate conductive composites that combine the mechanical flexibility of polymers with the excellent electrical properties of silver. This approach has been extensively explored for applications in flexible and stretchable electronics, where maintaining electrical conductivity under mechanical deformation is critical. Park et al. [46] infiltrated an AgCF_3COO precursor

into styrene butadiene styrene (SBS) rubber fibers to form AgNPs inside the fibers. When the composite was stretched, the Ag on the fiber surface fractured into segments that served as conductive bridges between adjacent fibers, making it easier to maintain a conductive pathway. Therefore, even after repeated deformation, the electrical properties were relatively stable.

In addition to 0D AgNPs, 1D Ag nanowires (AgNWs) have emerged as highly effective conductive fillers for stretchable electronics. Notably, AgNWs have a one-dimensional high-aspect-ratio structure, low percolation threshold, and a remarkable ability to form conductive networks [47]. As a representative example, Xu et al. [43] embedded AgNWs under a PDMS surface to create a stretchable conductor. Initially, this conductor exhibited higher resistance owing to sliding. However, after repeated cycling, new contact points were formed, resulting in electrical stability. Kim et al. [48] transferred AgNWs onto pre-strained PDMS to form a wrinkled structure, which acted as a buffer layer that absorbed deformation as the wrinkles unfolded during stretching.

Figure 5b shows the step-by-step process used to fabricate the composite materials. A solution containing

Ag nanowires (AgNWs) is coated onto a Si substrate, and then PDMS is laminated and cured to produce an AgNW/PDMS composite. Figure 5c shows a graph of the electrical properties of the fabricated composite; the graph on the left compares the resistance change in the initial state and after repeated stretching. The resistance measured after repeated stretching indicates that the electrical properties have stabilized. The graph on the right shows the ratio of resistance change according to strain. Even at 50% strain, the change in the resistance is small, confirming the excellent stretchability and stability of the fabricated composite [42].

Beyond 0D and 1D silver nanomaterials, two-dimensional (2D) silver flakes have also been extensively explored as conductive fillers. The 2D plate structure of Ag flakes, and their ability to move within elastic materials such as Ecoflex, allow conductive pathways to be maintained even during deformation. Kim et al. [8] used Ag flakes to fabricate a conductive layer by screen printing and transferring it onto a hydrogel–elastomer composite substrate, achieving an ultrahigh stretchability of approximately 1780%, similar to human skin. Matsuhisa et al. [49] developed a printable elastic conductive ink

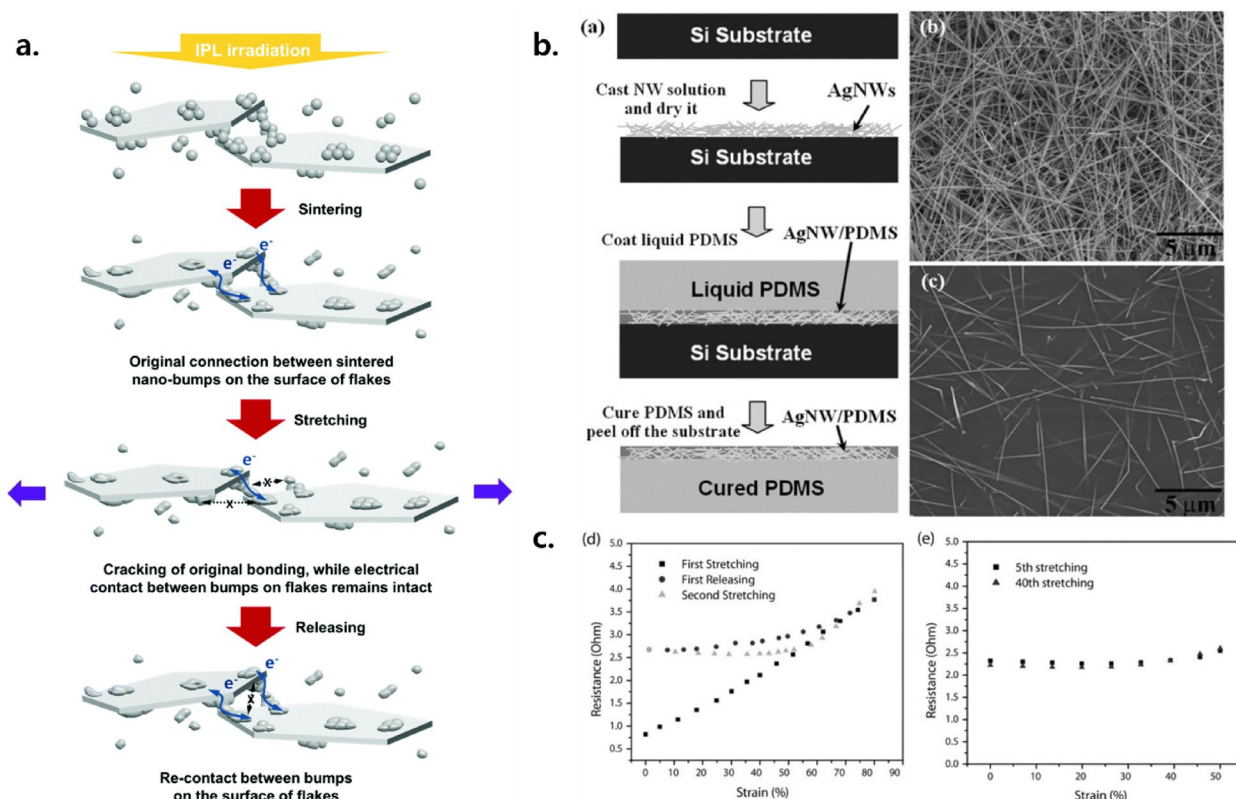


Fig. 5 Photonic sintering-based welding characteristics and stretch stability of Ag flake/AgNW composite electrodes. (a) Electrical contact between nano bumps formed via photonic sintering and stretch recovery mechanism [42]. Reproduced with permission from [42], Copyright 2018 The Royal Society of Chemistry. (b) Fabrication process of AgNW/PDMS composites and SEM images of AgNW networks [43]. (c) Resistance change characteristics of composites under repeated stretching and strain rates [43]. Reproduced with permission from [43], Copyright 2012 Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim

using Ag flakes and fluoro-rubber. This ink maintains conductivity above 182 S/cm, even at 215% strain, and can be printed on various flexible substrates without an adhesive layer.

Furthermore, post-treatment processes applied to Ag flake composites can significantly enhance their electromechanical performance. Figure 5a shows that IPA irradiation leads to the formation of nano bumps on the surface of the Ag flakes, enabling fine sintering between these bumps. Through this process, even if some formed bonds are partially broken under external strain, electrical contact is preserved. After the stress is released, contact is restored, and the conductive pathway is reformed.

In addition to single-component systems, hybrid composites that combine nanomaterials with different geometric dimensions have been developed to leverage the synergistic advantages of each component. Particularly, there is a case wherein 2D Ag flakes and 1D CNTs are mixed to form a 3D conductive network, achieving both printability and mechanical resilience. Composites prepared by mixing 0D AgNPs and 2D Ag flakes and have also attracted attention. As shown in Fig. 5, photonic sintering causes AgNPs to form nano bumps between the Ag flakes, reducing contact resistance. Consequently, a highly sensitive sensor with a gauge factor (GF) of 7.1 is realized.

