Review of Flexible Temperature Sensing Networks for Wearable Physiological Monitoring

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Abstract

Physiological temperature varies temporally and spatially. Accurate and real-time detection of localized temperature changes in biological tissues regardless of large deformation is crucial to understand thermal principle of homeostasis, to assess sophisticated health conditions, and further to offer possibilities of building a smart healthcare and medical system. Additionally, continuous temperature mapping in flexible and stretchable formats opens up many other potential areas, such as artificially electronic skins and reflection of emotional changes. This review exploits a comprehensive investigation onto recent advances in flexible temperature sensors, stretchable sensor networks, and platforms constructed in soft and compliant formats for wearable physiological monitoring. The most recent examples of flexible temperature sensors are firstly discussed regarding to their materials, structures, electrical and mechanical properties; temperature sensing network technologies in new materials and structural designs are then presented based on platforms comprised of multiple physical sensors and stretchable electronics. Finally, wearable applications of the sensing network are described, such as detection of human activities, monitoring of health conditions, and emotion-related bodily

sensations. Conclusions are made with emphasis on critical issues and new trends in the field of wearable temperature sensor network technologies.

1. Introduction

Advanced flexible and stretchable electronics could make seamless contact with soft, curved, and dynamically deformed human bodies,[1-4] therefore potentially initiating vast wearable applications such as continuous, long-term monitoring of health conditions,[1, 5-11] human-machine interface,[12] as well as artificially electronic skins.[5, 6, 13, 14]

Temperature, as a fundamental physical parameter, varies both temporally and spatially in an effort to monitor physiological activities, in particular, for heat transfer between the biological tissues and the environment.[15, 16] Precise and continuous detection of localized temperature changes in biological tissues regardless of large-scale deformation is crucial to understand thermal principle of homeostasis,[17] to monitor sophisticated health conditions, such as cardiovascular diseases, pulmonological diagnostics, and other syndromes,[7, 11, 18-22] and further to offer possibilities of building a smart healthcare and medical system.[7, 23-26] Besides that, real-time temperature mapping opens up many other potential areas, such as artificially electronic skins and reflection of emotional changes.[7, 16]

Wearable temperature detection demands the sensors with sufficient sensitivity and accuracy could directly attach to non-planar skin surface with different gesture and motion for continuous measurement in minimal user awareness.[7, 21, 24, 27, 28] To meet the requirements, the temperature sensor systems have to satisfy the following criteria.[2] First, the important characteristics a temperature sensor should possess are large sensitivity,[25] high accuracy, fast response,[24] good repeatability, wide-operating temperature range from 25 to 40°C, and long-time stability against ambient influences.[15, 16, 21] Second, the temperature sensors must exhibit softness,[29] biocompatibility, ultra-flexibility,[29] large fatigue life, and light weight.[16, 30-32] Furthermore, to realize scalable designs for multipoint tests on dynamically moving human subjects,[33] new demand for sophisticated sensor arrays or networks composed of interconnected lines with mechanical stretchability on an elastic substrate is essential to sustain sudden impact or large deformation of the human skins.[34-36]

This review exploits a comprehensive investigation onto the recent advances in flexible temperature sensors, stretchable sensor arrays or networks, and the whole assembly constructed in soft and compliant formats for wearable applications. At first, we review the latest examples of flexible temperature sensors and critical discussion is made from the aspects of electrical and mechanical properties, respectively. In the second section, stretchable temperature sensing networks made by either new materials or structural designs are described based on platforms containing multiple physical sensors and stretchable electronics. Thirdly, we discuss the state of art in flexible and stretchable temperature sensing networks applied in wearable physiological monitoring, such as monitoring of human activities, detection of health conditions, and emotion-related bodily sensations. Conclusions with emphasis on critical issues and new trends in the field of wearable temperature sensing technologies are made in the final section.

2. Flexible temperature sensors

Temperature is one of the basic physiological parameters in detecting human activities and determining critical and abnormal body conditions[9, 37] largely due to its indispensible relation to the physical, biological, and electronic systems.[9, 24]

Numerous sensor devices have been realized to detect temperature through certain physical changes, including resistive temperature detectors (RTD),[24, 38] thermally sensitive resistors (thermistors),[39] mercury thermometers,[7, 18, 38, 40] infrared sensors,[29, 41-44] thermocouple sensors,[26, 34] field-effect transistors,[16] optical sensors,[45, 46] silicon sensors,[28] as well as luminescent materials,[23] some of which have attracted substantial interest owing to their favorable properties.[47] For instance, RTD sensors are widely utilized in many applications for their merits in high accuracy, fast response, physiological stability, simplicity of fabrication, and ease of mass production. Optical sensors are of broad interest due to their compact size, immunity to electromagnetic interference and less susceptibility to harsh environments[45]. However, widespread application of the conventional temperature sensors is limited by the inconvenience for use outside of laboratory or clinical settings as those sensors are bulky, stiff, rigid, brittle, and with planar formats,[24, 29] and irritative to the skin. This inconvenience often prevents the sensors from conformal interface with soft, curvilinear surfaces of the human skins.[7, 29, 37, 42, 48] Hence, such sensors fail to have biocompatibility and are unsuitable for wearable situations.[16, 20, 21, 41]

To meet wearable requirements, the temperature sensors should be soft, flexible, biocompatible, light-weight, and naturally conformal to the surface of the skins with minimal user awareness.[21, 24] Flexible temperature sensors are, as a result, gathering numerous interest towards healthcare and medical applications.[16, 37] Many efforts have been made in soft and biocompatible temperature sensors,[7, 25] such as composite materials made by doping functional materials into polymer matrix,[2, 7, 9] resistive temperature detectors patterned on compliant substrates,[2, 7, 18, 24] flexible thermistors,[9] and flexible thermal-responsive field-effect transistors,[16] as summarized in **Figure 1**. They are required to be sufficiently sensitive to real-time record the temperature of the human skins, and responsive to temperature changes with relatively fast speed and accuracy (±0.1 ℃ from 37 to 39 ℃, and ±0.2 ℃ both below 37 ℃ and above 39 ℃)[16] in an active temperature range from 25 to 40 ℃.[49] It has been demonstrated that the conductive composites could achieve orders-of-magnitude changes in electrical resistance (sensitivity) with temperature. It is still challenging, however, to fabricate a flexible temperature sensor in a reproducible sensing response[25] in an appropriate temperature range needed for wearable applications.[19]

This section reviews the most recent examples of different types of flexible temperature sensors.[7, 18, 19] In particular, the former two kinds, conductive composites and sensitive conductors on flexible substrates, are carefully described and critically discussed from the aspects of electrical and mechanical properties, respectively.

2.1. Temperature-sensitive conductive composites

Conductive composites for detection of temperature through resistive changes have attracted considerable attentions owing to their high sensitivity,[16, 24, 41] light weight, mechanical flexibility,[25] as well as relatively simple and low-cost fabrication process.[41]

Most conductive composites, created by dispersing conductive fillers into complaint and insulative polymer matrix, exhibit an ohmic-contact electrical behavior demonstrated by their I-V characteristics. The bulk electrical resistivity of the composites varies linearly or non-linearly with absolute temperature, in which the slope of the curve has a relation to sensitivity or the temperature coefficient of resistance (TCR, α)[50-52] calculated by $\alpha = \frac{R_t - R_i}{R_i \Delta T}$, where R_t and R_i are the resistance of the conductive composite at t ℃ and i ℃, respectively; ΔT is the deviation in temperature (t ℃) from the reference temperature (i ℃).[28, 38, 39, 53-56]

There is a complicated conductive network in the temperature-sensitive conductive composite, formed by conductive fillers passing through the soft polymeric matrix, whose conductivity is primarily determined by loading level of the conductive fillers in the case of uniform dispersion.[52] As the filler contents rise, the whole resistivity drops slowly at first and then suddenly by many orders of magnitudes at a loading threshold for percolation theory, and maintains relatively constant after the critical point.[25] During the temperature change process, microstructure of the conductive network dominates electrical behavior of the conductive composite,[57] which displays a considerable variation in resistivity with temperature since microstructure of the conductive network is modified by the difference in thermal expansion coefficients between the matrix and the filler.[58] When the temperature increases, due to volume expansion of the polymer matrix, the distance of two adjacent fillers becomes larger, therefore resulting in an increase in the resistance.[48] With continuous rise of the temperature until melting point of the polymer whose volume expansion reaches largest, resistive change of the composite in this temperature range could be orders of magnitude.[16, 41, 48, 58] Several conductive mechanisms have been proposed, such as percolation, conduction pathway, hopping transport mechanism,[18] tunnel effect and electric field emission theories, to shed light on the thermal-mechanical and mechanical-electrical effects of the temperature-sensitive conductive composites.[48, 50, 53, 59] It suggests that the filler content should be somewhat higher than the critical volume fraction for a maximum TCR effect while without losing mechanical flexibility of the whole assembly.[19] The melting and crystallization are believed to have a significant effect on the composite structure, leading to a different temperature-dependent electrical behavior.[52]

2.1.1. Materials

Extensive efforts have been dedicated to create temperature-sensitive conductive composites by incorporating different conductive fillers, such as carbon-based materials, conductive polymers, and metallic particles[60], into complaint and insulative polymer matrix. Carbon-based materials[61], including carbon nanotube (CNT),[18, 51, 62] carbon black (CB), and graphite, are often used as conductive fillers owing to their extraordinary electronic and mechanical properties, chemical stability, and low-cost processing.[60] Several recent articles have evaluated their properties in detail.[58] We thus highlight only the most concerned properties for flexible temperature sensors. CB nano-particles with a diameter of 30–35nm and a low room-temperature resistivity $(1-10\Omega cm^{-1})$ could aggregate easily in the CB-filled polymer composites during mixing process, hence inducing electrical instability with subjected to temperature variations[60] with a high TCR effect.[48] A second carbon allotrope, graphene,[63] comprising of a thin layer of sp2-hybridized carbon atoms, possesses outstanding carrier mobility ($\mu \sim 20{,}000 cm^2 V^{-1} s^{-1}$),[58] which is also promising for sensing applications primarily due to its high mobility, remarkable thermal conductivity, transparency, flexibility and biocompatibility.[16, 64] The low conductivity of graphene oxide (GO), however, is not suitable for electronic devices, whereas reduced GOs (rGOs) synthesized by thermal reduction are largely used,[15, 18] providing enhanced electrical conductivity.[15] In addition, graphene nanowalls (GNWs), consisting of graphene nanosheets vertically on a substrate, have been recently applied for temperature sensors as they are able to be stretched to a considerably large strain because of their interlaced structure.[15, 16, 51] Except for carbon-related fillers, the other conductive materials include conducting polymers (such as poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS) with a very high conductivity of ~300S cm^{-1},[55, 65] PPy,[66] and polyaniline[51]) and metallic particles, like Ni micro- or nano-particles,[18, 19, 58, 67] which could achieve high conductivity ($40Scm^{-1}$) at concentrations beyond percolation threshold of the Ni fillers.[58]

Polymer materials in composites have to satisfy the following criteria, i.e., electrical insulation, flexibility, lightweight, a certain stretchability, large area applications and very low manufacturing cost.[54] Most polymers are electrical insulators. Composites based on amorphous polymers, including polystyrene (PS), poly methyl methacrylate (PMMA) and poly vinyl acetate (PVAc), exhibit small TCR (∼1 to 3 orders), because the amorphous polymer composites suffer a small expansion in their volume as temperature increases, which is insufficient to generate considerable variations in resistivity[19]. Differently, composites with semi-crystalline polymers, including PE, PEO and polyethylene adipate (PEA), display ∼6 to 7 orders of magnitude in the change of resistivity near their melting points.[19] To make the sensitive temperature range suitable for human body temperature measurements (25 ℃ to 40 ℃) and enhance the cycling stability of the conductive network, copolymer structures are recently proposed[25, 68] by polymerization of two monomers with different side chain lengths, for instance, semi-crystalline acrylate copolymers including butyl acrylate with a 4-carbon side chain and octadecyl acrylate with an 18-carbon side chain.[15, 68] In the binary composites, one of the polymers is selected when its melting point is close to the critical temperature region, while the other polymer was chosen to own a much higher melting point to preserve a reproducible morphology during repeated temperature cycling processes.[19]

2.1.2. Sensors and their properties

Various flexible polymeric temperature sensors for different applications have been developed through elaborate combination of conductive fillers and polymer matrix (physical mixture or polymerization of monomers), such as CB or carbon nano-fibrils or GNWs dispersed in polydimethylsiloxane (PDMS),[7, 16, 60, 64] graphite particles with a diameter of 2–3μm in acrylate copolymers,[25] CB-filled PEO/PE polymer composite,[57] rGO nanosheets into an elastomeric polyurethane (PU) matrix,[55, 69] CNT-polymer paste,[53, 70] PEDOT:PSS–CNT composite film,[18, 24] Ni microparticle-filled binary polymer composite,[16, 18, 19, 58] and Ag ink-jet printing together with Ni electroplating to create flexible resistive temperature sensors (**Figure 2**).[54] Their performance, including sensitivity, accuracy, repeatability, stability, and measurable temperature range, is related to the kinds and properties of conductive particles and polymeric matrix, and to the interaction between them (**Table 1**).

