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Flexible pressure and temperature sensors towards e-skin: material, mechanism, structure and fabrication

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Abstract

Electronic skin (E-skin) has gained significant attention due to its potential applications in the Internet of Things (IoT), artificial intelligence (AI), and flexible multi-sensing systems. Mimicking human skin, e-skin sensing devices can be employed in various scenarios. Among the most important sensing elements for tactile e-skin sensors are pressure and temperature sensors, which have increasingly garnered research interest over the past few decades. However, the design and fabrication of advanced pressure and temperature sensors can be challenging owing to complications such as signal interference, complex mechanism integration, and structural design issues. This review provides an overview of flexible pressure and temperature sensors used in e-skin, covering four main perspectives: material selection, mechanism integration, structural design, and manufacturing methods. The materials of different elements in the entire sensing system are comprehensively discussed, along with single and compound mechanisms of pressure and temperature sensing. Pressure and temperature sensors are divided into two types based on their electric output signals, which are exemplified in detail. The manufacturing methods used to fabricate these sensors, including printing methods, are outlined. Lastly, a summary of the future challenges faced by flexible pressure and temperature sensors used in e-skin is presented.

Keywords: Flexible electronics, electronic skin, printed sensors, MEMS, human-machine interaction

INTRODUCTION

The advancement of technology is mutually reinforcing. With the rapid development of artificial intelligence (AI) and the Internet of Things (IoT), electronic skin (e-skin) devices have manifested more and more potential in multifunctional sensing systems, which play a vital role in converting physical stimuli into electronic signals[1-3]. Specifically speaking, extensive efforts have been devoted to developing highly integrated, flexible, stretchable, and multi-responsive sensors that can adhere to the human skin in order to sense the surrounding environment, such as pressure, temperature, humidity, and some biochemical signals, and respond quickly[4,5]. Superior sensing performance has made e-skin a powerful candidate for intelligent healthcare, soft robotics, motion detection, and virtual reality[6-8].

As is known to us all, human skin not only protects us from external harm as a remarkable natural barrier but a complex and coordinated system where multiple biosensors attached to the skin surface realize functional sensing and signal processing of the nerve center. E-skin, as an imitation of real human skin, is not limited to mimicking its functions, such as pressure and temperature sensing, but more additional features beyond human skin, such as light, sound, magnetism, velocity, and acceleration[3,6]. Among the five basic human senses (visual, auditory, tactile, gustatory, and olfactory), tactile, as the most fundamental one, should not be ignored. It involves multiple physical signal measurements, primarily pressure, temperature, and humidity, and is the most direct demonstration of e-skin excellence[7]. Pressure and temperature sensing can help identify objects, sense warm or cold temperatures, and respond quickly in emergencies, making them highly valuable in a variety of application scenarios.

Undoubtedly, the fabrication of flexible pressure and temperature sensors towards e-skin faces numerous challenges. The selection of suitable active and substrate materials is surely a cornerstone for outstanding performance, while multiple combinations of sensing mechanisms can determine the types of composite sensors and serve as a bridge between material selection and structural design[8-10]. For instance, pressure detection based on piezoresistivity[11-16], capacitance[17,18], piezoelectricity[19-20], and triboelectricity[21-23] mechanisms have been demonstrated before and researched extensively. Simultaneously, thermoresistive-based[24,25] and thermoelectric-based[11-15] temperature sensors, namely thermistors and thermocouples, have been widely fabricated for temperature sensing. The integration of pressure and temperature sensing mechanisms is complicated and worthy of discussion[7]. In addition, a novel and effective structural design can help superior specifications, such as high sensitivity, high response time, and wide detection range. And last but not least, a cost-effective manufacturing process can combine all of the previous work to complete the whole system design. Accordingly, thorough consideration, such as those mentioned, should be prepared by sensor researchers.

Herein, this review article summarizes flexible pressure and temperature sensors towards e-skin from four perspectives, material selection, mechanism integration, structural design, and manufacturing methods, as illustrated in Figure 1. Meaningfully, this review presents flexible pressure-temperature hybrid sensors, especially from the perspective of manufacturing and processing methods, concluding the popular printing technology, comparing in detail the advantages, disadvantages, and applicability of different printing methods, and providing a route for pressure-temperature sensing arrays based on printing technology. The main contents include the following aspects: (1) Choices of materials for pressure and temperature sensors; (2) Basic sensing mechanisms and evaluation parameters for pressure and temperature sensors; (3) Multiple mechanism integration and structural design of pressure and temperature sensors; (4) Manufacturing methods for pressure and temperature sensors.