Conductive polymer

Conductive polymers achieve electrical conductivity through π -conjugated structures. Unlike sensors based on inorganic materials, polymeric materials are easy to process, flexible, and lightweight, which allows them to maintain stable operation even under deformation. Additionally, they can be easily printed and coated onto various substrates, such as paper, fabric, or polymer films, enabling applications in large-area flexible sensor arrays and low-power devices [50].

Conductive polymers use the Seebeck coefficient for thermoelectric effects, allowing self-powered sensors to convert temperature changes into electrical signals without an external power source. This is advantageous for applications such as biosensors, environmental monitoring, and wireless sensor networks, which require minimal power consumption. Conductive polymers have low thermal conductivity, density, stretchability, and chemical resistance, providing a more suitable combination of properties for flexible sensors compared with conventional inorganic thermoelectric materials (such as Bi_2Te_3 and Sb_2Te_3) [51, 52].

This section focuses on the representative conductive polymers PEDOT: PSS and PANI, and discusses examples of flexible temperature sensors using these materials. The objective of this review was to analyze their electrical

and mechanical advantages, and their strain-insensitive temperature-sensing characteristics.

PEDOT: PSS

The conductive polymer composite poly(3,4-ethylenedioxythiophene) (PEDOT) and its complex with poly(styrene sulfonate)(PEDOT: PSS) is widely used in the design of strain-insensitive flexible temperature sensors. It consists of a conductive π -conjugated backbone of PEDOT and PSS for stabilization. This structure provides both flexibility and electrical conductivity, making it suitable for use in flexible sensors.

Moreover, PEDOT: PSS can be easily coated onto various substrates, including paper, fabric, and polymer films, simplifying the fabrication of flexible devices. It retains its conductive properties under external pressure and mechanical stretching, thereby ensuring stable electrical performance. Collectively, these characteristics make PEDOT: PSS particularly well-suited for temperature-sensing applications that require minimal resistance variation during deformation and reliable temperature sensing [50]. A previous study demonstrated that coating PEDOT: PSS on paper enables the fabrication of a flexible p-type thermoelectric device that can be paired with an Indium Tin Oxide (ITO) electrode to establish a p-n thermocouple structure. In this study, a self-powered temperature sensor was fabricated using the Seebeck effect. The paper-based conductive layer provided flexibility and deformation resistance, enabling stable conductivity and temperature sensing, even under external physical stimuli such as stretching or compression [51].

Research on the thermoelectric properties of PEDOT: PSS is ongoing. Particularly, adding high-boiling-point solvents such as dimethyl sulfoxide (DMSO) significantly enhances electrical conductivity, while also increasing the thermoelectric power factor ($\text{PF} = S^2\sigma$). However, PEDOT: PSS has a low Seebeck coefficient. Therefore, to maximize the power factor while maintaining high conductivity, it is necessary to precisely control the doping level, substrate selection, and post-treatment conditions [52].

Owing to its outstanding mechanical flexibility and electrical conductivity, PEDOT: PSS has established itself as a crucial material for strain-insensitive flexible temperature sensors. Its versatility supports diverse applications ranging from paper-based thermoelectric devices to wearable biosensors, highlighting its significant potential in the field of flexible sensing technologies.

Moreover, PEDOT: PSS combines mechanical flexibility with stable electrical conductivity, making it a key material for strain-insensitive flexible temperature sensors. Its successful application in devices ranging from paper-based thermoelectric sensors to wearable

biosensors highlights its potential for advancing flexible sensing technologies.

PANI

Among conductive polymers, polyaniline (PANI) is one of the most widely investigated. Because of its inherent conductivity, flexibility, excellent environmental stability, and ease of doping, PANI is widely used in sensors, offering high electrical conductivity comparable to that of metals, in addition to the advantages of polymers such as processability and tunable structures. These characteristics make PANI a strong candidate for use in various flexible electronic devices such as biosensors, electrochemical sensors, and temperature sensors.

Three oxidation states are possible for PANI: leucoemeraldine, emeraldine, and pernigraniline. Depending on the oxidation-reduction state and doping conditions, PANI can assume these states, resulting in conductivity changes. By utilizing electron hopping, PANI sensors can respond sensitively to various environmental stimuli [54]. Recently, highly sensitive biosignal detection, biomarker detection, and thermoelectric response devices based on PANI have been developed. Notably, PANI can be fabricated into various structures, such as nanofibers, nanotubes, and nanoparticles, to increase its surface area and exhibit excellent electrochemical properties. Consequently, PANI sensors exhibit high sensitivity and fast response times.

Liu et al. [53] developed a highly linear temperature sensor by combining PANI and graphene as conductive polymers and compounding them with PDMS. Conventional sensors fabricated by integrating graphene and PDMS exhibit high sensitivity and fast response; however, their resistance changes are nonlinear. To address this issue, Liu et al. [53] used both graphene and PANI to create a temperature sensor with linear resistance changes. Figure 6a presents a schematic illustration of the PANI: Graphene/PDMS temperature sensor structure fabricated by Liu et al. The NTC of PANI complements

the positive temperature coefficient (PTC) of graphene/PDMS, and results in an overall linear resistance change. Therefore, the sensor achieved excellent performance with a sensitivity of 1.60% per °C, response time of 0.7 s, and linearity ($R^2 = 0.99$). Figure 6b displays the temperature-dependent conductivity behavior of the sensor. Furthermore, by adjusting the mixing ratio of PANI and graphene, the linearity could be tuned as required for specific applications.

Such studies have revealed that PANI can serve not only as a simple solid matrix, but also as an active sensing layer in combination with various nanomaterials such as CNTs and graphene.

PPy

Polypyrrole (PPy) is a conductive polymer synthesized through oxidative polymerization of pyrrole monomers. As a p-type semiconductor, PPy exhibits temperature-dependent electrical conductivity arising from thermally activated charge carrier generation, making it particularly suitable for temperature sensing applications. Its mechanical flexibility and biocompatibility enable integration into soft substrates for wearable temperature monitoring while maintaining stable thermal response under mechanical deformation [55]. This section presents two representative architectures of PPy-based flexible temperature sensors: PPy-integrated organohydrogel systems and PPy-coated textile substrates.

A novel PPy-based organohydrogel sensor was developed using lignosulfonate (LS) as a structural template and a dynamic redox initiation system [56]. This approach enabled the in situ formation of LS-PPy nanofillers within a glycerol/water co-solvent system, completing the polymerization process in only three minutes without external thermal or UV stimulus. This represents a significant advancement over conventional conductive hydrogel fabrication methods, which typically require prolonged polymerization times and substantial energy input.

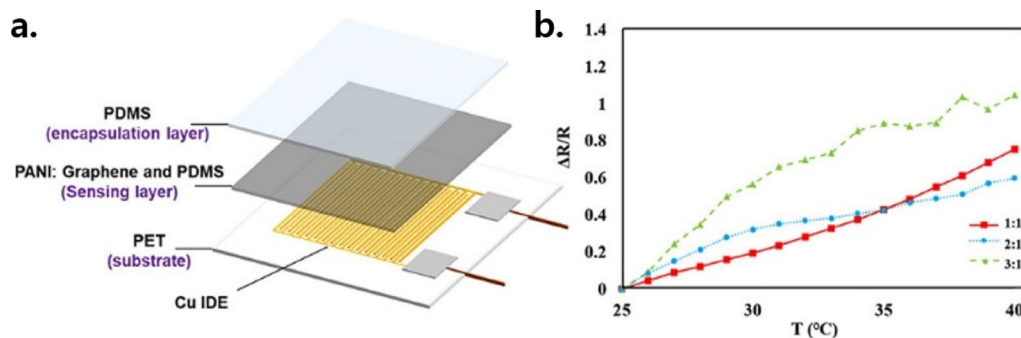


Fig. 6 PANI: Graphene/PDMS temperature sensor by Liu et al. [53]. (a) Schematic of temperature sensor structure [53]. (b) Temperature and conductivity curves of temperature sensors with varying concentration ratios (PANI to graphene ratios of 1:1, 2:1, and 3:1) [53]. Reproduced with permission from [53], Copyright 2022 American Chemical Society (ACS)

The temperature-sensing mechanism of the LS-PPy organohydrogel arises from synergistic ionic and electronic conduction effects. As temperature increases, enhanced ion mobility and diffusion within the hydrogel network improve ionic transport. Simultaneously, the p-type semiconducting nature of PPy contributes thermally excited charge carriers, further increasing electronic conductivity. These combined effects result in a negative temperature coefficient (NTC) behavior, wherein overall resistance decreases with increasing temperature.