Most of the conductive composites exhibit much larger TCRs than that of other types of flexible temperature sensors, typically like platinum (Pt) temperature sensors ($0.0055K^{-1}$).[60] For instance, the TCRs of the graphite-PDMS composites are $0.042K^{-1}$ and $0.286K^{-1}$ when volume fractions of the graphite are 25% and 15%, respectively;[60] sensitivity of the PEDOT:PSS–CNT composite film ranges from 0.25% to $0.63\%°C^{-1}$ as temperature rises from 21 to 80 ℃;[18] in particular, Ni micro-particle filled PE/PEO polymer composites have an extraordinarily large resistive change at the specifically designed temperature range, exhibiting larger TCR in orders of magnitude ($10\text{-}90\%℃^{-1}$) for monitoring human body temperature.[19, 25] Hence, no sophisticated amplifier circuits are required for the temperature sensors, and it is possible to realize wireless transmission, which demands at least 5% of TCR to generate a noticeable signal change at the base station.[19] To explain the large TCR phenomenon, important factors were derived to be percolation theory, outstanding stretchability of conductive particles, and remarkable expansion coefficient of the polymer matrix,[16, 50] according to the previously mentioned conductive mechanism. First, percolation effect was utilized to enhance the sensitivity, i.e., volume fractions were mostly chosen as near the percolation threshold for higher temperature sensitivity.[16, 53, 55, 60] Second, different conductive fillers and their morphology may affect TCR of the polymeric sensors. It has been demonstrated that carbon nano-fibers, due to their large aspect ratio, mixed in insulating PDMS could achieve higher sensitivity since the links of several conducting paths got separated with thermal expansion, hence increasing the electrical resistance. Comparing to CB and carbon nano-fibers, graphite powder as the conductive filler could enhance remarkable temperature sensitivity.[60] The third factor that contributes to the high sensitivity of the polymeric sensors is the use of semi-crystalline polymers, which could transfer from crystalline phase to amorphous phase near the melting point, resulting in a large volume expansion, thus increasing the inter-particle distance and corresponding conductivity.[19] Hence, sensitivity of the polymeric sensors was enhanced from the above aspects, which can simplify the readout circuits as no per-pixel amplification circuitry is required to external recording equipment.

It is noted, however, the polymeric sensors suffer a very narrow temperature range with semi-crystalline polymers,[19, 25] for instance, the polymeric sensor with PEO only exhibited a small dynamic range around 35 ℃ to 42 ℃,[19] which forbid their uses for wide-scale temperature sensing.[16, 55] To make the temperature range applicable for human body temperature measurement,[41] copolymers by using two specific monomers in different mixture ratios are preferable.[41] By adjusting mixing ratio of the two monomers, melting point of the polymer could be tuned in the measurable temperature from 25 ℃ to 45 ℃, which is suitable for the human body temperature.[41]

Additionally, the single polymer system suffers irreproducibility of resistivity as a function of temperature, often exhibiting less than 100 stable thermal cycles,[16, 25, 48, 81] which is primarily caused by morphological change of the conductive network since most conductive fillers are not chemically bonded to either the polymer or to each other, hence inducing that the resistivity could not return to its original value upon cooling.[16, 19] Instead, composites comprised of multiple polymers like PE and PEO have shown improved reproducibility, since large variations in resistivity occurred near melting point of PEO, whereas PE network maintained the morphology of the composite assembly, thus making the resistivity reversible.[16, 58]

Furthermore, there is still a great challenge to improve accuracy, response time and reduce the hysteresis of the polymeric sensors.[15, 16] For instance, accuracy of the Ni filled binary polymers was ±2.7 ℃, which was less accurate than conventional RTDs (±0.17 ℃).[19] One possible approach for future improvement could be tried by carefully changing the morphology of the polymer matrix and optimization of the domain size of polymers.[19]

The difference from the rigid silicon-based devices is polymeric sensors is mechanically flexible,[25, 60] and can be principally in any shape,[15, 25] which is vital for wearable applications.[19, 24, 70] Therefore, the polymeric sensors could be easily and conformally attached to a highly curved surface without a noticeable physical damage[27, 69] with the 3D temperature-mapping capability.[55] In addition, some polymeric sensors have been enabled the capability of repetitive mechanical deformation, although there is a slight variation in the recorded signal[25, 60, 69, 82] caused by the local bending stresses.[25, 81]

2.2. Temperature-sensitive conductors on flexible substrate

With the demand for wearable applications where mechanical flexibility is necessary,[30] another alternative approach to make temperature sensors flexible is heterogeneously implementing temperature sensing elements on a sheet-like soft and compliant substrate with thermal isolation and mechanical deformation.[30, 83-85] The major advantages of the temperature-sensitive conductors on flexible substrates are sufficiently compliant, foldable and twistable[84] to interface with any irregular surface,[30] and offer capacity in its simplicity of structure and fabrication,[81] mass-producibility, and cost reduction compared with the active-Si-based method.[9, 38, 40, 85]

The most common used temperature sensing elements on flexible substrates are RTDs,[7, 18, 38, 39, 54] operating based on the change in resistance of a conductor upon varying the temperature in an almost linear relation,[9, 54, 58, 86] expressed by $R(T)=R(T_0)(1+\alpha(T-T_0))$, where $R(T)$ and $R(T_0)$ are the resistances of the sensing element at temperature T and reference temperature of T_0, respectively; α is the temperature coefficient of resistance.[27, 30, 40, 84, 87, 88] As the environmental temperature increases, resistance of the RTD increases and usually has a positive temperature coefficient (PTC).[7, 54, 86]

2.2.1. Conductor

The relation between electrical resistance and temperature relies on the materials in the construction of the sensor.[9] The commonly used temperature-sensitive materials are pure metals, for instance, Pt,[67, 84] nickel (Ni), copper (Cu),[18, 89] gold (Au),[39, 58] and aluminum (Al)[31] in the form of films or wires,[40, 89] and liquid metal such as GaIn alloy with a conductivity of 3.4×10^6S/m.[90, 91] Pt, though it is expensive and does not have the highest TCR, is often employed as temperature-sensitive material owing to its desirable thermal properties, antioxidation,[81] linearity between electrical resistance and temperature.[30, 40, 77, 84] Ni with the highest TCR has been proved as a good candidate for the temperature sensing element because of its high reference resistance, sensitivity,[89] linear temperature-resistance relation in the temperature region from 0 to 100 ℃, and availability in the market and relatively low cost.[89, 92] To enhance both sensitivity and stability, the thermal elements could be made of composite materials, i.e., Ni is applied as the dominate thermal element, Pt as a cover material.[81] Au is used as the sensing material due to its better conductivity and flexibility[38, 40, 93] so that it can be made in any curved shape like a thin (50nm), narrow (20μm) serpentine trace.[42] Also, Au shows a good linearity at the operating temperature below 300 ℃.[94]

Besides metals, there are some other conductors, like thermo-sensitive and polymer conductive pastes,[70] CNT ink and PEDOT:PSS solution with the sensing mechanism of electron hopping at the interface,[10, 95] and organic silver complex compound.[54]

2.2.2. Flexible substrate

Flexible substrate provides outstanding flexibility and even stretchability to the temperature sensors and permits 3D temperature mapping of curved surfaces.[28, 55, 96] The primary substrates are thin films, including polydimethylsiloxane (PDMS),[97-102] polyimide (PI),[54, 81] polyethylene terephthalate (PET), polyethylene naphthalate (PEN), and polyurethane (PU),[58] papers,[103, 104] as well as textile substrates.[105, 106]

The most broadly used substrate is made of PDMS material,[97-102] which is flexible with Young's modulus of ~750kPa,[107] stretchable with strain over 200%,[108] electrically insulative with electrical resistivity of $1.2\times10^{14}\Omega$ cm^{-1} and relative permittivity of 2.3-2.8, thermally stable with a low glass transition temperature of -125°C and a linear coefficient of thermal expansion (CTE) of $325\mu m$ $m^{-1}.°C$,[58] as well as commercially available.[58, 60, 107] Hence, PDMS substrate is biocompatible with soft, curvilinear and extensible skin surface,[109-111] and suitable for biological applications.[16, 60, 102, 112] PI is another commonly used material as the flexible substrate for temperature sensors owing to its following characteristics, such as mechanical flexibility with Young's modulus of 2.8GPa,[27] electrical insulating with electrical resistivity of $1.5\times10^{17}\Omega cm^{-1}$,[84] as well as thermal properties with a comparatively high glass transition temperature of 355°C and low CTE of $16ppm°C^{-1}$.[77, 113] Recently, liquid PI is selected to enhance its lamination with pure conductors.[30, 60, 77, 84] Thermoplastic PU foil is also applied for flexible substrates owing to its biocompatibility, commercial availability, and low cost.[114] Textiles are thin, lightweight, soft, flexible, deformable, porous (or breathable),[115, 116, 117] durable, as well as washable,[118] hence desirable to be explored as soft substrates for wearable temperature sensors.[2, 119] To date, woven,[113, 115, 120, 121] knits,[89, 122] and nonwoven[115, 123, 124] fabrics have been proposed as flexible substrates[58] of physical sensors for textronic applications.[18, 58, 70] In particular, unlike woven and nonwoven substrates whose extensions are usually lower than 10%, knitted fabrics are able to be stretched up to 100% due to their 3D loops and the way in which neighboring loops fit together.[119, 125]

2.2.3. Sensors and performance

Conductors with different structural designs have been embedded on the soft substrates for detection of human body temperatures (**Figure 3**) through various printing technologies, such as inkjet, gravure, screen printing and dip-coating, or textile manufacturing technologies, for instance, weaving or knitting.[54] For instance, a Pt RTD was implemented on the PI substrate in a meandering pattern to make temperature-sensing devices;[18, 58, 77] an ultra-flexible and stretchable temperature sensor was created by printing temperature-sensitive material into semi-permeable PU film;[7] a stretchable temperature sensor was realized based on elastically buckled thin Cr/Au layer as the sensing element on an elastomeric substrate on the condition of a 30% pre-strain;[9] a flexible resistive temperature sensors was fabricated by printing silver ink and thick Ni on PET foils;[54] an organic silver complex compound including Ni was applied as the functional ink to produce designed pattern on Kapton;[54, 55] and a temperature sensing fabric was created by incorporation of fine metallic wires into a knitted substrate.[92]

Generally speaking, the temperature-sensitive conductors on flexible substrates are attractive for wearable applications because of their flexibility,[38] simple structure, compatibility with electronic readout approaches, small volume, high accuracy, short response time,[39, 88] and their capacity to be mass-produced (**Table 1**).[54, 58, 83] Response time of the flexible sensors could be less than 80ms,[7, 77] which is much lower than the standard ones owing to their small volumes to minimize the direct thermal capacity[7, 30, 77] and good thermal isolation effect.[30, 38, 84] Accuracy of the sensors could reach 0.3℃,[38, 40, 77, 86, 88, 126] particularly, the resolution of the meandering design of Pt as temperature-sensitive devices could achieve 0.03 ℃ for a broad range of temperatures.[58] Hence, these temperature sensors can precisely and continuously detect thermal characterization of the human skins.