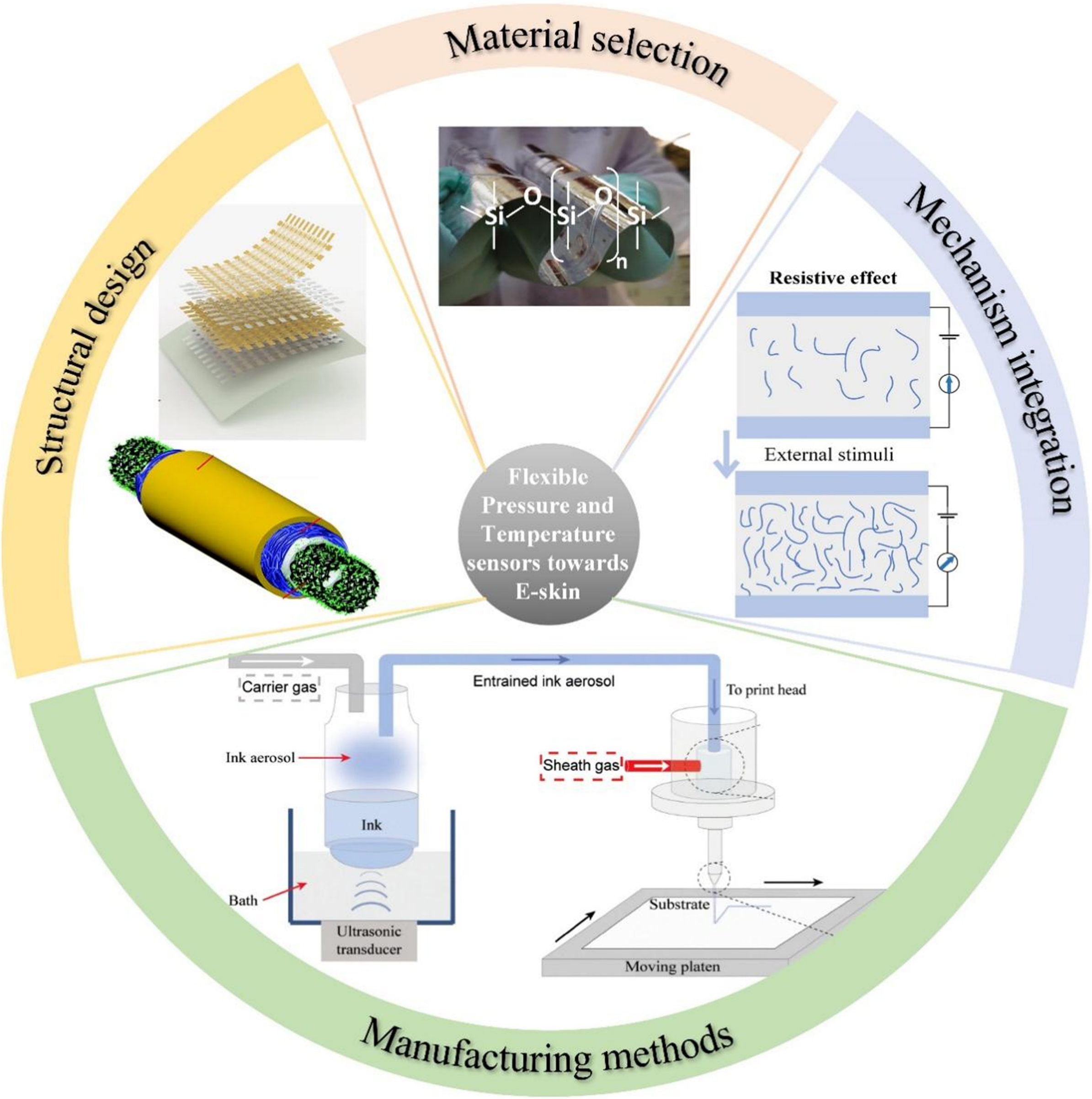

Figure 1. Overview of pressure and temperature sensors towards e-skin in terms of material selection, mechanism integration, structural design, and manufacturing methods. Figure "Material Selection", reproduced with permission[26]. Copyright 2010, Springer Nature. The lower of Figure "Structural Design", reproduced with permission[27]. Copyright 2017, The Royal Society of Chemistry. The upper of Figure "Structural Design", reproduced with permission[28]. Copyright 2018, Springer Nature. Figure "Manufacturing Methods", reproduced with permission[29]. Copyright 2020, Springer Nature.

CHOICES OF MATERIALS FOR PRESSURE AND TEMPERATURE SENSORS

The implementation of flexible pressure and temperature sensors is based on suitable material selection, which is the most fundamental among the four perspectives presented in this review. To realize the flexible sensing system towards e-skin, seamless interfaces between devices and human skin are mandatory. Obviously, suitable choices of materials, including substrates, electrodes, and active sensing layers, can help consolidate the delicate sensing structure. In general, three basic elements, namely the substrates, conductive interconnects, and sensing elements, are essential for hybridization to accommodate the demands of various sensing functions, as summarized in Figure 2[3]. By leveraging the properties of

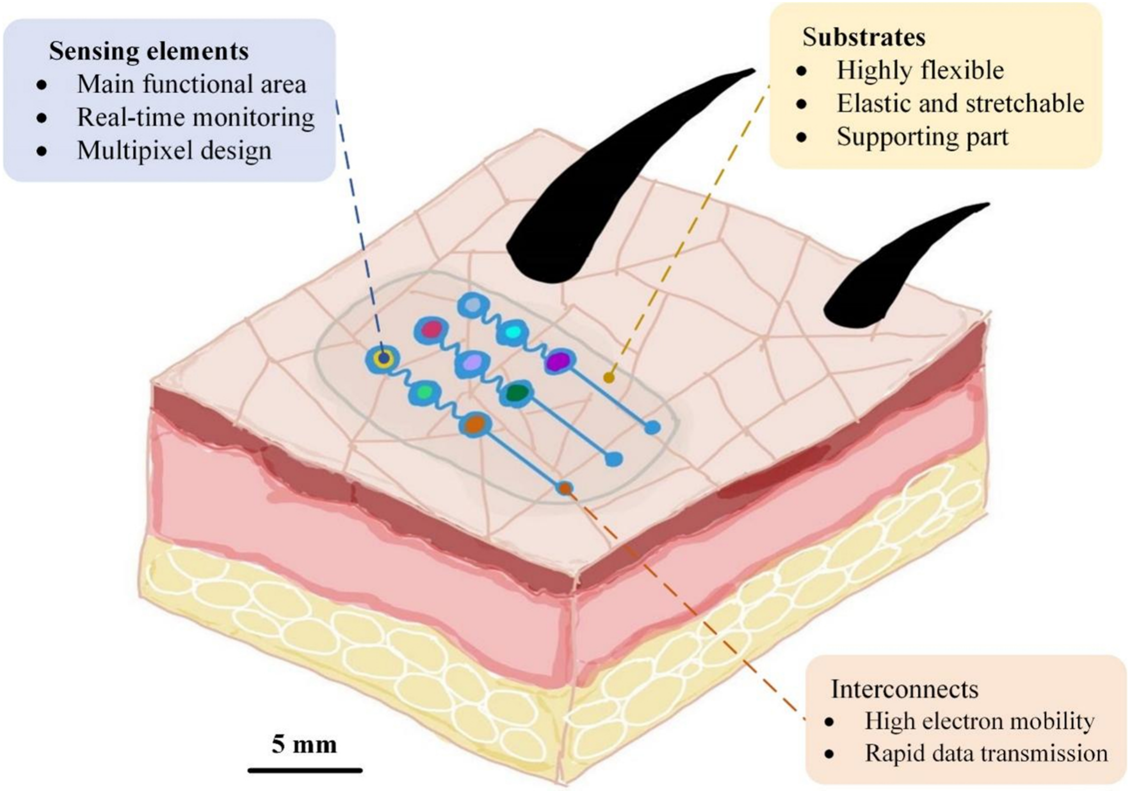

Figure 2. Flexible pressure and temperature sensors on the human skin divided into substrates, interconnects, and sensing elements.

composite functional materials, it is possible to expand the performance of single materials, enhance their advantages, and overcome their disadvantages. This enables the achievement of optimal mechanical and electronic properties, empowering multifunctional sensing[8]. In this section, we first consider the selection of materials for three basic elements. The flexible substrate primarily influences the mechanical and physical properties of the devices, while the sensing elements determine the electrical properties, and the conductive interconnections ensure the electron mobility and data transmission.

Substrates

Substrates, which serve as the bottom layer of the overall sensing system, influence the properties of all elements and are critical to achieving desirable system performance. The molecular structure and complex arrangements of substrates, such as stretchability and flexibility, largely determine their effectiveness[8]. From the perspective of conventional materials, polymers stand out as the best material option, which provides broad options for various sensing designs and fabrication, as shown in “Polymers” of Figure 3[30].

More importantly, elastic stretchability is an essential parameter aimed at high deformation in extreme conditions. Therefore, in order to store and dissipate energy, it is necessary to alter the conformational structure of polymers[31]. In particular, side chain modification can be used to confer traditional polymers the charming property to undergo high stress and large deformation, as seen in “Silicone rubbers” of Figure 3[32]. Plenty of silicone elastomers can be exemplified to apply rapid model validation, such as polydimethylsiloxane (PDMS), extensively used in stretchable electronics owing to its easy attainment and large-scale fabrication[33,34]. Besides PDMS, platinum-catalyzed silicones, including Ecoflex, Silbione, and DragonSkin, have captured much attention[8-31].