The LS-PPy/PAA organohydrogel sensor exhibits exceptional mechanical properties, sustaining up to 800% tensile strain and achieving a tensile strength of 56 kPa. It demonstrates strong adhesion to diverse substrates including wood, glass, metal, plastic, and human skin, underscoring its excellent wearability. The sensor operates reliably across a wide temperature range from $-20\text{ }^{\circ}\text{C}$ to $100\text{ }^{\circ}\text{C}$ with a temperature resolution of $0.5\text{ }^{\circ}\text{C}$. Within the physiologically relevant range of $36.5\text{--}40\text{ }^{\circ}\text{C}$, it exhibits a temperature coefficient of resistance (TCR) of $-$ sensor exhibits exceptional mechanical properties, sustaining up to 800% tensile strain. stPPy organohydrogel sensor particularly suitable for continuous body temperature monitoring and soft robotic applications.

An alternative strategy involves integrating PPy onto polyamide 66 textile substrates via a simple immersion-based polymerization process [57]. The textile is sequentially immersed in a pyrrole monomer solution and an oxidizing agent solution (sodium persulfate), leading to in situ chemical polymerization and the formation of a uniform $0.5\text{--}1\text{ }\mu\text{m}$ -thick PPy coating on individual fiber surfaces. This process is scalable, cost-effective, and preserves the intrinsic flexibility and softness of the original fabric due to the ultrathin nature of the conductive layer.

The temperature-sensing principle of PPy-coated textiles relies on the semiconducting behavior of PPy. As temperature increases, thermal energy enables electrons to overcome the bandgap barrier, increasing the population of mobile charge carriers. This results in enhanced electrical conductivity and decreased overall resistance. The sensor exhibits stable and reproducible thermal response characteristics even under continuous mechanical deformation such as bending or stretching, demonstrating strong potential for wearable and environment-adaptive electronic textiles.

The aforementioned examples clearly demonstrate that PPy is a highly versatile conductive polymer capable of adapting to diverse material platforms—from soft organohydrogels to flexible textiles—without compromising electrical or mechanical performance. The combination of excellent conductivity, high strain tolerance, temperature responsiveness, and facile synthesis makes PPy an ideal candidate for next-generation

soft electronics. Future research on PPy-based systems is expected to focus on enhancing long-term stability, multi-stimuli selectivity, and biocompatibility, thereby expanding their applications in wearable healthcare monitoring, smart clothing, and human–machine interface devices.

Geometrical structural design

Another key approach for achieving strain-insensitive flexible temperature sensors is the adoption of structural design strategies that disperse or absorb external deformations. By engineering the sensor structure to accommodate mechanical deformation, mechanical stability can be enhanced without substantially altering the intrinsic properties of the sensor material. In wearable applications, sensors are frequently subjected to complex mechanical deformations, such as repeated bending, stretching, and compression, underscoring the importance of structure-based design.

Representative structural designs include serpentine, helical/spiral, kirigami, multipolygonal, and fractal patterns, each offering distinct mechanisms for strain accommodation. These architectures collectively preserve the integrity of conductive network and electrical functionality of conductive network under deformation. This section systematically analyzes the materials and fabrication methods employed for each structural design, the effectiveness of each structure in absorbing mechanical deformation, and the resulting changes in the electrical properties and geometry of the sensors under strain. This analysis provides a comprehensive overview of structural strategies that can be leveraged in future sensor designs to enhance strain insensitivity.

Serpentine design

The serpentine structure represents one of the most widely employed design strategies for enhancing the mechanical deformability of stretchable sensors [34, 58, 59]. This snake-like, meandering geometry is specifically engineered to structurally absorb strain induced by applied mechanical deformation, thereby minimizing stress concentration at critical device components [27]. The fundamental design principle of serpentine structures lies in mechanically decoupling the system-level deformation from local strain experienced by individual sensor elements and interconnects. By eliminating strain-induced interference through this architectural approach, the serpentine configuration ensures that even when the entire system undergoes large mechanical deformation, only minimal local strain is transmitted to the active sensing components. This mechanical decoupling is crucial for maintaining device integrity and electrical performance under dynamic loading conditions. When devices

are mounted on complex, non-planar surfaces such as human skin—particularly at high-deformation regions like knees and elbows where strains can reach up to 100%—the serpentine interconnect lines accommodate system-level tensile strains through microscale buckling and twisting mechanisms [27]. These deformation modes enable the structure to redistribute applied loads effectively, allowing the device to conform to natural skin movements without compromising the stability of the underlying sensor elements.

This strain-accommodation capability makes serpentine structures particularly advantageous for wearable temperature sensors intended for direct skin attachment [11]. By preserving electrical performance while withstanding significant mechanical strain, the serpentine design enables reliable, continuous temperature monitoring during various body movements and activities, thereby expanding the practical applications of epidermal sensing platforms.

Tran et al. [11] fabricated free-standing stretchable fibers (FSSF) comprising rGO and PU and subsequently formed these fibers into a serpentine structure to achieve high flexibility and resistance to deformation. The FSSF was partially embedded within a PDMS substrate, facilitating direct skin attachment and further minimizing the influence of mechanical deformation on sensor performance through an optimized geometric design. The resulting FSSF exhibited a stretchability exceeding 90% and a temperature sensing resolution of 0.1 °C. Notably, even under 50% tensile strain, the response error remained within ± 0.37 °C, indicating excellent strain insensitivity.

By adjusting the reduction time of rGO, the mechanical properties of the composite fibers could be effectively tuned, resulting in the elongation at break exceeding 500%. This indicates that the fiber exhibited excellent mechanical elasticity under various conditions, enabling reliable operation even in wearable applications subject to repeated skin deformations.

Yan et al. [59] embedded crumpled graphene as a temperature-sensing channel and Ag NWs as electrodes, with both components fully encapsulated within a PDMS matrix. The sensing channel was designed in a serpentine configuration to maximize the spatial efficiency and effectively distribute mechanical stress. This structural design preserves the thermoelectric properties of the sensor even when subjected to 50% tensile strain. Furthermore, the thermal index can be modulated by mechanical deformation, which is not possible with conventional ceramic-based thermistors.