Almost all of the flexible temperature sensors vary their electrical resistance in a linear response with a correlation coefficient of beyond 0.997 to the temperature with a positive TCR[9] in a measurement range from 30 to 80°C (**Table 1**).[30, 31, 58, 77, 84, 88] Though the relative resistance change could be improved by the increment of initial resistance through the design of serpentine trace,[30, 31, 92] sensitivity of the sensitive conductors on flexible substrates is almost a constant value,[84] for instance, with an average of $0.00427°C^{-1}$ for silver ink-jet printing combined with Ni electroplating on PET foils,[54] $0.00248°C^{-1}$ for Al on flexible substrate,[27, 31] and $0.00291°C^{-1}$ for flexible Pt sensors,[40, 58, 86, 87] which is significantly smaller than the theoretical sensitivity of the bulk pure Pt ($0.00394^{o}C^{-1}$).[27, 77, 84] This reduction was often detected in printed metallic thin films,[54] possibly caused by electron scattering at grain boundary,[30] geometry dimension of thin-film sensors, deposition condition, as well as the adhesion layers (e.g., Ti).[77, 84] Hence, such flexible temperature sensors require complex post amplification of low signals, complicating readout circuits.[25, 30, 58] The variation of the performance over time of the sensors has also been investigated,[15] which may be affected by the distinction in CTE between the metal and the substrate that possibly generates stresses in the metal layer[77] and the oxidation of some metal conductors.[30] For instance, Ag thin-film sensor suffered a rise in resistance of $\pm 50\Omega$ and a change in sensitivity of $0.1\times 10^{-3}°C^{-1}$ with a 20-day interval due to oxidation of Ag.[54] Hence, a post treatment, such as annealing[81] and encapsulation,[100, 112] is preferred in order to enhance the stability of the sensors.[54]

2.3. Other types of flexible temperature sensors

Besides the above two types, several other approaches have been proposed for flexible temperature sensors,[61] as listed in **Figure 4**. For instance, a thermal diode was created to detect temperature through change of the drain-source current (I_{DS}) by integrating the thermistor, constructed of silver nanoparticles in the pentacene thin film, to the gate electrode of a pentacene OTFT;[20] a flexible temperature sensor constructed by the serpentine Au and PIN diode using Si nanoribbons on elastomers possesses an outstanding sensitivity of ~1.34% ℃$^{-1}$;[16] a temperature-sensitive TS-gated sensor was established by serially connecting the thermistor to the drain–source electrode of the switching OFET and could be conformally covered to human skins for detection of skin temperature;[55, 69] a capacitive cellulose/rGO composite temperature sensor[15] was created and temperature responses occur based on the capacitive change;[15, 66, 127] a stretchable Gr thermistor by embedding 3D crumpled Gr into an elastomer matrix has been made with the capability of being stretched up to 50%;[18, 55] different thermocouples based on Seebeck effect have been established with a sensitivity up to 1μVK^{-1},[19, 26, 34, 43, 127] in which the thermocouple made by the liquid metal ink exhibited perfect linear dependence between thermoelectric voltage and temperature;[91, 128] a micro-temperature sensor was realized by incorporating discrete temperature sensor chips on a stainless-steel foil[38] with an accuracy of ±0.7°C from 0 to 70°C,[35, 85, 129] sensitivity of 0.01V ℃$^{-1}$,[35] and response duration of 1.7-2.3s;[38] a stretchable temperature sensor for thermal measurements by combining colorimetric temperature indicators with wireless devices[18] could make a full coverage of the skin;[29] a self-healing disulfide-cross-linked PU and PU/Ag-microparticle composite was created to sense temperature due to an electron-hopping mechanism, which is suited for a wide linear temperature range of 10-42 ℃ with a sensitivity of ~0.41 MΩ°C^{-1}.[130]

3. Temperature sensor networks

Wearable applications demand multiple temperature sensors are attached on the freely curved surfaces of the dynamically moving subjects and detect their spatial and temporal temperature gradients with sufficient resolution.[10, 25, 32] Wearable temperature sensor array or network is therefore urgently required,[58] where in addition to the performance with superior sensitivity, linearity, and accuracy,[131] it is equally vital that the sensor networks mimic the mechanical behaviors of the human skins to accommodate its large deformation, meanwhile, without influencing the functions of the temperature sensors. The primary characteristics of the human skins are porous and hairy, functioning as transportation between the human skins and the environment; soft and flexible, with low Young's modulus of less than 1MPa; extensible from 3 to 55% without physical damage.[132, 133] To make an intimate association with biological interfaces in a long time and to imitate the natural human skin with flexibility and large deformation,[134] efforts have been made toward developing breathable, soft, flexible and cyclically stretchable electronic devices.[58, 135, 136, 137] In addition, more capabilities have been proposed, like self-healing, biodegradable and transient electronics, for more practical applications.[58]

Advanced technology for the wearable temperature sensing networks, same to the "island-bridge" strategy for most of stretchable electronics,[138] mainly depends on the incorporation of multiple discrete temperature sensors, including conductive composites and conductors on flexible substrates, physically linked in a manner by passive electrical wirings or active circuits for data readout[25] on a thin, elastic substrate.[35, 55] A typical temperature sensing array is thus comprised of soft distributed temperature sensor islands in different locations, giving accurate temperature distribution mapping,[35] organic or inorganic electrical interconnect (or passive) bridges[131] or signal processing circuits, and their physical contacts embedded in a soft and large-area substrate[139] so that the arrayed system can be easily attached to curved human bodies.[55] Such integrating strategy could also be utilized as multifunctional sensing platforms with other sensing elements in an array form[58] for various external stimuli,[55, 69, 131] including mechanoreception, thermoception and nociception.[131] To make large deformation, the interconnect bridges in the assembly were created either by a novel material or mechanical structural designs of conventional rigid metals or semiconductors[58] with wavy, serpentine, or net-shape patterns that can endure large external strain up to a few tens of percents,[69] whereas the temperature and other sensor elements are almost steadfast, without being stretched.[112]

The significance behind the strategy is to independently fabricate the temperature sensors, stretchable interconnects, and other electronic components, then link them on a flexible and stretchable substrate.[140] Hence, the crucial aspects toward the advancement of temperature sensor arrays include the development of novel mechanically durable, flexible and stretchable electrical interconnects and reliable contacts with acceptable strain gradient.[112, 141] Besides mechanical compliance, both electrical property and compatibility with large-area manufacturing technology are of great importance to develop devices with high performance.[58] Based on the stretchable electronics, various types of flexible and stretchable sensor arrays can be further developed through the integration of novel sensing elements and processing technologies.[142]

Recent advancements for stretchable electronics will be described in this section, from the aspects of stretchable interconnects and contacts between discrete components, respectively,[58, 143] followed by a selected number of advanced temperature sensor arrays.

3.1. Stretchable interconnects

A large number of stretchable interconnects have been created through three approaches.[144-147] The first method relies on novel organic materials with inherent stretchability (**Figure 5 and Figure 6**),[144, 145, 147, 148] such as (well controlled) graphene/PDMS composites,[149-151] SWNT conductor[152] or MWNT/Ag composites[153] or over-twisting CNT ropes,[154] PANI conductive polymer,[155] and PEDOT:PSS/PDMS composite.[156] Such new material-based interconnects, except MWNT/Ag composites, are not sufficiently conductive to perform as electrical wires in integrated circuits.[157] More seriously, their conductivity often decreases by several orders in magnitude with mechanical strain of less than 10%.[155-157] Hence, both the inherently poor conductivity and the variant electrical resistance with applied strain hinder stretchable materials to maintain electrical integrity.[97, 112, 158]

The second method attempts optimal mechanical structures to make rigid and brittle inorganic conductors or semiconductors stretchable (**Figure 5 and Figure 6**).[152, 159] The commonly used conductors are metal films,[160, 161] such as Au[100, 112, 162] and Cu.[101, 113, 163] Nanoribbons of semiconductors are made as the bonding layer to develop integrated stretchable circuits due to its modest mobility values,[164, 165] electrically insulative feature and a reliable adhesion to the PDMS substrate.[102, 164, 166] Both pure conductors and semiconductors can only endure a small deformation less than 1%.[100] It is thus vital to maintain their strains at an extremely low value,[144] without damaging their electrical integrity.[167] In the structural design, inorganic conductors or semiconductors are firstly bent into a curved geometry by reducing their thicknesses and flexural rigidities,[168] secondly adhere to a thick and elastic substrate, and finally realize a bi-layer stretchable interconnect.[169] For instance, a brittle metal film is deposited on an elastomeric substrate,[143, 157, 162, 170, 171, 172] inducing micro-cracks, because of different thermal expansion coefficients,[173-175] which are capable of being stretched by deflecting and twisting out of plane (**Figure 5a**).[161, 171, 176] An elastic antenna was realized by coupling stretchable Cu in a twisted helical spring pattern with a polymer, PI, to provide structural support (**Figure 5b**).[177] With net geometries,[148, 149] electrical function of the conductive rubber based artificial skin conformal to three-dimensional surfaces remains the same with applied strain due to the shape change of the struts (**Figure 6a**).[99, 148, 178] A rigid conductor in an elastic substrate in periodic horseshoe patterns[101, 111, 179] could stabilize the electrical performance owing to the change in its angles and radius (**Figure 5c**).[101, 158, 179, 180] Brittle silicon ribbons on the PDMS substrate with wavy geometries,[140, 146, 147, 174, 175, 181, 182-184] popup configuration,[137, 185] non-coplanar mesh,[186, 187] as well as serpentine bridges,[135, 140, 184, 188] are stretchable by means of out-of-plane deflection of the ribbons,[189, 190] enduring large-scale deformation over 140% strain (**Figure 5d**).[102, 132, 146, 163, 181, 186, 187, 191, 192, 193] Such bi-layer systems with well controlled buckles realized either by difference in thermal expansion coefficients[160, 167] or first pre-stretching and then relieving strain of the substrate[109] yield large deformation through adjusting their amplitude and wavelength.[137, 161, 192] Precisely controlled formation of the wrinkles,[194] however, demands an outstanding mismatch in thickness between the stiff conductors or semiconductors (Young's modulus: ~130GPa, thickness: ~20-50nm) and the soft substrate (Young's modulus: ~2MPa, thickness: ~1mm).[194-196] The thick substrate and further encapsulation,[193] therefore, limit flexibility[135, 183] of the whole system.[197] Furthermore, local delamination of the brittle components from the substrate,[110, 145, 197] induced by stress concentration in the crest and the trough,[101] gives rise to cohesive and adhesive fracture, hence resulting in short circuits and further reducing the stretchability.[111]

The third approach incorporates electronics into fiber assemblies, i.e., textiles, which are porous (or breathable), in addition to being flexible and stretchable. At present, textile-based elastic interconnects have been created either by weaving, knitting, or embroidering conductive fibers (or yarns) into fabrics or coating conductive materials on fabric substrates. Among which, woven (or nonwoven) circuits can only endure a maximum strain of less than 20-30%,[106, 198] whereas, the knitted interconnects consisting of three-dimensional looped metal fibers exhibit an outstanding electrical integrity with no any change in electrical resistance as a function of 300% strain in both horizontal and vertical directions.[124, 125, 199, 200] For comparison, the typical electro-mechanical performance, i.e., the strain and its corresponding relative resistance change, of the stretchable interconnects made by new organic materials and structural optimization is summarized in **Figure 6**. The stretchable capacity ranges from 3%[201] to 400%.[151] The relative resistance change, whereas, varies from 2.1%[158] to 7300%[153] with applied strain, which is much larger than that of knitted interconnects.[157, 202] Hence, the efforts to develop knitted stretchable interconnects could open doors to new applications in areas where new organic materials and thin film-based electronics are not effective, such as next-to-skin electronics or intimately wearable devices.