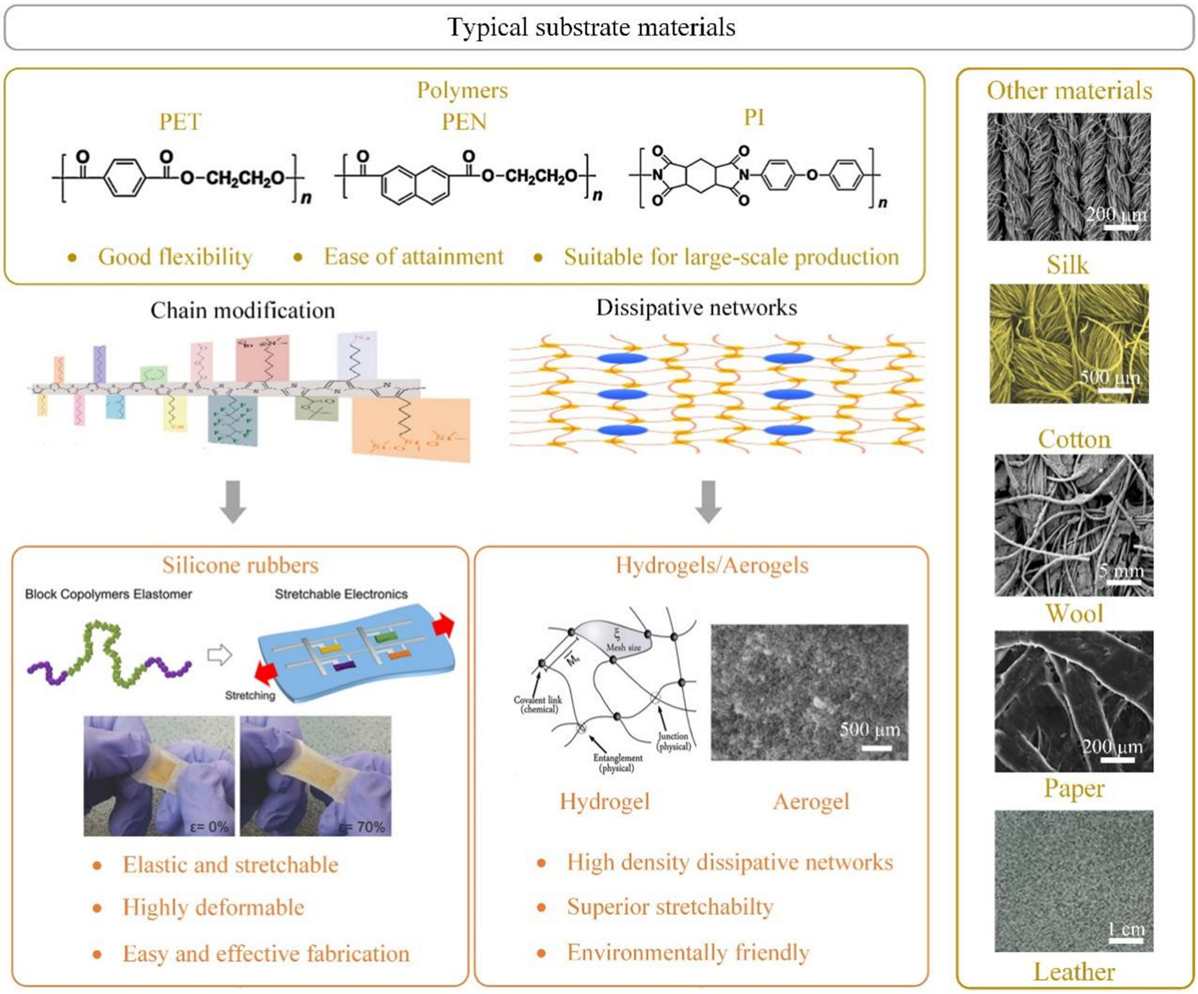

Figure 3. Overview of substrate materials of pressure and temperature sensors towards e-skin. Figure "Polymers" reproduced with permission[30]. Copyright 2015, Elsevier. B.V. PET, PEN, and PI represent polyethylene glycol terephthalate, polyethylene naphthalate two formic acid glycol ester, and polyimide, respectively. Figure "Chain modification" reproduced with permission[32]. Copyright 2014, American Chemical Society. Figure "Dissipative networks" reproduced with permission[36]. Copyright 2017, The Royal Society of Chemistry. The upper of Figure "Silicone rubbers" reproduced with permission[33]. Copyright 2018, American Chemical Society. The lower of Figure "Silicone rubbers" reproduced with permission[34]. Copyright 2014, John Wiley & Sons, Inc. Figure "Hydrogel" reproduced with permission[37]. Copyright 2012, Elsevier B.V. Figure "Aerogel" reproduced with permission[38]. Copyright 2012, Springer Nature. Figure "Other materials" from top to bottom reproduced with permission[39-43]. Copyright 2017, American Chemical Society[39]. Copyright 2017, John Wiley & Sons, Inc[40]. Copyright 2018, American Chemical Society[41]. Copyright 2011, John Wiley & Sons, Inc[42]. Copyright 2019, John Wiley & Sons, Inc[43].

Additionally, an interesting method of reducing density to increase free volume has been widely used to enhance the extensibility of polymers. The compounds, divided into plasticizers, cross-linkers, and dissipative networks, can interpose among chains of polymers and change elastic modulus[35-36]. Hydrogels[37] and aerogels[38], the specific examples of dissipative networks penetrated with liquid and air, are implied in "Hydrogels/Aerogels" of Figure 3, noteworthily, which can remain robust mechanical energy under strong deformation. Due to their fabulous properties, gel-state materials have been adopted in various functions, such as self-healing, self-reinforcing, and self-regulating[35].

Despite the numerous advantages of polymers and extensive efforts to reinforce their properties, there exist a sea of natural and semi-natural materials, such as textile and paper, that distinguish them from the aforementioned polymetric strategies. "Other materials" of Figure 3 list some typical textiles, including silk[39], cotton[40], and wool[41], which can enable isotropic deformation and realize a more suitable contour for human skin. Apart from textiles, paper-based devices have been put into research and production due to multiple virtues, such as universality, eco-friendliness, low cost, and easy fabrication[14,42]. Porous cellulose nanofibers packed in the paper promote convenience for liquid penetration without an external pump when fabricating and also provide the possibility of sweat-based biosensing[14]. Other unconventional materials, such as leather, can also be used[43].

Conductive interconnects

Significantly, conductive interconnects undertake the function of sensing data transmission between active elements and external interfaces, which relates to the whole electronic performance. For stretchable electronic devices, a tradeoff between mechanical flexibility and charge transmission is obviously not negligible[44]. Compared with electrodes on the rigid substrate, interconnects require stable high-conductivity independent of flexibility and stretchability from the substrate. The deformational robustness of materials ensures a high signal-to-noise ratio and efficient information transmission for the overall sensing system. In this section, interconnects are classified into solid-state, gel-state, and liquid-state and then discussed separately.