Webb et al. [27] developed an ultrathin conformal device featuring a sandwich structure comprising polyimide layers and a metal serpentine pattern. This structural design enhanced skin adhesion and ensured

sustained precision in thermal measurements, enabling the device to maintain both accuracy and sensitivity even after prolonged attachment to the skin. Various sensor materials, including PEDOT: PSS and silicon positive-intrinsic-negative (PIN) diodes, have been integrated into this architecture to measure temperature and thermal conductivity. Finite element analysis (FEA) validated the strain-insensitive characteristics conferred by the serpentine structure. For TCR-based devices with serpentine structures utilizing gold as the sensing material, FEA revealed that when 10% uniaxial strain was applied at the system level, the average strain experienced by the sensor itself remained below 0.02%. Since TCR sensors rely on the temperature-dependent resistance of gold to measure temperature, any strain-induced resistance change can be misinterpreted as a temperature variation. However, the minimal local strain of 0.02% translates to a measurement error equivalent to an apparent temperature shift of less than 50 mK. This negligible deviation demonstrates that the serpentine design effectively isolates the sensing element from mechanical deformation, thereby maintaining the accuracy of resistance-based temperature measurements even under substantial skin movement. Similarly, FEA performed on PIN systems (Si diode sensors) confirmed that maximum principal strains in the sensor remained below 0.55% under comparable system-level deformation. These results demonstrate that the serpentine structure effectively maintains measurement stability by inducing only minimal local strain on core sensing elements, even under large system-level deformations (e.g., 10%), thereby ensuring strain-insensitive performance for wearable temperature sensors intended for direct skin attachment.

The serpentine structure has a geometric design that effectively absorbs external mechanical stress without damaging the material's intrinsic electrical properties. Therefore, it has been widely adopted in stretchable temperature sensors, enabling precise and stable temperature measurements even on curved surfaces or in highly dynamic environments.

Multipolygonal design

The multi-polygonal structure comprises repeating polygonal units designed to accommodate mechanical deformations, including stretching and bending, in multiple directions. The mechanical superiority of multipolygonal structures in achieving strain-insensitive characteristics stems from their inherent ability to distribute mechanical stress effectively across the entire geometry. The polygonal configuration disperses externally applied strain throughout the structure rather than concentrating it at specific locations, thereby minimizing localized stress on the temperature-sensitive conductive layer. This optimized stress distribution mechanism

protects the sensing material from microcrack formation and preserves the continuity of conductive pathways, ensuring that the intrinsic electrical resistance remains stable under mechanical deformation and responds exclusively to temperature changes—the fundamental principle underlying strain-insensitive performance. Wang et al. [26] employed 3D direct writing to fabricate a PEDOT: PSS/graphene/polyvinyl alcohol (PVA)

composite ink, which was subsequently printed onto a multipolygonal structure on a breathable thermoplastic polyurethane (TPU) nanofiber substrate. This design strategy enhances the mechanical flexibility and sensing stability of the resulting skin-attachable temperature sensor, further demonstrating the effectiveness of multi-polygonal architectures in accommodating complex mechanical deformations while maintaining reliable

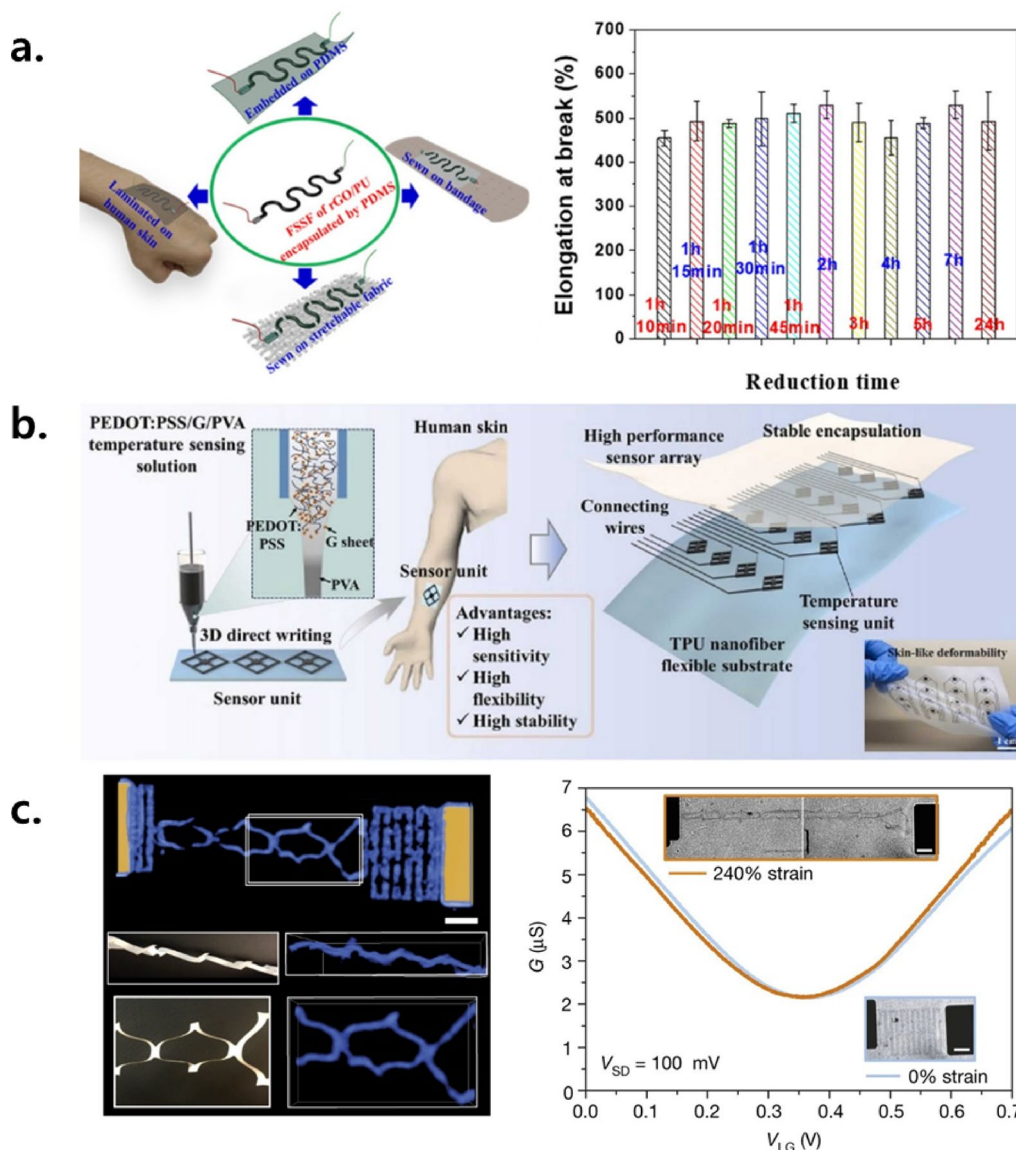


Fig. 7 Geometry-inspired deformation absorbing structures: serpentine, multipolygonal, kirigami. (a) Schematic diagram of free-standing stretchable fibers (FSSF) temperature sensor embedded into PDMS substrate, sewn onto stretchable fabric or bandage, and directly applied to human skin; elongation at break of reduced GO (rGO)/PU composite fibers derived from stress-strain curves [11]. Reproduced with permission from [11], Copyright 2019 American Chemical Society (ACS). (b) Schematic diagram of temperature sensor unit fabricated using 3D direct writing method and 4×4 temperature sensing array structure [26]. Reproduced with permission from [26], Copyright 2019 American Chemical Society (ACS). (c) 3D reconstruction from z-scan focal series of graphene spring, with right side adhered to surface and left side lifted; insets show sectional views of graphene (right) and paper models (left), with top images showing side views, bottom images showing top views, and thin grey lines indicating bounding box of reconstruction (aspect ratio of side-view paper model (compressed $\times 1.8$), scale bars = $10 \mu\text{m}$). Electrical conductance G as function of liquid-gate voltage V_{LG} at source-drain bias $V_{SD}=100 \text{ mV}$ in $\sim 10 \text{ mM}$ KCl solution is plotted before stretching (blue) and after 240% stretching (orange); the stretched device's top inset (orange-boxed) is split because its size exceeds visible area [10]. Reproduced with permission from [10], Copyright 2015 Springer Nature

sensor performance. Figure 7b shows the configuration and fabrication process of the sensor. On the left, the composition of the temperature-sensing material and printing process are shown; at the center, the sensor unit attached to the human body is shown; and on the right, the structure of the sensor array and its implementation on a flexible substrate are illustrated.