3.2. Connections between components

The strategy of “island-bridge” combination for packaging flexible and stretchable temperature sensor arrays is electrically and mechanically connecting distributed temperature sensors to stretchable interconnects and/or other electronic components[207] on the elastic substrate.[208] Previous studies showed that most of the electric contacts were established by contact pad necking,[112] hook-shape pattern,[207] conductive pastes,[198, 209] (e.g., Ag-filled silicone or epoxy adhesives[55, 210] and CNT rubber[133]), a patterned Cu layer,[35] solder joints,[117, 208, 210] in combination with encapsulation, such as PDMS rubber,[133] epoxy resin,[198] and glob-top coverage.[113, 210] Such established electric contacts resulted in low resistance in the range of 10^{-2}–$10^{-1}\Omega$, several orders of magnitude lower than that of discrete temperature sensors.[70] However, most of them are flexible but not extensible, degrading electrical performance of the whole system in the stretching process.[174] To overcome it, the compliant substrate was stiffened at corresponding areas, stabilizing the connected regions against strain, but degrading the extensibility of the whole substrate,[211] meanwhile causing strain gradient. As shown in a typical island-bridge stretchable assembly (**Figure 7**), strain of the interconnect bridge could reach to 3.2% near the contact region, where the silicon endures a maximum strain of 0.16%, at 34% external mechanical strain of the whole system.[144, 212] The electro-mechanical behavior of the integrated device would be thus drastically degraded.[140] To create intimate and effective electronic connections, our group has developed a stretchable, instead of rigid, connection with helical structure, which could be stretched by adjusting its geometrical parameters, such as in-plane radius, radius angle, as well as pitch between two adjacent loops, without sacrificing the extensibility of the whole assembly (**Figure 7**).[199, 200]

3.3. Temperature sensor networks

To detect temporal and spatial temperature gradients of the human body that is covered with extremely soft, curved and elastic skins (with a mean extension from 3% to 55%),[2, 150, 211, 214] a class of temperature sensor arrays that combine precise measurement with mapping capabilities have been created through advanced technologies in stretchable electronics (**Figure 8**).[11, 42, 55, 215] The examples include an elastic polyaniline nanofiber temperature sensor array with an active SWCNT TFTs on a soft Eco-flex substrate and temperature sensors on stiff PET films with a sensitivity of 1.0%°C^{-1} and response time of 1.8s in the temperature region from 15 to 45 °C;[51] a temperature sensor array on Cu/PI substrate consisting of Pt resistors with a resistivity of 10.6μΩ.cm^{-1} and Cu layer with a resistivity of 1.68μΩ cm^{-1} on both sides forming row and column circuits;[87] a temperature sensor array comprised of Cu interconnects in a certain pattern to form a complete scanning circuitry;[60] a stretchable sensor array utilizing the thin (100nm), narrow (10 μm) serpentine patterns of Au for precise measurements, linked by serpentine traces for external addressing;[21] a thermal characterization incorporating microscale temperature sensors on elastic sheets, linked by either serpentine traces of Au films (50nm) or PIN diodes;[42] a temperature array consisting of temperature sensing parts, S-shaped interconnects and extraction pads in the neutral plane to reduce the strain in the bending process;[7] a 12×12 active matrix with polymeric temperature sensors on PI substrate for measuring spatial temperature gradients;[25] an assembly with a patterned Cu layer serving as the contact pad for bonding discrete temperature-sensing chips;[129] a flexible 16×16 temperature sensor array with an active matrix for directly conformal coverage of human bodies.[55]

Such temperature sensing networks have been developed by applying multiple mechanically compliant discrete temperature sensors[21, 27] to the soft, ultra-thin, and compliant[29] substrate with individual wirings for data readout.[24-26] The collection of temperature sensors aims to acquire simultaneous temperature distribution around the stagnation point.[216] Integrated collections of the island-bridge construction on the flexible substrate yield highly stretchable performance and reduction in the strain of the interconnects and temperature sensors,[21] thus offering conformal interface with human skins in a manner that does not constrain natural motions, for which strains are typically 15%,[21, 42] and spatial temperature mapping could be achieved without external influence[7] in large-scale deformations.[51, 131] In addition, the fabricated temperature sensor array is soft, flexible with a comparability to human epidermis, hence providing geometrical matches to human tissues with a type of conformable integration.[21, 49] In particular, some sensor array is ultrathin to adhere to human epidermis with van der Waals force with minimal irritation or discomfort.[7, 42] In summary, with the features of permeability, softness, flexibility, and extensibility, the arrays possess outstanding biocompatibility to the human skin, which guarantees their wearable applications.[7]

4. Applications

Temperature, as a fundamental physical parameter, is variant in both spatial and temporal formats in an effort to monitor physiological activities,[217] for instance, for heat transfer between the human body and the environment (**Figure 9a**).[15, 16] Accurate and real-time detection of discrete temperature changes regardless of large deformation is crucial to monitor sophisticated health conditions,[7, 11, 18-22] and further to provide possibilities of building a smart healthcare and medical system.[7, 23-26] The flexible and stretchable temperature sensor arrays could seamlessly contact the human bodies with sophisticated geometries and curvilinear surfaces,[22, 42] and simultaneously maintain high levels of electronic function.[7, 8] Therefore, such integrated electronics with an array of sensor pixels could trace the coordinates and shape of the contacted object,[55] and would enable a plethora of new e-skin applications,[135, 189, 218] such as personal healthcare,[55, 131, 149, 219] sensory skins for robotics/prostheses,[131, 144, 190, 220, 221] and human-machine interactive interfaces.[10, 112, 131, 144] In the following, we present the state of the art in the temperature sensing arrayed technologies being applied in wearable applications, such as detection of human activities,[58, 222] healthcare and medical monitoring,[37] and emotion-related bodily sensations,[7, 16] and sensory skins for robotics/prostheses.

4.1. Detection of human activities

The temperature of the human body plays an important role in monitoring human activates. In practical uses of advanced electronic skins, multimodality in simultaneous detection of multiple stimuli including temperature, pressure and strain, is demanded (**Figure 9**).[58, 60] For example, to monitor human activities, the flexible sensor array was attached to the human neck and arm to simultaneously measure the temperature variation and muscle movements,[69] then store data and deliver feedback.[5] However, it needs sophisticated fabrication technologies at the condition of large-area integration of the discrete sensors with different kinds of operational principles in a single pixel of the highly functional electronic skins.[6] Furthermore, quantitative sensing of arbitrary stimuli, e.g., temperature, strain, and pressure, from the sensors in multimodal electronic skins have been limitedly studied[139] since the target signals from sensors are usually affected by the other stimuli. For instance, signals from both strain and temperature sensors in the electronic skin are affected by other external stimuli of temperature and strain, respectively. Such interferences could be partially reduced by calibration of the output signals via compensating circuits and reference devices, although it has limited effects.[223] Another solution uses novel temperature sensitive materials that are resistant to strain, e.g., rigid material, so that interferences caused by strain could be effectively minimized. The usage of heterogeneous sensing materials and devices, however, often involves complicated structural design, fabrication steps, integration technologies, and large power consumption.[139] A device array by integrating the piezo-pyroelectric gate dielectric and piezo-thermoresistive organic semiconductor channel into FET platforms with pressure and temperature sensor pixels was constructed to mimic the function of human fingers,[139] which greatly enhanced structural integration and eliminated interferences coupled by each other through AV gate bias technique. This approach may be extended to achieve multimodality in large-area flexible and stretchable electronic skins with heterogeneous stimuli.[139]

4.2. Healthcare and medical monitoring

Human body temperature is one of the four important indicators, in addition to heart rate, blood pressure and respiratory rate, for the medical assessment of the health conditions.[29, 42] The deviation of few degrees from the average value of 37 ℃ may cause impairment and fatality to the human body,[55, 89] for instance, the physiological temperature varies from 32 ℃ at the fingertips to over 42 ℃ in the core during hyperpyrexia.[7, 225] Hence, real-time monitoring of rhythmic patterns of local body surface temperature is extremely important for management of thermal status in healthcare and many areas of medicine, such as cardiovascular health, the cognitive state, pulmonological diagnostics, breast cancer, and other syndromes.[9, 226] Flexible electronic sensors, in particular, flexible temperature sensors, with the functionality of integrated bio-parameter monitoring systems,[53] have been attached to the human body or its organs to offer accurate thermal distribution (**Figure 10**).[33, 55, 217] For instance, flexible temperature sensor arrays have been mounted on the positions of forehead,[55] underarm,[7] thumb,[131] upper extremity,[131] and lobe of the lung[25] to record temperature of the skins and organs for evaluation of local heat production and circulation.[227] Such flexible sensor-array devices could precisely measure temperature distributions with response time faster than 100ms and sense small physiological temperature variations of 0.1 ℃ in the range from 22 to 45 ℃, which is suitable for the variation range of the human body temperature,[7] without physical damage to the skin and organs or restricting their motions.[25, 131] The physiological conditions could be then reflected through correlations between skin thermal information and human pathophysiology, where the effect of skin emissivity, skin humidity, convective heat transfer coefficient, metabolic rate and the blood perfusion have to be considered.[226, 228] Compared with IR camera, however, there is a noise on some pixels of the sensor array caused by the presence of an air gap between the sensor and the skin; the detected temperature value is hence smaller than that of the skin, which could be solved by a thinner substrate to enable the device conformable to the skin. In addition, the spatial resolution of the temperature sensor array is not good as that of the IR camera, which could be improved by further reduction of the size of sensors for diagnostic purposes.[55, 229]

4.3. Emotion-related bodily sensation

We always experience emotions directly in our body, like excitement, anger, fear, anxiety, which are related to discrete maps of bodily sensations (**Figure 11a**).[230] The relation between subjective feelings and temperature variation has validated that thermograms could indicate emotional parameters (**Figure 11b**).[231] Temperature changes measured by a temperature sensor array further indicated the blood perfusion fluctuates on the palm because of the sympathetic activity of arteriovenous anastomoses during the application of mental stimuli (**Figure 11c**).[42] Hence, thermography, as a valid index for emotions, has increasingly been applied in the area of psychology with potential to solve scientific and philosophical problems associated with emotions,[231] particularly psychological stress, which may cause many diseases like shock, cardiovascular diseases, neuropsychiatric diseases, gastro intestinal diseases, and even tumors.[31] The peripheral skin temperature was proved to have a negative relationship with the chronic stress (response over 3 seconds) through real-time measurement by a monitoring patch containing temperature sensors with compact size and high flexibility(**Figure 11d**).[31] Thus, flexible and stretchable temperature sensing arrays with improved wearing comfort has potentials for multimodal bio-signal monitoring applications and emotion sensing applications using mobile electronics and wearable devices.[31]