Solid-state interconnects, divided into metallic, non-metallic, and hybrid materials, are mainly used due to their high conductivity and inertness. Different from traditional electrodes in large-scale applications, micro/nano-scale interconnects tend to be designed with unique structures, such as serpentine structures[45] shown in Figure 4A and wavy[46] structures. Two main strategies are adopted, namely chemical material modification and deterministic hierarchical architectures[30]. Mostly, reducing the dimensionality is widely adopted since non-3D structures can adapt better to flexible and stretchable substrates. Figure 4B lists some metallic and non-metallic interconnect materials that comprise nanoparticles[47] (NPs), nanowires[48] (NWs), nanosheets[49] for metal and carbon nanotubes[50] (CNTs), graphene[51], and conductive polymers (CPs)[52] for non-metal. Metallic nanostructures not singly form an excellent matrix with electrical conductivity but absorb mechanical strain to ensure high flexibility as well[44]. Contrastively, non-metallic materials tend to possess relatively poor conductivity, whereas some carbon-based materials with enhanced electrical conductivity, represented by CNTs and graphene, become suitable and promising interconnect candidates[50,51]. Polymers mostly exploited owing to mechanical properties can be granted the conductive capacity using a chemical doping method to create charge mobile pathways[52,53]. Interestingly, the hybrids of metallic and non-metallic materials can be researched for the purpose of reinforcing the properties of a single material. For instance, hybrid fillers comprising graphene and silver NWs (AgNWs) are incorporated into extremely stretchable spandex to fabricate strain sensors by Vo *et al.*, as implied in Figure 4C[54].

Gel-state materials, aforementioned as decent substrate materials, can be introduced to form interconnects. For example, Liu *et al.* reported electrically conductive hydrogel-based elastic microelectronics with Young's modulus values in the kilopascal range for localized low-voltage neuromodulation, as shown in Figure 4D[55]. Lastly, liquid-state materials can be integrated into substrates as microfluidic interconnects. For example, a microfluidic tactile diaphragm pressure sensor based on embedded Galinstan microchannels is demonstrated for ultra-low pressure detection by Gao *et al.*, as summarized in Figure 4E[56].

Sensing elements

After discussing a wide range of material approaches on the substrates and interconnects, strategies on sensing materials are considered prudently. In essence, high-performance sensing materials have been fabricated and applied all the time, which can look back to the Eastern Han Dynasty when Zhang Heng made the famous seismoscope[57]. With the development of the electronic industry, sensors have ranged

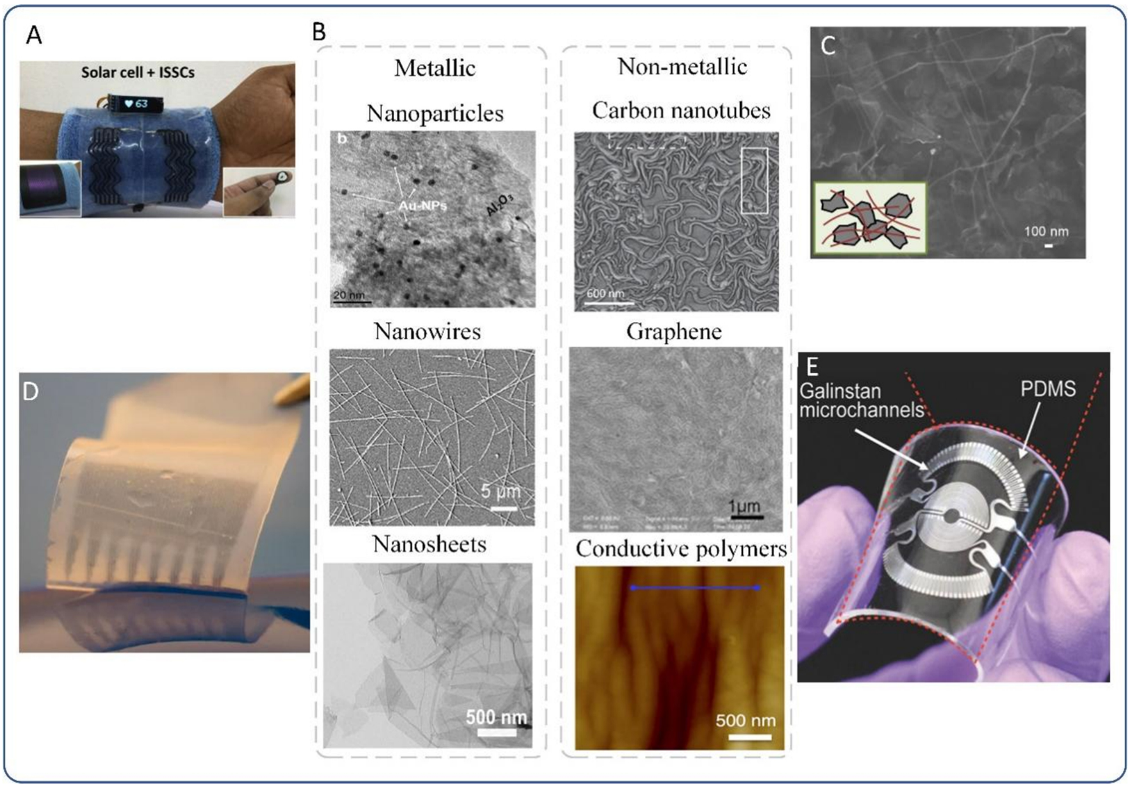

Figure 4. Overview of interconnect materials of pressure and temperature sensors towards e-skin. (A) All-printed, interdigitated, and freestanding serpentine interconnect-based flexible solid-state supercapacitors for self-powered wearable electronics. Reproduced with permission[45]. Copyright 2019, Elsevier B.V. (B) Metallic and non-metallic interconnect materials. Reproduced with permission[47-52]. Copyright 2020, Springer Nature[47]. Copyright 2020, John Wiley & Sons, Inc[48]. Copyright 2022, Springer Nature[49]. Copyright 2011, Springer Nature[50]. Copyright 2022, MDPI[51]. Copyright 2017, American Association for the Advancement of Science[52]. (C) Graphene/silver nanowire hybrid fillers on highly stretchable strain sensors based on spandex composites. Reproduced with permission[54]. Copyright 2020, MDPI. (D) Conductive hydrogel-based elastic microelectronics for localized low-voltage neuromodulation. Reproduced with permission[55]. Copyright 2019, Springer Nature. (E) Wearable microfluidic diaphragm pressure sensors for health and tactile touch monitoring. Reproduced with permission[56]. Copyright 2017, John Wiley & Sons, Inc.

from single signal detection on the rigid substrate to multi-sensing integration combined with flexible electronics, connected intelligence, and advanced algorithms to implement enhanced biocompatible and conformal advantages[1-3,57]. In contrast to conventional rigid and fragile sensing materials, soft electronics towards e-skin makes additional requirements for sensing materials, which include the highly physical and biochemical sensitivity and structural compatibility with the whole system.