Finite element method (FEM) simulations conducted to quantitatively validate this mechanical advantage demonstrated that polygonal structures exhibit substantially lower stress levels compared to linear sensors under applied force, indicating reduced strain impact on the sensing layer. The polygonal design enhanced the strain resistance capability of temperature sensors by 200% relative to linear configurations. Performance testing revealed that linear sensors exhibited increased resistance at 20% strain, with sensing layer failure observed at 30% strain. In contrast, polygonal sensors maintained stability and only showed resistance increase trends at 40% strain. When polygonal sensors were subjected to 20% strain and subsequently released, the relative resistance change remained below 0.5%, and resistance returned to its initial value upon force removal, demonstrating excellent mechanical stability. These quantitative comparisons confirm that the polygonal geometry experiences the lowest stress among common structural configurations (including linear, serpentine, and mesh designs), establishing it as an optimal architecture for strain-insensitive stretchable temperature sensors. Fabricated on a breathable and flexible TPU nanofiber substrate, the sensor exhibited excellent sweat resistance and enabled prolonged skin attachment without causing discomfort or performance degradation. Even during physical exercise or in high-humidity environments, the signal-to-noise ratio remained below 4.8%, thereby ensuring stable temperature measurements under actual conditions. The sensor achieved a resolution of 0.1 °C and rapid response time of 0.35 s, exceeding the performance of conventional mercury thermometers and commercial electronic temperature sensors.

Collectively, these results indicate that the multi-polygonal structure offers highly reliable temperature sensing in both static and dynamic environments. Its mechanical and sensing characteristics make it well suited for wearable applications requiring stable, long-term attachment to nonuniform surfaces such as the human skin.

Kirigami design

The kirigami structure is inspired by the traditional Japanese art of cutting and folding paper to create geometric patterns. By introducing deliberate cut patterns into the material, this design overcomes mechanical limitations by structurally alleviating tensile and bending stresses. When deformation is applied to the two-dimensional

structure, controlled out-of-plane expansion occurs, imparting enhanced stretchability and maximizing mechanical flexibility and durability.

The most critical advantage of kirigami structures lies in their inherent strain-insensitivity—the ability to maintain electrical properties of the sensing material despite significant structural deformation. This characteristic is essential for realizing next-generation stretchable electronics intended for skin attachment and applications requiring substantial bending and stretching. The fundamental mechanism enabling this strain-insensitive behavior is the conversion of in-plane tensile strain into out-of-plane bending deformation. When tensile force is applied to a kirigami-patterned material, the atomic lattice itself does not stretch like a rubber band. Instead, pre-cut strips accommodate the external force by buckling and rising into three-dimensional space. The overall stretchability is therefore achieved not through tensile deformation of the material lattice, but through geometric bending of the cut structural elements. This deformation mode conversion allows kirigami structures to efficiently transform tensile energy into out-of-plane bending energy, effectively decoupling system-level stretching from material-level strain and thereby preserving the intrinsic electrical properties critical for accurate temperature sensing.

Blees et al. [49] implemented a Kirigami structure in monolayer graphene synthesized using CVD through photolithography and wet-etching techniques. Although conventional graphene exhibits limited stretchability owing to its intrinsic stiffness and atomic thinness, the kirigami pattern enables large deformations without compromising its lattice structure.

The fabricated kirigami-structured graphene transistor maintained approximately constant electrical conductivity under tensile strains of up to 240%, exhibiting effective stress relaxation via structural expansion (Fig. 7c). The left panel of Fig. 7c illustrates the actual Kirigami structure with Au electrodes, while the right graph shows a comparison of the conductivity changes at 0% and 240% strain. The data confirmed that the conductivity of graphene remained approximately unchanged across varying gate voltages despite significant strain.

This kirigami design features repeated cut lines that provide substantially enhanced strain accommodation compared with simple linear structures. Moreover, the device did not exhibit performance degradation after more than 1,000 stretching cycles, indicating its high reliability under repeated mechanical deformations. These characteristics highlight the potential of kirigami-patterned graphene for applications in durable strain-insensitive wearable sensors and transistors.

The application of kirigami structures overcomes the intrinsic limitations of two-dimensional materials,

providing a balanced combination of electrical performance and mechanical flexibility. Therefore, kirigami designs hold great potential for advancing the development of ultrathin, flexible sensors, and highly durable wearable devices.

Helical/spiral design

Helical and spiral structural designs have emerged as an effective geometry-based strategy to enhance mechanical tolerance and decouple undesired strain effects in stretchable temperature sensors. These coiled, spring-like configurations enable large mechanical deformations to be accommodated through structural unfolding and rotation rather than direct stretching of the active sensing material. Consequently, the local strain experienced by the functional layer remains minimal even under substantial external elongation, leading to significantly improved strain insensitivity and durability.

The mechanical advantage of helical and spiral architectures lies in their high design tunability. Parameters such as pitch, coil diameter, and winding density can be systematically adjusted to achieve an optimal balance between stretchability, sensitivity, and response stability. When applied to temperature sensors, these geometries effectively isolate thermoresistive or thermoelectric responses from mechanical deformation, enabling accurate thermal detection in dynamically moving environments. Such structural decoupling has made helical and spiral designs particularly attractive for wearable and textile-integrated electronics, where reliable performance under bending, twisting, or repeated stretching is essential. A representative example of this approach was demonstrated by Wang et al. [60], who developed an ionogel-based fiber sensor with a helical-inspired S-shaped configuration. The sensor was fabricated through wet-spinning of a thermoplastic polyurethane (TPU) and ionic liquid ([EMIm][NTf₂]) composite, yielding fibers with high stretchability (up to 700%) and excellent ionic conductivity. When patterned into an S-shape and integrated into elastic fabric, the fiber exhibited remarkable immunity to mechanical strain. The geometric deformation was absorbed by bending and rotation of the loops rather than stretching of the conductive pathway, thereby maintaining stable ionic mobility within the ionogel matrix.

This structural decoupling enabled the sensor to achieve exceptional temperature accuracy (± 0.15 °C under 30% strain) across a wide sensing range (−15 to 100 °C) while preserving rapid thermal response and stable negative temperature coefficient (NTC) behavior. The design demonstrated seamless integration into textile substrates for real-time, deformation-insensitive monitoring of human motion, respiration, and environmental temperature. Overall, this work exemplifies how helical

and spiral geometries—when combined with intrinsically soft, ion-conductive materials—provide a practical and scalable route to decoupling strain and temperature stimuli in wearable sensors, offering an instructive framework for the structural design of next-generation flexible thermal devices.