4.4. Sensory skins for robotics/prostheses

Flexible temperature sensing networks that contain a large number of temperature sensors on a flexible sheet could be attached to the clothing or directly laminated in the skin of robotics/prostheses,[58, 229, 232] providing input to the feedback controllers as well as allowing robots/prostheses to sense the environment and interact with surrounding objects (**Figure 12**).[35, 129] For instance, a temperature sensing array as an artificial skin has been wrapped around some fingers of a robot to detect temperature distribution of objects holding by the fingers.[35] A flexible temperature sensor array including Pt microresistors is used in the field of robotic sensation.[60] A 2cm×2cm thermal sensor array with mechanical adaptability was mounted on a soft prosthetic hand to measure temperature variations, while maintaining same value of resistance with different posture of soft prosthetic hand such as success, victory, and four fingers together[61]. Sensing temperature is a key functionality of human skin that helps to prevent injury and provides information about the surrounding environment.[58] A thin and conformal device consisting of temperature sensor arrays was applied to detect temperature variation on the skin surface with environmental change, such as water dropping and wind blowing,[7] which can be used to avoid danger of heat.[139] Such sensors should be highly stretchable and flexible to mimic complex and large deformations of the human skin or clothing.[229]

5. Critical issues and development trends

5.1. Critical issues

5.1.1. Flexible temperature sensors

The current flexible temperature sensors exhibit a sufficient sensitivity and resolution of ~0.1 ℃,[37] which are typically applied in the daily healthcare. For medical applications, however, there are some critical requirements, i.e., a higher sensitivity with 0.01 ℃ accuracy for precise detection[15, 28, 43] under dynamic motion; high-resolution temperature distribution using temperature sensor arrays.[24] The sensitivity of the polymeric sensors has been greatly enhanced, which can eliminate the need of amplification circuitry. However, most of the polymeric sensors suffer a very narrow temperature range,[16, 19, 25, 55] which is not suitable for the human body temperature.[41] Furthermore, there is still a great challenge to improve the accuracy, response time, reproducibility of resistivity as a function of temperature,[16, 25, 48, 81] and reduce the hysteresis of the polymeric sensors.[15, 16, 19] The sensitivity of the conductors on flexible substrates is almost a constant value,[84] which is, however, often smaller than the theoretical sensitivity of the pure free-standing conductors.[27, 77, 84] A sophisticated electronic circuit is therefore demanded for accurate detection, making it difficult for integration and wearable uses.[58]

5.1.2. Temperature sensor networks

Development of a wearable temperature sensor array based on combination of multiple discrete temperature sensors and stretchable electronics with high mechanical elasticity is desirable but remains a significant challenge.[69] Advances in novel materials and mechanical analysis have accelerated development of stretchable electronics.[144-147] However, there are several remaining issues for effective integration of stretchable interconnects with temperature sensors,[134] since most of the connections are flexible but not extensible, degrading electrical performance of the whole system in the stretching process.[174] To overcome it, the compliant substrate was stiffened at corresponding areas, stabilizing the connected regions against strain, but degrading the extensibility of the whole substrate,[211] meanwhile causing strain gradient. In addition, from a practical view, encapsulation is required to protect the bare system from mechanical and environmental attacks.[112, 196] However, it often reduces elongation of the whole system.[233] Moreover, resolution of the flexible sensor arrays has to be improved.

5.2. New trends

5.2.1. Multifunctional sensors

Flexible and stretchable electronic devices that incorporate conductive materials into compliant supporting dielectric matrix make towards the generation of a large number of delicate wearable components, including soft electrodes,[14, 234] circuits,[3, 106, 113, 121, 198, 235] transistors,[236] antennas,[237] sensors and actuators[70, 238], organic light-emitting devices,[239] as well as energy harvesting,[240] conversion and storage systems.[241] In which, wearable sensor systems comprising of various sensors (temperature, pressure, and strain sensors) that are responsive to different kinds of physical stimuli (thermoception and mechanoreception),[131, 229] are the kernel of wearable electronics[7, 25] as they are able to provide smart functions of physiological detection,[8] like health monitoring, disease diagnosis and therapy.[9, 10]

In addition to single temperature sensors, an integrated platform consisting of a multitude of sensors, such as temperature, pressure, strain, biological or chemical sensors,[9] will be of great interest for wearable applications since it is able to simultaneously detect multiple stimuli.[29, 216, 220] It is not straightforward, however, to enable the multifunctional electronic skins that can simultaneously perceive and discriminate among various spatiotemporal external stimuli,[216] because the fabrication of such multifunctional sensors typically involves integration of a number of sensing devices on heterogeneous substrates and sophisticated layouts of interconnect lines or signal processing circuits, which often causes signal interference between each other.[139, 220, 242] Hence, it would be of great importance to decouple a target signal from the others,[139] and the involvement of organic field-effect transistor (OFET) in multi-functional sensory devices sounds a promising solution.[131, 243]

5.2.2. Self-powered sensors

Incorporation of flexible energy harvesting,[240, 244] conversion and storage systems[241] capable of converting mechanical and (or) thermal stimuli or light into electric energy into sensing integrated systems could be very useful for wearable purpose as they are constantly under physical stimuli of various types during their operation.[9, 58, 104, 188, 245] Hence, an integrated system consisting of flexible power source and physical sensors is another important trends for wearable applications.[246]

5.2.3. Textile-based integrated sensors

Truly wearable application of flexible and stretchable electronics relies on a thin, lightweight, flexible,[247] as well as porous (or breathable) textile substrate to seamlessly integrate with electronic functions to accomplish electronic textiles that are capable of compliant interaction with zoetic,[17] soft, curved, and dynamically deformed human bodies.[1-4, 7] Textile-based integrated sensors are therefore essential to advance wearable electronics in soft, deformable and porous formats, as an alternative to conventional ones that are “bulky, stiff and brittle” and the other flexible ones supported by plastics or elastomers without permeability, potentially initiating vast applications such as continuous, long-term health monitoring system,[1, 5, 6] human-machine interface,[12] as well as artificially electronic skin.[5, 6, 13, 14]

6. Conclusion and perspective

Flexible and stretchable electronics, as an alternative to conventional bulky and stiff electronic devices, could fully integrate into human bodies with curved shapes.[1-4] As one kernel of wearable electronics,[5, 6, 13, 14] temperature sensor networks comprising of discrete temperature sensors and interconnected lines or data processing circuits,[131] could provide real-time monitoring of temperature distribution of the human skin regardless of large deformation,[17] thus potential for wearable applications,[1, 5-12] such as smart functions of physiological detection,[8] like health monitoring, disease diagnosis, and therapy,[9, 10] robotic skins, and reflection of emotional changes.[7, 16]

This review exploits a systematic overview of the newest development in flexible temperature sensors, wearable temperature sensor networks, and integrated platforms in flexible and stretchable formats for physiological monitoring applications. Many efforts have been made in soft and biocompatible temperature sensors[7, 25] through different approaches, such as functional materials[2, 7, 9] doped with polymer matrix, and MEMS based technology with soft substrate.[2, 7, 18] It has been demonstrated that some conductive composites could achieve orders-of-magnitude improvement in sensitivity. It is still challenging, however, to fabricate a flexible temperature sensor in a reproducible sensing response[25] in an appropriate temperature range needed for wearable applications.[19] For continuous monitoring of electrophysiological activity generated from the subject, the sensors must be connected to passive or active electrical transmission modules, data acquisition devices, power supplies, and display interface through wired or wireless technologies.[7-9] By incorporating flexible sensors and the other discrete elements to lightweight, ultrathin, and elastic membranes like silicone and textiles, the wearable electronic devices could interface with the human bodies with curved surfaces, complex geometries, and time dynamic tissues,[22] and simultaneously maintain high levels of electronic function.[7, 8] The naturally flexible and stretchable polymeric substrates in combination with the interconnects offer soft, conformal interface with the non-coplanar surfaces of the body in a manner that does not constrain naturally motional behaviors.[8] To effectively relieve strain, sophisticated layouts of interconnected lines in the format of passive or active integrated circuits or transistor arrays is required to be stretchable realized either by innovative structural patterns,[11] like open mesh, wavy, serpentine, net-shape, or stiff-island structures, or by novel material designs.[10, 11, 21, 69, 148, 216, 248] Hence, the integrated collections of such components enable intimate adhesion with minimal discomfort, and without noise that may be generated from relative motion of the sensors and the soft tissues.[7, 42, 248, 249] As a result, the device can be fixed on the biological tissues without awareness.[20, 24, 55, 248], and be employed in wearable applications, such as monitoring of health conditions, robotic skin, and emotion-related bodily sensations.

However, for practical applications of flexible temperature sensing networks in monitoring personal healthcare, certain issues remain and should be solved in future work. In terms of polymeric sensors, most of them exhibit a resolution of ~0.1 ℃, which is often limited in the daily healthcare. For medical applications, however, precise detection is required with 0.01 ℃ accuracy;[24] most of the polymeric sensors suffer a very narrow temperature range, which is not suitable for the human body temperature; the sensitivity of the polymeric sensors has been enhanced, however, it is still challengeable to improve response time, reproducibility of resistivity as a function of temperature, and reduce the hysteresis of the polymeric sensors. Regarding packaging of the temperature sensing networks, it remains difficult to effectively integrate temperature sensors with power, signal conditioning, communication, and data transmission units; most of the connections often degrade electrical performance of the whole assembly in the stretching process; encapsulation is necessary to protect the bare sensing network from mechanical and environmental attacks, although it often reduces elongation of the whole system; resolution of the flexible sensor arrays has to be improved; comfortability, washablity, fatigue life of the flexible temperature sensing networks and their applications on the condition of sweat are still not systematically investigated. Therefore, appropriate structural design would be very important in the fabrication process of the flexible temperature sensing arrays.

In addition to single temperature sensors, an integrated platform consisting of a multitude of sensors, such as temperature, pressure, strain, biological or chemical sensors, will be of great interest for wearable applications since it is able to simultaneously detect multiple stimuli, in which involvement of organic field-effect transistor (OFET) sounds a promising approach to decouple a target signal from the others. Furthermore, incorporation of flexible energy harvesting, conversion and storage systems into the sensing integrated platform could be very useful for wearable purpose as they are constantly under physical stimuli of various types during their operations. However, the present level of power generation and power capacity is urgently needed to be drastically improved for practical applications. For comfort consideration, porous textile-based integrated sensors are still essential to truly wearable usages, where the mechanical behavior of the textile substrates should be particularly optimized with selection of materials and structural design.

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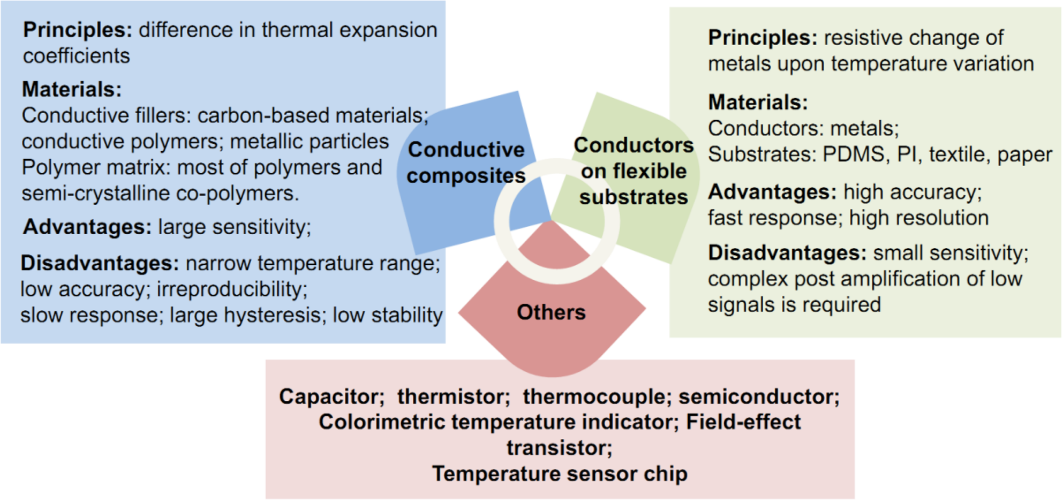


Principles: difference in thermal expansion coefficients

Materials:
Conductive fillers: carbon-based materials; conductive polymers; metallic particles
Polymer matrix: most of polymers and semi-crystalline co-polymers.