Variations exist in the conductive properties of materials between interconnects and sensing elements, which means that rapid data transmission can be ensured owing to interconnects with high electrical conductivity, whereas it is not ideal for active sensing applications. In fact, sensing materials that are sensitive to aimed physical parameters, namely pressure and temperature, are needed. It is noteworthy that lots of carbon-based materials or CPs exhibit an excellent multi-sensing capacity. Hence, Table 1 briefly summarizes common active sensing materials based on different pressure and temperature mechanisms[58-64]. In brief, active materials sensitive to pressure and temperature cover metal or metal oxides (e.g., Ag/Au/Cu nanomaterials[14,15,17,20,22,25], $BaTiO_3$[23]), carbon nanomaterials (CNTs[11,12,14,25], graphene[18,65], reduced graphene oxide (rGO)[23]), CPs {e.g., Poly(3,4-ethylenedioxythiophene):poly(styrenesulfonate) (PEDOT: PSS)[13,14,17,19,22,25], poly(vinylidene difluoride and trifluoroethylene) [P(VDF-TrFE)][20]}, ionic liquid[66,67], and MXene[13]. Clearly, multiple active materials tend to be utilized for simultaneous pressure and

Table 1. A brief summary of active materials of pressure and temperature sensors towards e-skin

Mechanisms		**Material categories**		
		Metal- and metal-oxide-based	**Carbon- and polymer-based**	**Hybrids and others**
Static pressure sensing	Piezo-capacitive (Dielectric materials)	/	CNMs Graphene GO PDMS Ecoflex PMMA	Fbric Fluidic ionic liquids
	Piezoresistivity	Ag/Cu/Au NMs	CNMs Graphene GO rGO	MoS_2 MXene
Dynamic pressure sensing	Piezoelectricity	ZnO $BaTiO_3$ Mn particles	PVDF Graphene P (VDF-TrFE) PLLA	$PbTiO_3$ NWs/graphene heterostructures
	Triboelectricity	Al/Cu	FEP TPFE	Silk Paper
Temperature pressure sensing	Thermoeletricity	Ag NMs Bi_2Te_3	CNMs Graphene PETOD:PSS	IOTEs(e.g., Te NWs)
	Pyroelectricity	ZnO NMs $BaTiO_3$ PZT BFO	PVDF Graphene P(VDF-TrFE)	PVDF/CuO composite PVDF/graphene film
	Thermoresistivity	Pt Cu Ni	CNMs NIPAM Poly(ionic liquid)	MoS_2 $MoSe_2$

$BaTiO_3$: Barium titanate; BFO: bismuth ferrate; CNMs: carbon nanomaterials; FEP: fluorinated ethylene propylene; GO: graphene oxide; IOTEs: inorganic thermoelectric materials; NIPAM: n-isopropyl acrylamide; PEDOT:PSS: poly(3,4-ethylenedioxythiophene):poly(styrenesulfonate); PLLA: polylactic acid; PMMA: polymethyl methacrylate; PTFE: polytetrafluoroethylene; PVDF: polyvinylidene difluoride; P(VDF-TrFE): poly(vinylidene difluoride and trifluoroethylene); PZT: lead zirconate titanate piezoelectric ceramics; rGO: reduced graphene oxide.

temperature sensing. Nevertheless, we need to employ artificial means to identify coupled signals or minimize the troublesome crosstalk[3]. Data processing methods, such as machine learning, are applied for decoupling different kinds of sensing information[68]. Therefore, many explorations and much research of new active sensing materials have been continued to raise the compatibility with the increasingly advanced fabrication of pressure and temperature sensors.

BASIC SENSING MECHANISMS AND EVALUATION PARAMETERS FOR PRESSURE AND TEMPERATURE SENSORS

Before proposing a comprehensive scheme for integrated pressure and temperature sensors, it is extremely vital to understand multiple single pressure and temperature sensing mechanisms and evaluation methods in this section. This not only matches the active materials described above to the various sensing mechanisms but also provides a theoretical basis for the next step in the design of integrated pressure and temperature sensors. In general, wearable sensors transduce physical signals (pressure, strain, or temperature) into electrical signals (resistive, potential, and capacitive signals) and nonelectrical signals (mainly optical and magnetic signals), as presented in Figure 5. Thanks to sensitive and convenient detection, electrical output signals are broadly predominant, which can be increasingly reported in recent studies. Additionally, the change of resistance, capacitance, and voltages can be detected with the help of multiple instruments to achieve a wider range, higher resolution, and more rapid response. More importantly, the piezoelectric and triboelectric output can achieve self-powered elements for eco-friendly applications[2].

Basic sensing mechanisms and evaluation parameters for pressure and temperature sensing are discussed in this section. With regard to pressure sensing, we can classify mechanisms into two categories, respectively, for static and dynamic stimuli detections. In summary, piezoresistive and capacitive pressure sensors are

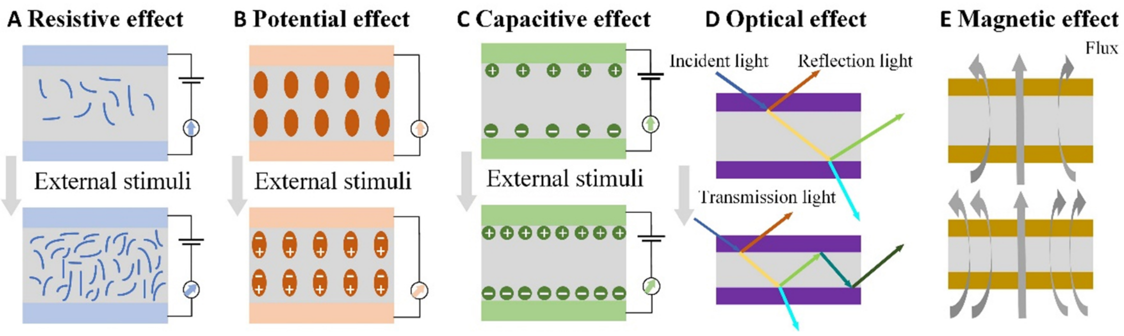

Figure 5. The schematic diagram for basic sensing mechanisms: (A) resistive effect. (B) potential effect. (C) capacitive effect. (D) optical effect. (E) magnetic effect.

able to detect the static pressure/strain change and transduce rapidly, which can be demonstrated potential in medical examination and physical exercise[69]. Compared to static pressure sensing, piezoelectric and triboelectric sensors are suitable for dynamic applications owing to their positive sensing mechanism. Mechanical strain signals can be changed into alternating current (AC) electrical signals, which can be analyzed for sensing data collection and self-powered applications[58-61]. As far as temperature sensing is concerned, thermoresistive, thermoelectric, pyroelectric, ferroelectric, and capacitive (for temperature-sensitive materials) effects are exploited to construct flexible temperature sensors[62-64]. Overall, we can classify the aforementioned sensing strategies into three general effects: resistive, potential, and capacitive effects, as shown in Figure 5A-C.