Fractal design

Fractal structures represent a class of self-similar geometries that exhibit pattern repetition across multiple scales, mimicking complex morphologies found throughout nature such as fern leaves, snowflakes, and vascular systems. These hierarchical architectures possess inherent space-filling characteristics that enable exceptionally high surface-area-to-volume (SA/V) ratios and efficient stress distribution pathways. In the context of flexible and stretchable electronics, fractal geometries offer a strategic approach to achieving both mechanical compliance and signal stability under deformation. Rather than concentrating strain at discrete points, the distributed branching network of fractal patterns redistributes mechanical stress throughout the entire structure, thereby minimizing localized fracture and electrical resistance variations during stretching or bending.

From a sensing perspective, fractal layouts substantially enhance the active interaction area between functional layers and external stimuli—whether thermal, mechanical, or chemical—while maintaining continuous conductive pathways. Their geometric scalability enables sensors to retain high fidelity and linearity across wide deformation ranges, making them particularly suitable for strain-insensitive thermal sensing applications. Through bioinspired design principles and advanced fabrication techniques such as printing and photolithography, fractal architectures have emerged as a versatile platform for next-generation soft sensors, combining the robustness of hierarchical organization with the adaptability required for wearable and deformable systems.

A representative demonstration of fractal geometry's functional advantages in sensing devices was reported by Hassan et al. [61], who developed bioinspired chemoresistive sensors patterned with space-filling fractal motifs including Sierpinski, Peano, and Hilbert curves. Using extrusion printing of graphene-based ink on flexible PET substrates, the researchers translated natural fern leaf architecture into two-dimensional fractal networks that maximized active surface area while preserving electrical continuity. Among these designs, the Hilbert fractal exhibited the highest Hausdorff dimension ($D \approx 1.73$) and achieved an effective SA/V ratio approximately ten times greater than conventional interdigitated electrodes. This geometrical enhancement enabled more efficient analyte adsorption and charge transfer, resulting in superior sensing performance (14% response at

30 ppm ethanol) with rapid response/recovery times (6 s/36 s at room temperature). Critically, the fractal geometry also conferred excellent mechanical robustness: the Hilbert-patterned sensor maintained stable performance under bending deformation, with positive bending further accelerating response kinetics due to compression-induced shortening of conductive pathways.

Although this study focused on volatile organic compound detection, the underlying design principle—leveraging self-similar, hierarchical fractal geometry to enhance signal uniformity and mechanical tolerance—is readily extensible to thermal sensing modalities. In temperature sensors, fractal architectures can facilitate uniform thermal distribution across the sensing area and mitigate strain-induced signal drift, offering a promising route toward high-accuracy, deformation-insensitive thermal sensing for wearable electronics and structural health monitoring applications.

Post-fabrication approaches

Another effective strategy to mitigate the effects of mechanical deformation on flexible temperature sensors involves enhancing the stability of conductive pathways through post-fabrication treatments. Such post-processing methods can improve both the electrical performance and mechanical durability of sensors without altering their fundamental structures or constituent materials. Moreover, these approaches offer practical advantages including simplified processing steps and scalability, making them highly suitable for developing reliable strain-insensitive wearable temperature sensors.

Representative post-fabrication techniques include welding and soldering, which are employed to reinforce material junctions, and surface treatments designed to control adhesion and interfacial properties. By rearranging or stabilizing the conductive network, these methods can effectively suppress the disruption of conductive pathways under external mechanical deformation. For example, localized heat treatment can facilitate neck formation between nanoparticles, while plasma or chemical surface modifications can enhance the interfacial adhesion between conductive fillers and the polymer matrix.

Representative post-fabrication techniques include welding and soldering to strengthen material junctions, and surface treatment to control adhesion and interfacial properties. By rearranging or fixing the conductive network, these methods suppress the breakage of conductive pathways under external deformation. For example, local heat treatment can induce neck formation between nanoparticles, and plasma/chemical surface modification can enhance the interfacial adhesion between conductive particles and the polymer matrix.

This section reviews key examples of post-processing applied to flexible temperature sensors, focusing on their

effects on conductivity retention, reliability, and durability under repeated deformation. Figure 8 provides an overview of various post-processing techniques, including welding, soldering, and surface treatments. Hence, the crucial role of post-fabrication treatments in achieving practical and stable performance in future flexible sensor technologies is emphasized (8).

Welding

Welding is a post-fabrication technique employed to join conductive materials, thereby enhancing their electrical and mechanical properties. This process uses various energy sources such as heat, pressure, laser irradiation, and mechanical force to reduce the contact resistance at the junctions between nanowires or thin films. Welding methods can be categorized based on the type of energy applied and the application approach, which influences the bonding strength and electrical performance of the resulting nanostructures.

Beyond simple junction formation, welding—particularly electrofusion or Joule heating-based self-heating welding—plays a critical role in reorganizing the microstructure and conductive pathways within conductive filler-polymer matrix composites. During the welding process, localized heating induces the rearrangement of conductive fillers, promoting the formation of more efficient percolation networks and reducing interfacial barriers between adjacent conductive elements [42]. This microstructural reorganization directly translates to improved electrical conductivity and enhanced sensitivity to temperature variations. The restructured conductive pathways exhibit lower baseline resistance and greater responsiveness to thermal stimuli, thereby amplifying the temperature coefficient of resistance (TCR) and overall sensing performance [53].

For flexible temperature sensors, welding serves a dual function: it not only reinforces the physical connections within the conductive network to ensure structural stability under mechanical deformation but also optimizes the charge transport characteristics that govern temperature sensing accuracy. By tailoring the distribution and connectivity of conductive fillers through controlled welding processes, the sensor's ability to detect subtle temperature changes is significantly improved, making welding an indispensable technique for advancing high-performance flexible temperature sensing devices [62].

A representative example is the mechanical-chemical welding of Ag NWs using a roll-to-roll compression process combined with salt treatment. This process flattens the surface of the Ag NW electrodes, reduces contact resistance, improves conductivity, and achieves both mechanical flexibility and thermal stability. Continuous