Advantages: large sensitivity;

Disadvantages: narrow temperature range; low accuracy; irreproducibility; slow response; large hysteresis; low stability

Principles: resistive change of metals upon temperature variation

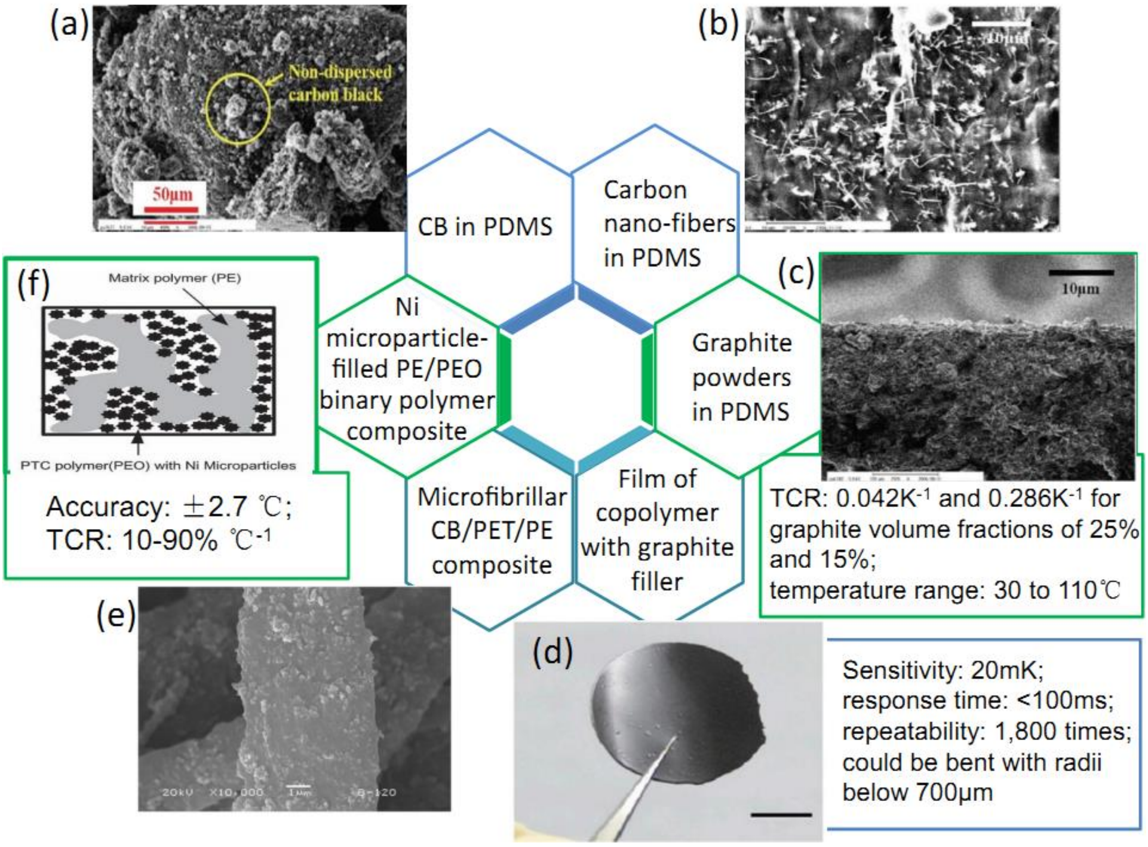
Materials:
Conductors: metals;
Substrates: PDMS, PI, textile, paper

Advantages: high accuracy; fast response; high resolution

Disadvantages: small sensitivity; complex post amplification of low signals is required

Capacitor; thermistor; thermocouple; semiconductor; Colorimetric temperature indicator; Field-effect transistor; Temperature sensor chip

Figure 1. Different types of flexible temperature sensors.



Accuracy: ±2.7 ℃;
TCR: 10-90% ℃$^{-1}$

TCR: 0.042K^{-1} and 0.286K^{-1} for graphite volume fractions of 25% and 15%;
temperature range: 30 to 110℃

Sensitivity: 20mK;
response time: <100ms;
repeatability: 1,800 times;
could be bent with radii below 700μm

Figure 2. Various flexible temperature sensors based on conductive polymers. (a). SEM images of carbon black in PDMS.[60] (b). Carbon nano-fibers in PDMS.[64] (c). The cross-sectional SEM image of a graphite-PDMS composite.[60] (d). Photograph of a film of copolymer with graphite filler.[25] (e). SEM micrograph of microfibrillar CB/PET/PE composite.[57] (f). A schematic illustration of a Ni microparticle-filled binary polymer composite.[19]

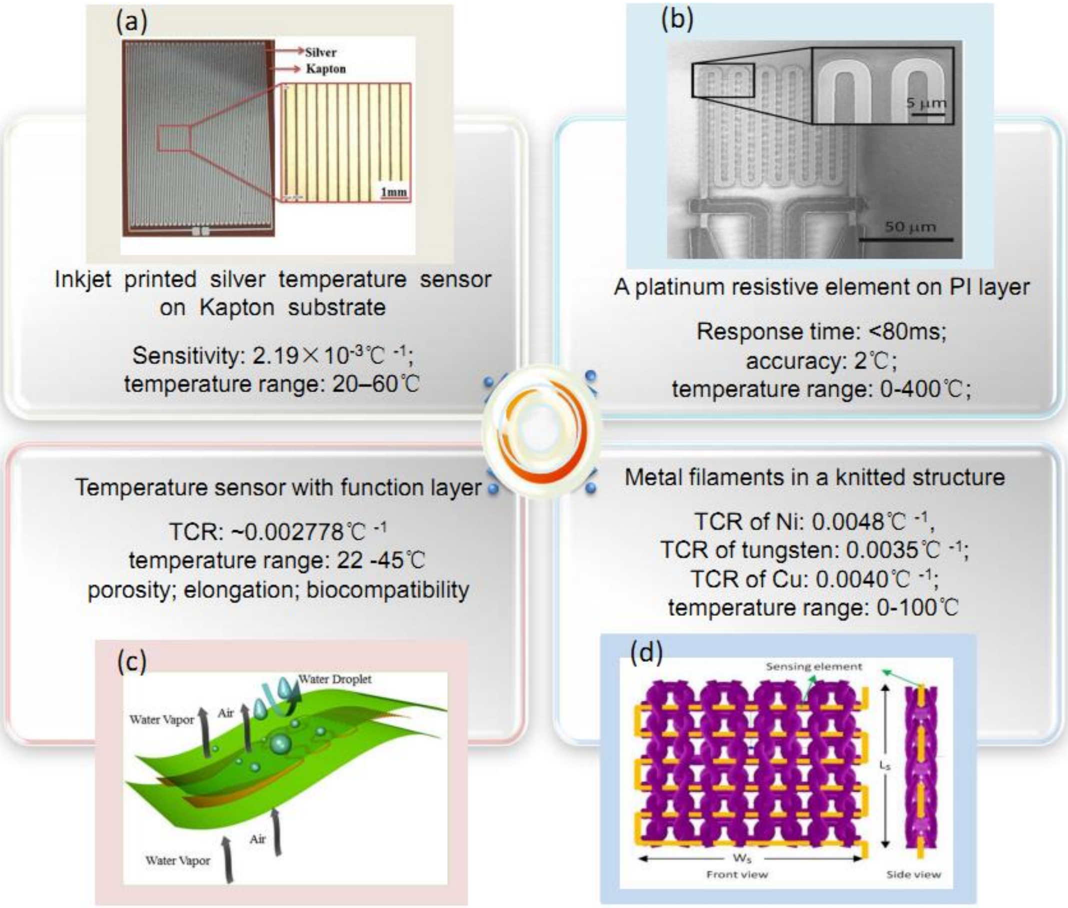


Figure 3. Examples of temperature-sensitive conductors on flexible substrates. (a). Inkjet printed silver temperature sensor on Kapton substrate.[54] (b). A platinum resistive element on the polyimide layer.[77] (c). Water proof and vapor permeable temperature sensor.[7] (d). Temperature sensing fabric.[92]

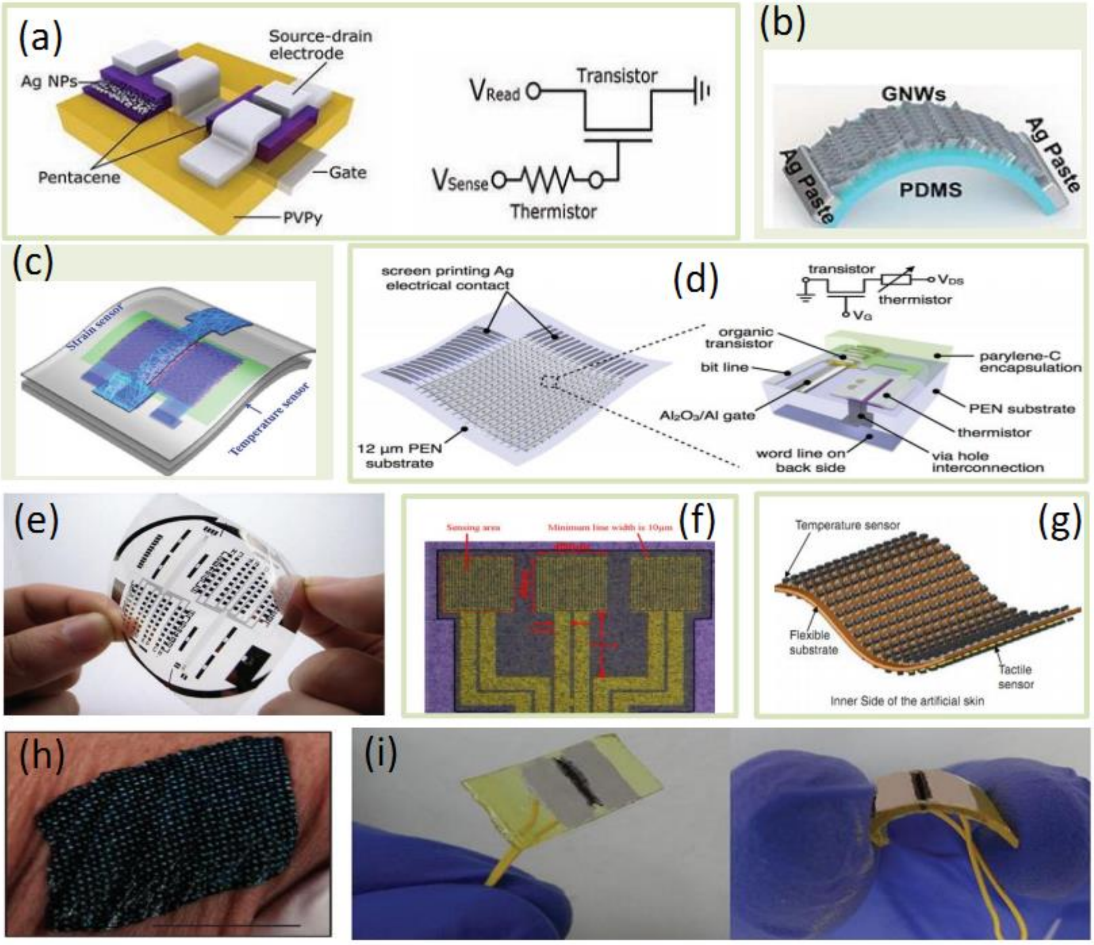


Figure 4. Examples of other types of flexible temperature sensors. (a). The schematic diagrams of the (one transistor)–(one thermistor) temperature sensor.[20] (b). Schematic for GNWs/PDMS temperature sensors.[16] (c). Transparent and stretchable integrated platform of temperature and strain sensors.[69] (d). Electrical sign and enlarged schematic diagram of a single temperature sensor.[55, 69] (e). A photograph of a 8 × 8 Ni temperature sensor arrays on a piece of PET substrate.[19, 26, 34, 43, 127] (f). Flexible micro-temperature sensor.[38] (g). A schematic of the artificial skin including temperature sensors.[35] (h). Picture of a temperature sensor array on the skin deformed by pinching in a twisting motion.[29] (i). A self-healing chemiresistor consisting of AuNP film.[130]