Meanwhile, optical and magnetic sensing systems are reported for sensing, which can be supplements of traditional electric output sensing, as implied in Figure 5D and E. Briefly speaking, physical stimuli can change the light path and critical parameters concluding reflection and transmission coefficient. In contrast to electric sensing, various optical sensing mechanisms have powerful advantages in medical diagnosis applications, which can be combined with wearable devices for physiological testing, such as blood oxygen and glucose[3]. In regard to magnetic sensing, Faraday’s law of electromagnetic induction is the most important theoretical cornerstone, namely, the change of magnetic flux affected by external stimuli generates the electrodynamic potential. Restricted by the complicated sensing mechanism, material combination, and measuring apparatuses, there exists a long way to incorporate optical and magnetic mechanisms into wearable applications.

Basic sensing mechanisms

Resistive mechanism

The resistive mechanism implies that exerting external stimuli changes the internal quantities and pathways of internal conductive fillers indirectly, so the whole resistance alters associated with the physical stimuli, as hinted in Figure 5A. It has become an outstanding sensing strategy, which is derived from intrinsic excellent features, including low energy consumption, simple structural design, and relatively easy readout[59,69].

For the piezoresistive effect, the initial resistance stems from the active layer without applied pressure/strain, which mostly stems from the tunneling of charged carriers between adjacent conductive fillers. After being applied force on the sensor, the micro/nano-scale distance of the conductive fillers changes with the force, thus resulting in the exponential change of the tunneling resistance, and additionally, conductive pathways have been increased. A complex physical process happens when external stimuli exist, which leads to the non-linear pressure-to-resistance response. In this situation, mathematical fit analysis is applicable, segmenting the sensing curve into lines and defining the sensitivity (S_P) of each linear region as Equation 1, where ΔR and R_0 represent the resistive change caused by applied force change δP and the initial resistance[69], respectively.

$$S_P = \frac{\delta(\Delta R / R_0)}{\delta P} \tag{1}$$

Similar to the piezoresistive effect, a thermoresistive effect can be ascribed to the resistive change of active materials. In addition, it is both polymer substrates and active materials that play a critical role in the electron mobility by the expansion of the volume[64]. The temperature coefficient of resistance (TCR) is set as Equation 2 to measure the ratio of the amount of change in resistance with temperature, where ΔR and R_0 represent the resistive change caused by temperature change δT and the initial resistance, respectively.

$$TCR = \frac{\delta(\Delta R / R_0)}{\delta T} \tag{2}$$

Potential mechanism

Depending on the special properties of functional materials, a potential mechanism is applied in temperature and pressure sensing, especially in positive sensing. In essence, materials that can be suitable for the potential mechanism are able to transduce external pressure and temperature signals into electrical signals as a result of internal non-uniform charge distribution. Herein, we reveal four common potential mechanisms, piezoelectric, triboelectric, thermoelectric, and pyroelectric effects, respectively, from their definitions to corresponding evaluation parameters.

Widely known to all, dynamic pressure detection has great potential in real-time physiological monitoring, such as pulse and heart rates. A piezoelectric effect, which generates electrical polarization and potential differences inside the functional materials, is ideal for dynamic pressure detection. Interestingly, electric output signals can also be a supply for the whole sensing system. According to the constitutive model of piezoelectric materials, the piezoelectric coefficient (d_{33}) can be demonstrated as Equation 3 in which V_{OC} and ΔP represent open-circuit voltage and applied force change, respectively, d is the thickness of the sensor, and ε_r and ε_d represent relative permittivity and vacuum permittivity, respectively.

$$d_{33} = \frac{\varepsilon_r \varepsilon_d}{d}\left(\frac{V_{OC}}{\Delta P}\right) \tag{3}$$

Another dynamic pressure detecting method is known as the triboelectric effect, where positive and negative charges separate on the surface of two kinds of materials to form contact electrification. Besides pressure sensing, triboelectric nanogenerators (TENGs) are broadly studied and fabricated. In fact, four fundamental modes of TENGs conclude vertical contact mode, lateral sliding mode, single electrode mode, and freestanding triboelectric layer mode[70].

Moreover, some materials, such as semiconductors and CPs, can generate output AC voltage owing to the internal electron motion with external temperature stimuli, which is not only a symbol of temperature change but a generator for the self-powered fabrication[62]. The thermal voltage (V_{thermo}) is proportional to the Seebeck coefficient (S_T) and the temperature difference (ΔT), which is given in Equation 4.

$$V_{thermo} = S_T \times \Delta T \tag{4}$$

Lastly, a pyroelectric effect is another kind of temperature measurement that is widely used in energy harvesters. Generally, pyroelectric materials have excellent piezoelectric performances, which can be applied in the construction of bimodal pressure and temperature sensors. The relationship between pyroelectric voltage and temperature change can be defined as Equation 5[63]. A good linear relationship is expressed in the pyroelectric effect because open-circuit output voltage (V_{OC}) is proportional to temperature difference (ΔT) owing to the constancy of relative permittivity (ε_r), vacuum permittivity (ε_0), the distance (d), and pyroelectric coefficient (p).

$$V_{OC} = \frac{pd}{\varepsilon_r \varepsilon_0} \Delta T \tag{5}$$

Capacitive mechanism

According to the definition of the capacitor shown in Equation 6, the resulting capacitor (C) depends on the internal parameter of the structure, such as the applied area (S) and distance (d) between two active layers[58]. Similar to the resistive mechanism, the capacitive response is a vital scheme for transferring and detecting physical signals.

$$C = \varepsilon_r \varepsilon_0 \frac{S}{d} \tag{6}$$

For capacitive pressure sensing, the capacitance of the sample will change due to the varying effective area and distance of two active layers with applied pressure. Conductive fillers and microstructure of active layers can be used to increase the sensitivity of the capacitive pressure sensor. The sensitivity of the capacitive sensor is defined in Equation 7[69].

$$S_p = \frac{\delta(\Delta C / C_0)}{\delta P} \tag{7}$$

In terms of temperature sensing, a capacitance variation has a relationship with temperature, which mainly originates from the change of the volume and internal structure of the sensitive materials. Besides, temperature change also has an impact on the transportation velocity of carriers, thus changing relative capacitance[3].

Evaluation parameters

Flexible pressure and temperature e-skin sensors are supposed to possess excellent performance, including compliance, robustness, and timeliness. Therefore, based on several kinds of combined mechanisms, quantitative comparison can be realized since the output signals containing data information can be read out in numerical form. The main quantitative parameters comprise sensitivity, range, response time, and stability[7].

The sensitivity parameters are the most essential for the characterization of entire sensing systems. Both resistive and capacitive sensors have similar forms and units (Pa^{-1}) for their sensitivity parameters, as shown in Equations (1), (2), and (7). However, the unit of sensitivity can be expressed in V/Pa or V/℃ for sensors based on potential mechanisms due to a linear relationship between input stimuli and output response, as shown in Equations (3), (4), and (5)[62,69]. Most sensing systems exhibit non-linear stimuli-response changes. Hence, non-linear sensing curves are often segmented to calculate sensitivities for different scopes of stimuli. With the pressure or temperature increasing, sensitivity parameters decrease for most systems.