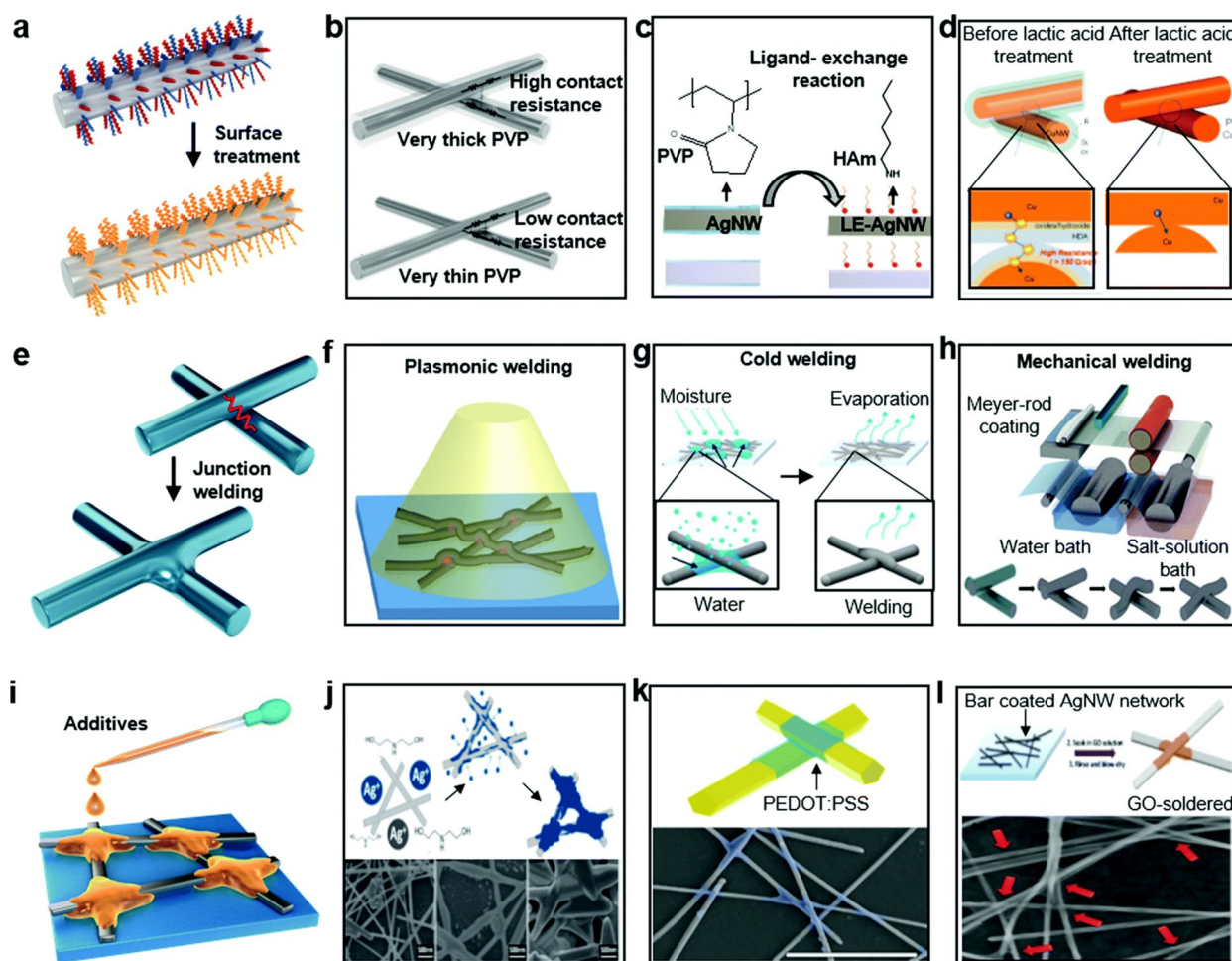


Fig. 8 Overview of various welding, soldering, surface treatment techniques. (a) Schematic illustration of surface treatment technique [58]. (b) Diagram showing Ag NWs coated with polyvinylpyrrolidone before and after solvent washing process [58]. (c) Illustration of reaction for ligand-exchanged Ag NWs where polyvinylpyrrolidone ligand is replaced with hexylamine via NOBF₄ treatment [58]. (d) Schematic of lactic acid treatment to remove residual hexadecylamine and surface oxides/hydroxides [58]. (e) Illustration of welding technique for Ag NWs [58]. (f) Diagram of Ag NW junctions illuminated with light for plasmonic welding [58]. (g) Schematic of cold welding of Ag NWs induced by capillary forces through moisture treatment [58]. (h) Illustration of three-step Ag NW film treatment: solvent spraying, roll compression, and salt treatment followed by washing [58]. (i) Schematic of additive-based soldering [58]. (j) Diagram of nanosoldering process (top) and SEM images of Ag NWs treated with Ag ink for 1, 5, and 10 min (bottom) [58]. (k) Illustration (top) and SEM image (bottom) of nanosoldering Ag NWs using PEDOT:PSS at junctions [58]. (l) Diagram showing GO-assisted soldering of Ag NW network on glass substrate (top), alongside SEM image of Ag NW junctions created through this soldering method (red arrows indicate junctions) [58]. Reproduced with permission from [58], Copyright 2019 The Royal Society of Chemistry

roll-to-roll compression facilitates the fabrication of large-area, highly efficient, and flexible electrodes [13].

Capillary-force-induced cold welding based on humidity exposes Ag NW networks to humid air, inducing capillary forces that cause self-welding at the contact points and reduce the overall sheet resistance. This method is notable for enabling welding at low temperatures without damaging the substrate, making it suitable for flexible electrodes. Moreover, applying humidity to damaged Ag NW electrodes can restore their conductivity, providing a self-healing effect that contributes to high reliability under repeated use and environmental changes [63].

In addition to cold welding, self-limited plasmonic welding employs localized electromagnetic fields

generated by light to selectively heat the Ag NW junctions with high spatial precision. The pronounced field enhancement at the nanometer-scale gaps induces localized heating and welding; however, once junction formation is complete, the plasmon resonance is quenched, which prevents damage caused by excessive heat. This technique is particularly advantageous for developing flexible devices fabricated on plastic substrates or polymer solar cells because it enhances the overall network conductivity without adversely affecting surrounding regions [62].

Welding-based post-fabrication treatments play a crucial role in enhancing the electrical and mechanical integrity of flexible temperature sensors. By reinforcing

the inter-nanowire junctions and reducing contact resistance, these techniques significantly improve network conductivity while preserving mechanical flexibility. Furthermore, welding approaches such as mechanical–chemical welding, capillary-force-induced cold welding, and self-limited plasmonic welding enable scalable, low-temperature processing compatible with flexible substrates, thereby preventing damage and maintaining device integrity. The resulting improvements in the structural stability and self-healing capabilities contribute to the long-term durability and consistent sensing performance of flexible temperature sensors under repeated mechanical deformation. Collectively, these advantages underscore the importance of welding-based post-processing as an effective strategy for realizing reliable, strain-insensitive, and flexible sensing platforms suitable for wearable and dynamic environments.

Soldering

Soldering is a post-fabrication technique that forms conductive joints using low-melting-point alloys or various additives, thereby establishing stable electrical pathways at relatively low processing temperatures. This method is particularly important for flexible electronic devices because it reinforces nanowire junctions through solution-based physical and chemical bonding without high thermal or mechanical stresses. Consequently, effective soldering preserves the integrity of flexible substrates by minimizing damage risk, while simultaneously enhancing the conductive network's electrical and mechanical stability.

In the context of temperature sensing, the solder layer provides an additional advantage by establishing efficient thermal conduction pathways at the interface between the polymer matrix and conductive wires [64]. Poor interfacial thermal contact in conventional composites often limits the speed and accuracy with which thermistors respond to external temperature changes [26]. By filling gaps and creating intimate contact at junction points, the solder facilitates rapid heat transfer across the sensing network [12]. This improved thermal coupling enables the thermistor to achieve faster thermal equilibration and more precise detection of temperature variations, thereby enhancing both response time and sensing accuracy—critical parameters for flexible temperature sensors operating in dynamic thermal environments [26].

Various soldering techniques have been developed, including additive-based methods, CNT or graphene network soldering, PEDOT: PSS-assisted approaches, and GO-based soldering. Particularly, for CNT- and graphene-based nanomaterials, soldering often involves vacuum-assisted infiltration into porous PDMS substrates, enabling the deep integration of the conductive network and stable formation of electrical pathways. This

infiltration process facilitates strong interfacial bonding and enhances the mechanical robustness and electrical stability of composite sensor systems [65].

Soldering assisted by PEDOT: PSS involves applying a PEDOT: PSS solution to Ag NW networks followed by drying. During solvent evaporation, capillary forces drive the infiltration of PEDOT: PSS into the interstitial spaces between the nanowires, resulting in enhanced adhesion at junction points. This process effectively reduces contact resistance and improves the conductive network's mechanical robustness and electrical performance without requiring high-temperature annealing. Owing to its compatibility with low-cost, large-area manufacturing techniques, such as the roll-to-roll and rod-casting processes, PEDOT: PSS-assisted soldering represents a practical and scalable approach for fabricating flexible electronic devices [12].