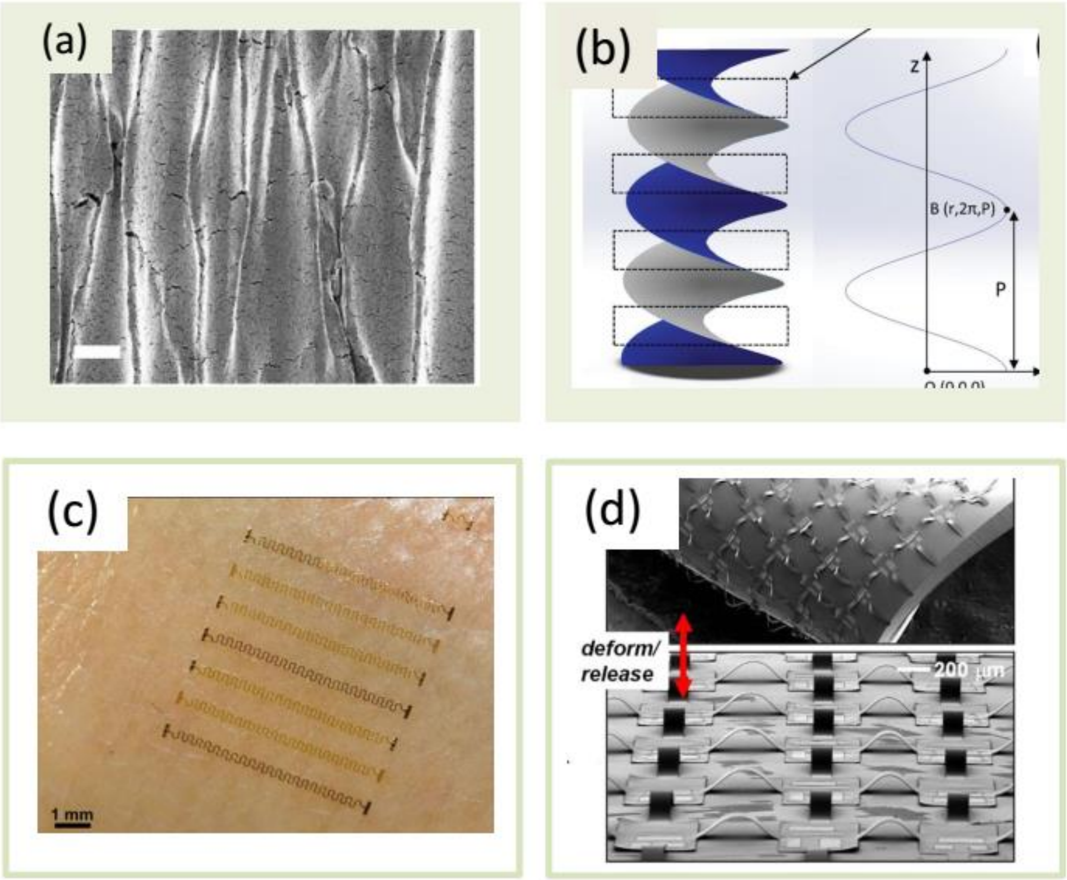


Figure 5. Inorganic stretchable electronics based on mechanical structural designs. (a) SEM image of buckled metal electrode film.[161] (b) A 3D model illustrates that the original circumference of the spring makes an out-of-plane helical structure.[177] (c) Photograph image of the stretchable transmission line array laminated on the back of hand.[180] (d) Images of buckled polymer bridges interconnecting silicon islands.[163, 187]

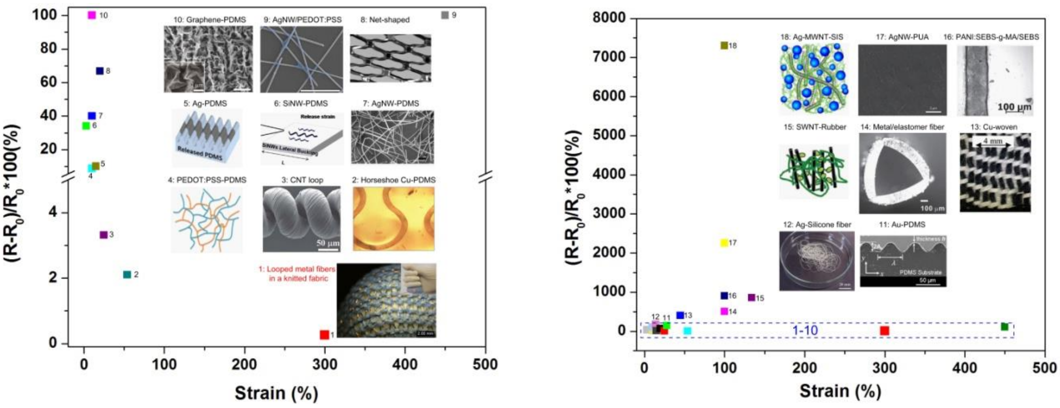


Figure 6. Stretchable interconnects with their stretchability and corresponding relative change of electrical resistance (1;[199, 200] 2;[158] 3;[154] 4;[156] 5;[203] 6;[201] 7;[204] 8;[148] 9;[205] 10;[151] 11;[175] 12;[157] 13;[113] 14;[170] 15;[152] 16;[155] 17;[206] 18[153]).

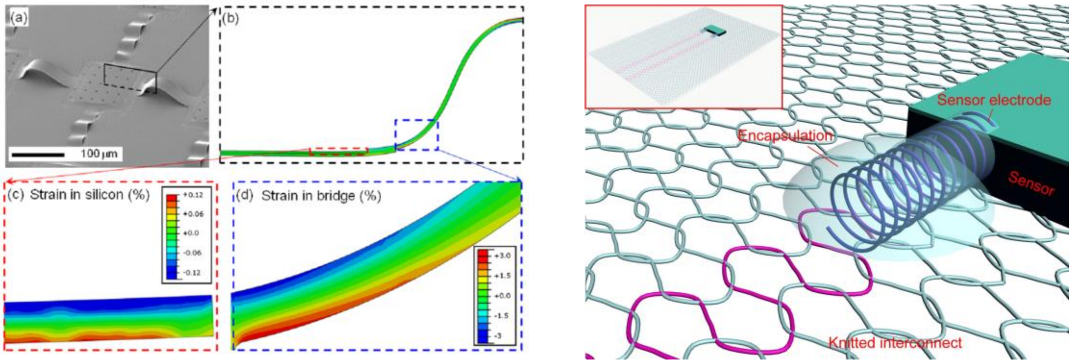


Figure 7. Connections in stretchable integrated system. (a). A typical island-bridge structure of stretchable electronic systems.[213] (b). Helical electrical connection with a semi-spherical encapsulated layer.[199]

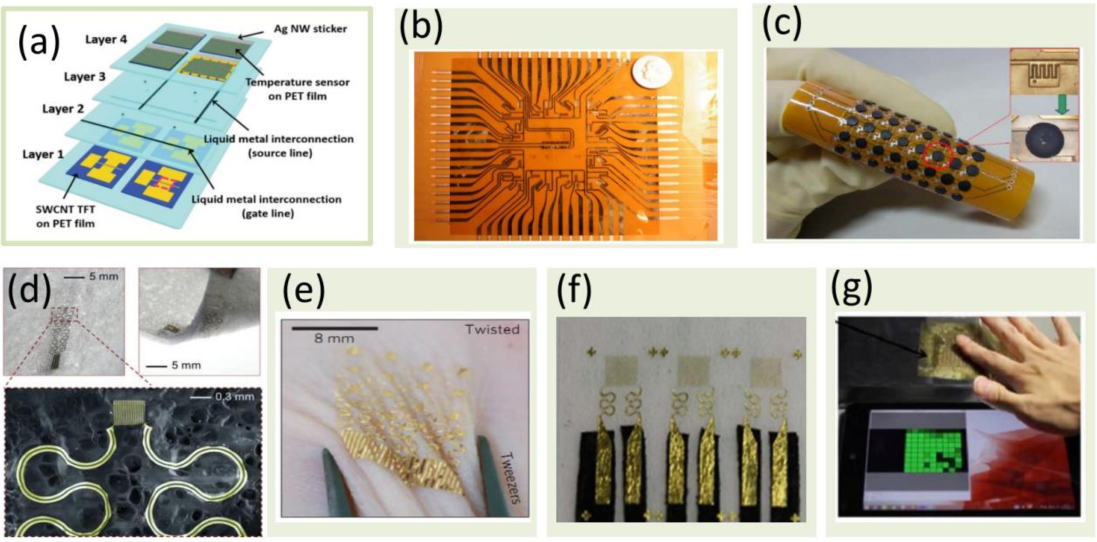


Figure 8. Temperature sensor arrays. (a). Stretchable active matrix temperature sensor array.[51] (b). Completed 48-sensor flexible array with Cu interconnect lines converging to a ribbon tail.[87] (c). Flexible temperature sensor array consisting of the interdigitated electrode and composites on the electrode, respectively.[60] (d). Optical images of a device with polyurethane (PU) foam as the separation material and enlarged view of a temperature sensor.[21] (e). Ultrathin, compliant, skin-like arrays of precision temperature sensors and heaters.[42] (f). Biocompatible and stretchable temperature sensor.[7] (g). Flexible temperature sensor sheet for large-area temperature mapping.[25]

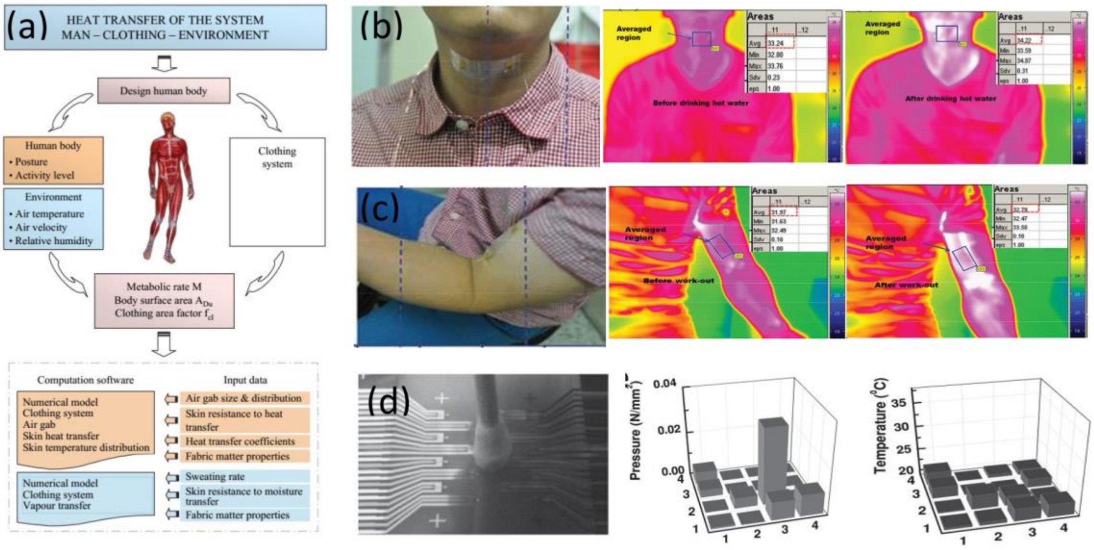


Figure 9. Temperature sensor arrays for monitoring human activities. (a) Heat transfer of the system: “man-clothing-environment”.[224] (b)-(c). Integrated platform of temperature and strain sensors on a human neck (b) and arm (c) responding simultaneously to the temperature of human skin and to muscle movement during human activities.[69] (d). Bimodal sensing in an array of FET sensors.[139]