The sensing range defines the maximum and minimum ranges that a sensor system can measure under normal conditions. Maximum and minimum sensing data originate from sensors in a limited state, so their accuracy is doubtful. For e-skin sensors with pressure and temperature sensing, the focus is primarily on tactile sensation and body temperature, such as pulse, respiration, gesture, and motion. From this point of view, the sensitivity is more significant than the sensing range, as e-skin sensors have a relatively narrow desired sensing range.

The response time is also a vital evaluation parameter, which implies how rapidly the output of the sensor changes with the varying external stimuli. It can be calculated by measuring the time difference between the input time of stimuli and the stable (or 90% position) time of output response[7]. Stability, symbolizing the robustness of the sensing system, can be measured by the shifting of output response after thousands of cycles of external stimuli. The more cycles the sensors bear, the less irreversible deformation occurs, resulting in better robustness.

MULTIPLE MECHANISM INTEGRATION AND STRUCTURAL DESIGN OF PRESSURE AND TEMPERATURE SENSORS

In a brief review, we have listed details about material selection and basic mechanisms for signal detection of pressure and temperature. However, systematic design and construction are undoubtedly important, as it integrates multiple materials, mechanisms, and structures to achieve composite sensing functions, and even manufacturing methods are briefly considered. In regard to pressure and temperature sensing, two strategies are adopted so as to design highly-integrated pressure and temperature sensors, respectively, new structures with traditional materials and new materials with traditional structures. Actually, common structures used in sensing systems include multilayer films[23,24,27,71,72], porous structures[11,15], multipixel[73], 3D structures[11], nanofibers[74], pyramid (pyramid-like) microstructures[14,23,75], and serpentine configurations[45,76]. Herein, we start with the integration of sensing mechanisms dividing flexible pressure and temperature sensors into two categories, namely, the same and different output signals[3]. Because of extensive applications of electric outputs and decoupling-free, sensing systems with different electric output signals (DEOS) are mainly concerned and presented in detail, while sensing systems with the same electric output signals (SEOS) are introduced briefly. Typically, some pressure and temperature (or more physical and biochemical sensing functions) sensor devices based on the DEOS system and the SEOS system are compared in Table 2.

Table 2. Summary of typical flexible e-skin sensors and comparison of their sensing performance

Authors	Mechanism	Stimuli	Sensitivity	Main materials	Structure	Fabrication
Wang *et al.*[11]	PR-TE	P-T	P: 0.0918 /kPa T: 17.1 μV/K	PANI, CNT, PDMS	3D porous structure	Freeze-drying
Li *et al.*[13]	PR-TE	S-T	S: 220.8 (0-5%), 1933.3 (53%-62%) T: 0.2 ℃ (resolution)	MXene, AgNW, PEDOT:PSS, TeNW	"Brick and mortar" structure	Screen printing
Jung *et al.*[14]	PR-TE	P-T	-	PEDOT: PSS, AgNP, MWCNT, PDMS	Micro-pyramid structure	Paper-based inkjet printing
Zhang *et al.*[15]	PR-TE	P-T	P: 28.9 /kPa T: < 0.1 K (resolution)	PEDOT:PSS, PU	Porous structure	Chemical vapor deposition
Rao *et al.*[23]	TrE-TR	P-T	P: 5.07 mV/Pa T: 0.015 /℃	BiTO NP, rGO, PDMS	Micro-pyramid structure and multilayers	Coating
You *et al.*[24]	PC-TR	S-T	-	EMIMTFSI, AgNW, SEBS	Multilayers	Spin-coating
Zhang *et al.*[27]	PR-TE	S-P-T	P: - T: 0.025 /℃	SWCNT, ZnO, PVDF	Barrel multilayer structure	Electrostatic spinning
Shin *et al.*[71]	PE-TR	P-T	P: - T: 0.0052 /℃	Li, ZnO, PDMS, AgNW, PEDOT: PSS	Multilayers	Spray-coating, spin-coating
Gao *et al.*[72]	PC-TR	P-T	P: 0.75 /kPa (below 2 kPa) 0.0549 /kPa (above 2 kPa) T: 0.00284 /℃	PU, MWCNT, XNB	Multilayers	Lamination process
An *et al.*[73]	PC-TR	P-T	P: 0.00178 /kPa (below 350 kPa) 0.0000965 /kPa (above 350 kPa) T: -	AgNF-AgNW, PEDOT: PSS, IGZO	Multipixel	Electrospinning and electrospraying
Kim *et al.*[77]	PC-TR	S-P-T	P: 0.86 /kPa T: -	MWCNT, PDMS	Foam	Self-assembling
Wang *et al.*[74]	PR-TR	P-T	P: 1185.8 /kPa T: -	PDMS, AgNP, PEDOT:PSS	Nanofibers	Electrospinning and coating
Kim *et al.*[75]	PR-TR	P-T	P: 2 /kPa T: 0.0032 /℃	PEDOT:PSS, PUD, AgNW	Micro-pyramid structure	Inkjet printing
Song *et al.*[78]	PE-PyE	P-T	P: 0.044 V/kPa T: 0.048 V/℃	$BaTiO_3$, Ag, PDMS	Sandwich layer	Coating
Lei *et al.*[79]	Capacitive	P-T	P: 0.45 /kPa T: -	PDMA/NaCl/SDS hydrogels	Sandwich layer	3D printing
Cao *et al.*[80]	Frequency	S-T	S: 0.699 T: 58.4 Hz/K	Graphene, SiO_2, Silicon rubber	Patterned films	Redox process

PR-TE: piezoresistive and thermoelectric; TrE-TR: triboelectric and thermoresistive; PE-TR: piezoelectric and thermoresistive; PC-TR: piezo-capacitive and thermoresistive; PR-TR: piezoresistive and thermoresistive; PE-PyE: piezoelectric and pyroelectric; P: pressure; T: temperature; S: strain.

Different olectric output signals

In essence, the different electric output signals (DEOS) system can realize simultaneous pressure and temperature sensing on account of distinguishable output, which intrinsically determines two charming strengths. One is to avoid the design of complex back-end decoupling circuits to separate pressure and temperature signals. The other is to dramatically reduce crosstalk between pressure and temperature signals at the device level. Mostly, three combinations, including piezoresistive and thermoelectric sensors, piezoelectric/triboelectric and thermoresistive sensors, and piezo-capacitive and thermoresistive sensors, are discussed. Furthermore, we list recent studies on the above three mechanism combinations and summarize them in respect of structural design.