Graphene oxide (GO) soldering involves immersing Ag NW networks into a GO solution followed by drying. During this process, GO sheets envelop the nanowire junctions through electrostatic interactions and capillary forces, effectively stabilizing conductive pathways. Sensors fabricated using this method exhibit less than 3% change in electrical resistance even after more than 12,000 bending cycles, and maintain conductivity at tensile strains up to 130%. These results confirm that GO-based soldering is a highly effective approach for realizing reliable, stretchable electrodes suitable for flexible electronic applications [66].

These diverse soldering techniques serve as essential post-fabrication processes for reinforcing conductive networks in flexible temperature sensors and wearable devices. By forming robust conductive joints at low temperatures, they minimize substrate damage while enhancing electrical conductivity and mechanical durability. Methods such as PEDOT: PSS-assisted infiltration and GO wrapping enable scalable, cost-effective manufacturing, and provide excellent resilience under repeated bending and high strain. Consequently, soldering-based post-processing is a key strategy for achieving durable strain-insensitive flexible sensors and facilitating the advancement of practical wearable sensing technologies.

Surface treatment

Surface treatment encompasses a range of physical and chemical modification techniques applied to the surface of nanomaterials with the aim of reducing contact resistance and enhancing conductivity, adhesion, and mechanical durability. In flexible electrodes based on Ag NWs, surface treatment is particularly effective in strengthening interfacial bonding with hydrophobic substrates and improving junction properties. By precisely controlling the contact resistance and tailoring the interfacial characteristics, these treatments enhance the

overall conductivity and stability of the conductive network, ensuring reliable performance in flexible temperature sensors.

Critically, surface treatment significantly improves the temperature sensing characteristics of resistance-based flexible temperature sensors by enhancing interfacial adhesion between conductive fillers and the polymer matrix, thereby stabilizing the conductive network [11]. At the filler–matrix interface in conventional composites, poor contact and chemical incompatibility give rise to phonon scattering and electron transfer barriers that impede both thermal and electrical transport. These interfacial impedances reduce the sensor's responsiveness to temperature changes and introduce signal noise. Surface treatment addresses these limitations by modifying the surface chemistry and topography of conductive fillers, creating more intimate interfacial contact that minimizes phonon scattering and facilitates efficient electron transfer [58]. This enhanced interfacial coupling ensures that thermal fluctuations are rapidly and accurately transduced into resistance changes, directly improving the sensor's sensitivity, response time, and signal stability—key performance metrics for flexible temperature sensors in wearable and dynamic monitoring applications.

For example, when dried at 70 °C, Ag NWs with elongated morphology exhibit electrical conductivities several orders of magnitude higher than those of Ag NPs. This significant difference is attributed to the presence of insulating ligand residues such as polyvinylpyrrolidone, which increases contact resistance. Therefore, the effective removal or thinning of these insulating layers is critical for enhancing the overall conductivity of Ag NW networks [67].

In omnidirectional printing, increasing the concentration of Ag NP ink and stabilizing the surface with poly(acrylic acid), followed by high-temperature sintering at or above 250 °C, effectively secures conductive pathways while enhancing both adhesion and cohesion within the composite. These improvements contribute to the increased stretchability and mechanical durability of printed electrodes, which are critical for the reliable performance of flexible temperature sensors subjected to repeated deformations [68].

When Ag NWs are sprayed onto hydrophobic PDMS substrates, poor adhesion often compromises device performance. This issue can be effectively addressed by coating the substrate with polydopamine (PDA), which renders the surface hydrophilic and promotes strong interfacial bonding with Ag NWs. Electrodes fabricated with PDA-coated Ag NW networks exhibit high optical transmittance exceeding 80% and low sheet resistance around 35 $\Omega/\square$, maintaining stable electrical conductivity under tensile strains over 20%. These characteristics

ensure excellent mechanical flexibility and operational reliability, highlighting the potential of PDA surface treatment to enhance the performance of flexible temperature sensors on hydrophobic substrates [69].

In summary, surface treatment plays a pivotal role not only in enhancing adhesion, but also in ensuring interfacial stability throughout the subsequent fabrication processes. Moreover, it contributes significantly to the mechanical robustness and structural durability of flexible electrodes under repeated stretching and contraction during practical applications. Hydrophilic surface modifications substantially improve interfacial bonding between the constituent materials, which is critical for maintaining reliable and consistent electrical performance in nanonetwork-based flexible electrodes such as Ag NWs. These attributes underscore the importance of surface treatment as an essential post-fabrication strategy for the development of durable, strain-insensitive, and flexible temperature sensors.

Conclusion

As wearable electronics advance toward seamless human-body integration, the development of strain-insensitive temperature sensors has emerged as a critical research priority. While previous reviews have comprehensively surveyed materials, sensing mechanisms, fabrication techniques, and computational strategies, a significant knowledge gap persists: the systematic examination of design methodologies that achieve strain insensitivity by fundamentally engineering the sensor's intrinsic physical properties, rather than compensating for performance deficiencies through post-acquisition signal processing. Computational decoupling methods, despite demonstrating effectiveness in controlled laboratory environments, inherently require auxiliary signal processing infrastructure that increases system complexity, power consumption, and response latency. More fundamentally, these approaches address symptoms rather than root causes, shifting the burden of strain interference from sensor design to electronics and software—a strategy that becomes progressively untenable as next-generation wearable systems impose stringent requirements for miniaturization, energy efficiency, and real-time responsiveness.

This review addresses the identified knowledge gap by presenting a comprehensive framework for achieving strain-insensitive flexible temperature sensors through intrinsic design engineering. We advocate a paradigm shift from “measure-then-correct” to “design-then-prevent” philosophy, wherein strain sensitivity is eliminated at the fundamental sensor design stage rather than mitigated through retrospective computational algorithms. This approach embeds mechanical robustness directly

into the physical architecture, fundamentally decoupling thermal sensing from mechanical deformation.

Our systematic analysis reveals that genuine strain insensitivity emerges from the synergistic integration of three interdependent design pillars rather than from isolated material selection or single-level structural modifications. First, material-level engineering strategically selects and hybridizes constituents with inherently decoupled thermal and mechanical responses. Carbon-based nanomaterials (carbon black, graphene, carbon nanotubes), metal nanostructures (gold, silver), and conductive polymers (PEDOT: PSS) are optimized through dimensional geometry control and composite design strategies, including one- and two-dimensional network architectures, hybrid material integration, and strain-engineered programming. Second, geometrical structural design implements sophisticated architectures—serpentine, multipolygonal, kirigami, and fractal networks—that mechanically decouple sensing regions from substrate deformation, enabling uniform stress distribution and maintaining consistent performance under the complex, multidirectional, and cyclic mechanical loading conditions encountered in practical wearable applications. Third, post-processing optimization employs techniques such as welding, soldering, and surface treatments to reinforce conductive network junctions, eliminate strain concentration points, and maximize interfacial stability, thereby ensuring long-term durability and operational reliability.

The integrated design framework established in this review provides a systematic foundation for next-generation strain-insensitive temperature sensors and establishes clear pathways for emerging research directions, including bio-inspired hierarchical architectures, multiscale structural innovations, and hardware-level signal decoupling through architectural engineering. By unifying material selection, structural design, and post-processing strategies within a coherent design philosophy, this work enables the development of intrinsically strain-insensitive flexible temperature sensors capable of delivering reliable, real-time physiological monitoring in the demanding mechanical environments characteristic of advanced wearable and implantable health monitoring technologies.

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Author contributions

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Data availability

No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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