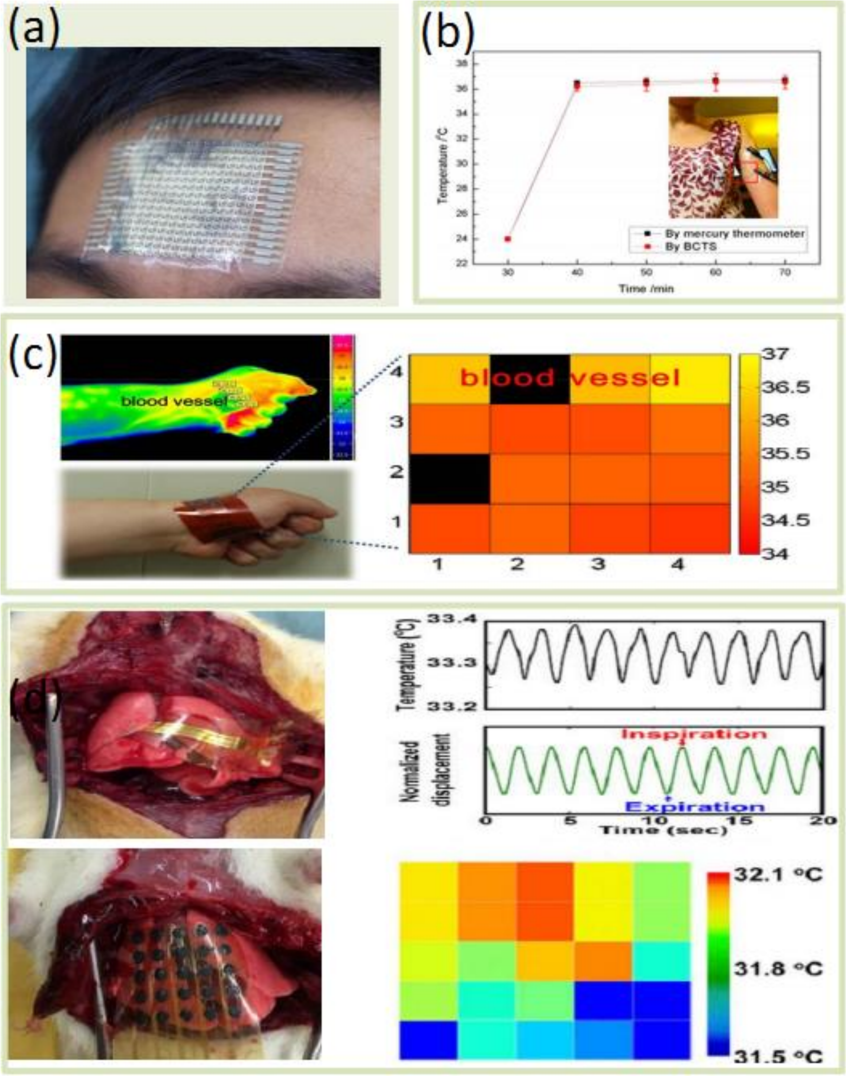


Figure 10. Mapping of the temperature distribution from flexible sensor arrays attached to forehead (a),[55] underarm (b),[7] upper extremity (c),[131] and the lung (d).[25]

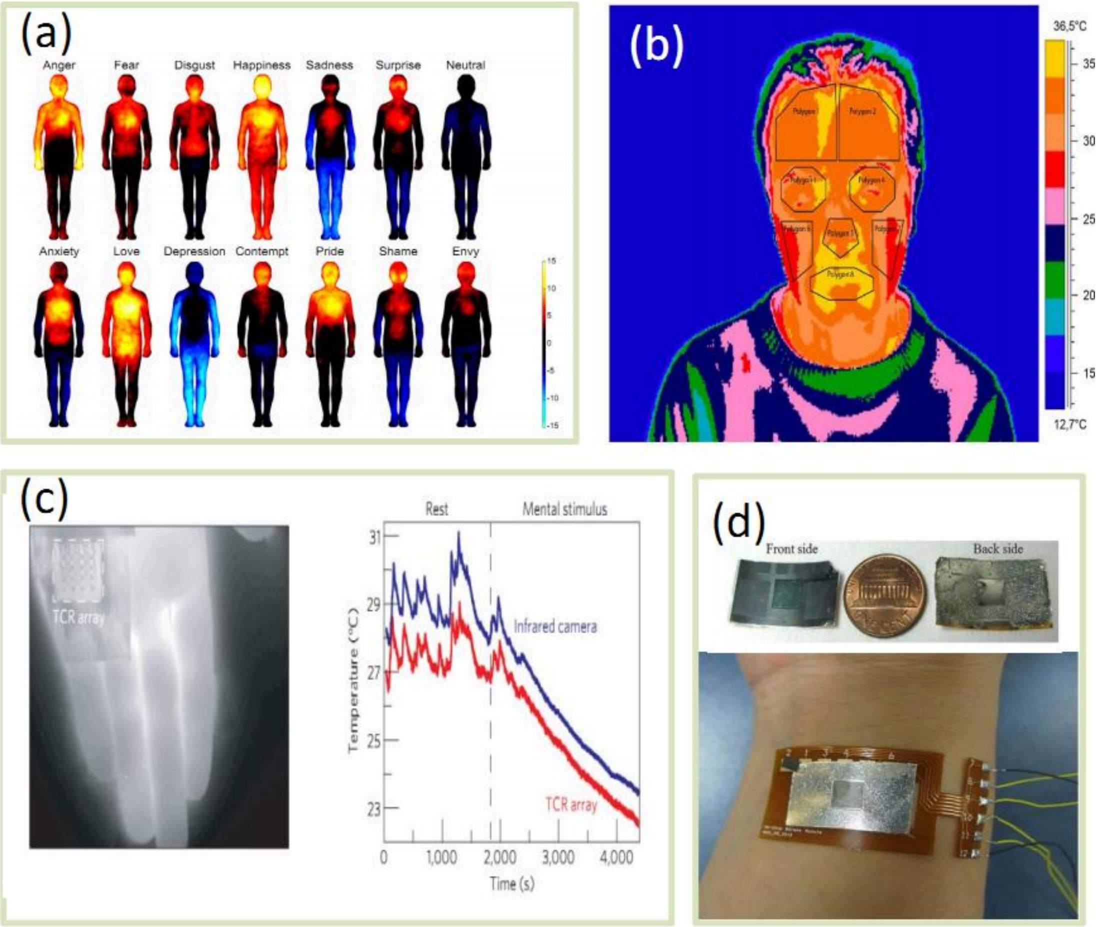


Figure 11. Temperature sensors for psychological stress monitoring. (a). Bodily topography of emotions.[230] (b). The face coded in eight separate regions with temperature distribution.[231] (c). Epidermal electronic evaluations of skin temperature at rest and during mental stimulation.[42] (d). The stress monitoring patch attached to human wrist.[31]

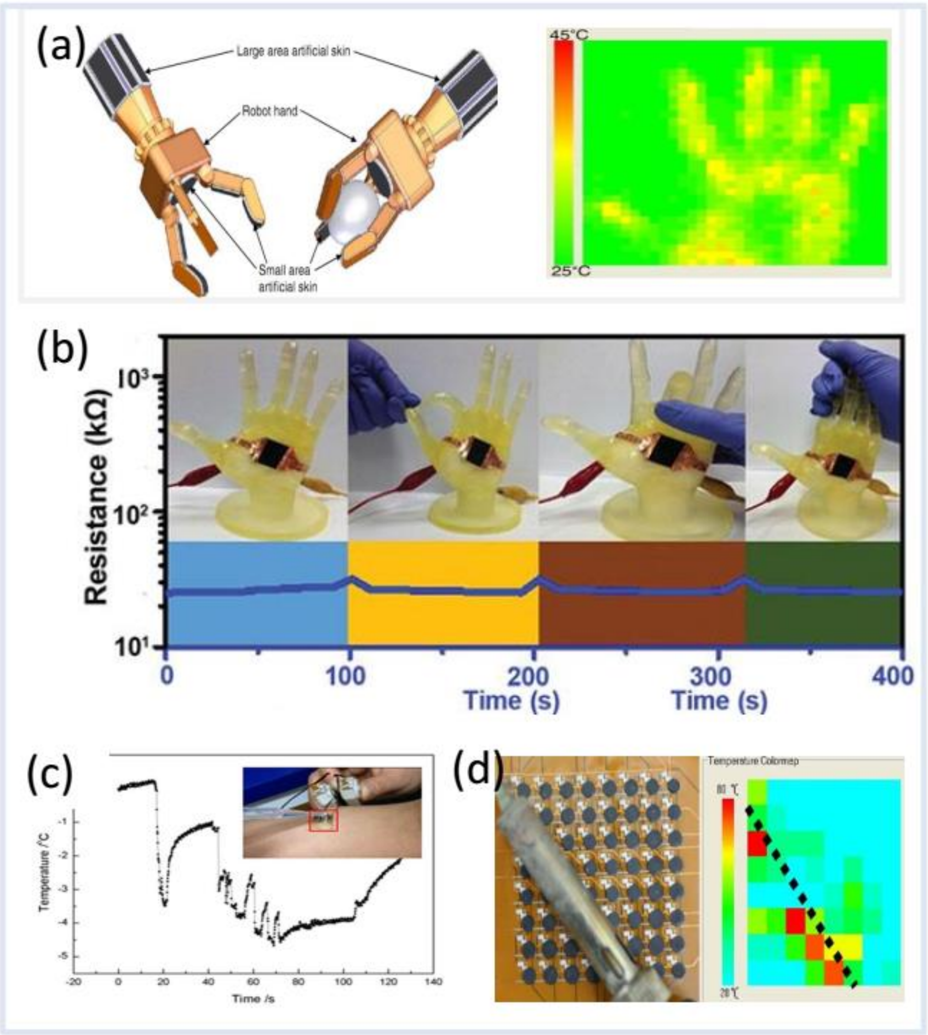


Figure 12. Temperature sensing networks as sensory skins for robotics/prostheses. (a). A temperature sensing array on the fingers of a robot.[35] (b). A thermal sensor mounted on a soft prosthetic hand with constant resistance at different posture.[61] (c). Temperature measurement in water dropping.[7] (d). Measured temperature distributions of the fabricated sensor array subjected to a heated rod.[60]

Table 1. Sensing performance of various temperature sensors

Temperature sensors	Measurement range	Sensitivity	Accuracy	Response time	Recovery time
GNWs/PDMS based temperature sensor[71]	35-45 ℃	0.214 ℃$^{-1}$	---	1.6s	8.52s
Ni microparticle-filled binary polymer composite[72]	---	0.10-0.90 ℃$^{-1}$	±2.7 ℃	---	---
Graphite powders in PDMS[73]	30-110 ℃	0.286 ℃ $^{-1}$	---	---	---
rGO/PU temperature sensor[74]	---	0.0134 ℃$^{-1}$	0.2 ℃	---	---
CNTs powder deposited on elastic polymer tape[53]	20-70 ℃	-1.26% ℃$^{-1}$	---	---	---
Water proof and vapor permeable temperature sensor[75]	22-45 ℃	0.002778 ℃$^{-1}$	---	---	---
Pt/PI temperature sensor[76, 77]	20–60 ℃	0.00219 ℃$^{-1}$	2 ℃	<80ms	---
Temperature sensing fabric with Ni fibers[78]	0-100 ℃	0.0048 ℃$^{-1}$	---	---	---
Temperature sensor including Au as the sensing layer[79]	30-80 ℃	0.8Ω°C^{-1}	0.3 ℃	1.7–2.3s	---
A chemiresistor consisting of AuNP film[80]	10–42 ℃	0.41MΩ°C^{-1}	0.1 ℃	---	---