Piezoresistive and thermoelectric sensors

The pressure and temperature sensors based on piezoresistive and thermoelectric effects are a common type of DEOS systems, whose active sensing materials are typically blended by the thermoelectric and other conductive materials. For instance, Li *et al.* demonstrated a stretchable bimodal sensor for strain (up to 60%) and temperature monitoring based on piezoresistive and thermoelectric effects with printable polyurethane (PU) nanocomposites comprising MXene/AgNWs/PEDOT: PSS/tellurium NWs (TeNW)[13], as illustrated in Figure 6A. Jung *et al.* designed a multilayer structure consisting of two active layers with different mechanisms[14], namely, the flexible conductive paper substrate printed with PEDOT:PSS and AgNPs were used as a temperature-sensitive layer, while the micro-pyramid PDMS film deposited with MWCNTs was performed as a pressure-sensitive layer, as illustrated in Figure 6B. Zhang *et al.* reported a PEDOT: PSS-coated PU composite that can detect pressure and temperature instantaneously by constructing porous microstructures and utilizing thermoelectric properties of PEDOT:PSS and polyaniline (PANI) separately[15], as shown in Figure 6C.

Piezoelectric/Triboelectric and thermoresistive sensors

The second method to realize pressure and temperature sensing is to combine piezoelectric/triboelectric effects with thermoresistive effects. By this means, output signals exist with no coupling, and piezoelectric/triboelectric signals provide the sensing system with AC supplies. For instance, Zhang *et al.* reported a strong and flexible vessel-like sensor that consists of a self-supported braided cotton hose substrate[27], single wall carbon nanotubes (SWCNTs)/ZnO PVDF function arrays, and a flexible PVDF function fibrous membrane. The whole system possesses the function of detecting the pressure and temperature of pulsed fluids, as illustrated in Figure 7A. Shin *et al.* reported a simple method to realize a multifunctional flexible motion sensor using ferroelectric lithium-doped ZnO-PDMS[71], which enables piezoelectric dynamic sensing and provides additional motion information to more precisely discriminate different motions, as shown in Figure 7B. Rao *et al.* designed a tactile e-skin that can simultaneously detect and distinguish between temperature and pressure in real time[23], based on a single-electrode-mode TENG with a specially prepared thermoresistive electrode combining BiTO and rGO, as shown in Figure 7C.

Piezo-capacitive and thermoresistive sensors

The third scheme to realize pressure and temperature sensing is combining piezo-capacitive and thermoresistive effects to implement varying output capacitance and resistance representing pressure and temperature, respectively. Due to a capacitive detecting mechanism, a common practice is to use a multilayer structural design, which normally comprises two electrode layers and one dielectric layer with specific micro-patterns. For example, You *et al.* presented a deformable artificial multimodal ionic receptor that can differentiate thermal and mechanical information without signal interference[24], which is derived from the analysis of the ion relaxation dynamics: the charge relaxation time as a strain-insensitive intrinsic variable to measure absolute temperature and the normalized capacitance as a temperature-insensitive extrinsic variable to measure strain, as illustrated in Figure 8A. Gao *et al.* reported a bifunctional self-healing e-skin with PU and CNTs as the sensing materials by integrating a resistance temperature sensor on top of a capacitive pressure sensor on the same flexible cellulose substrate[72], as shown in Figure 8B. An *et al.* developed a transparent and flexible[73], capacitive fingerprint sensor array with multiplexed, simultaneous detection of tactile pressure and finger skin temperature for mobile smart devices, whose networks of hybrid nanostructures using ultra-long metal nanofibers and finer NWs were formed as transparent, flexible electrodes of a multifunctional sensor array, as illustrated in Figure 8C. Kim *et al.* introduced a versatile droplet-based microfluidic-assisted emulsion self-assembly process to generate three-dimensional microstructure-based high-performance capacitive and piezoresistive strain/pressure/temperature sensors for e-skin applications[77], as illustrated in Figure 8D.

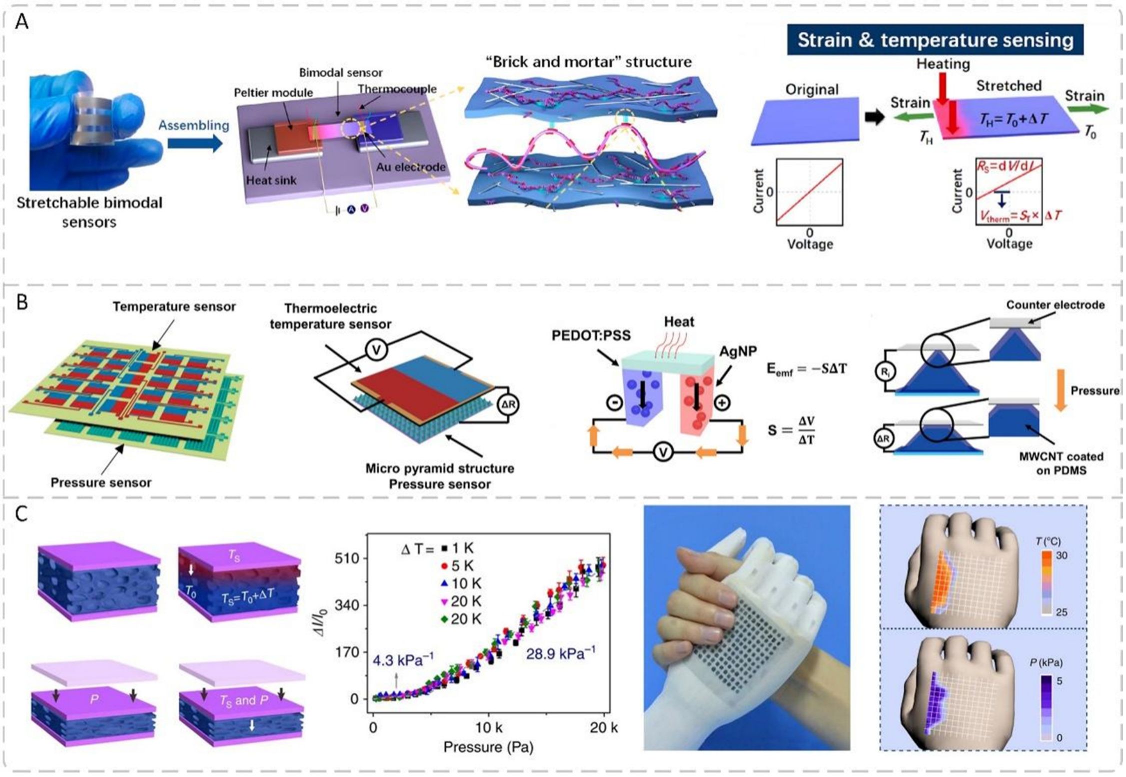

Figure 6. Typical piezoresistive and thermoelectric sensors. (A) Printable and stretchable temperature-strain dual-sensing nanocomposite with high sensitivity and perfect stimulus discriminability. Reproduced with permission[13]. Copyright 2020, American Chemical Society. (B) Paper-based bimodal sensor for electronic skin applications. Reproduced with permission[14]. Copyright 2017, American Chemical Society. (C) Flexible and self-powered temperature-pressure dual-parameter sensors using microstructure-frame-supported organic thermoelectric materials. Reproduced with permission[15]. Copyright 2015, Springer Nature.

Same electric output signals

As previously stated, a DEOS system avoids the crosstalk and decoupling process between pressure and temperature signals. However, it is inevitable for the same electric output signals (SEOS) system to generate interference as a result of two same integrated mechanisms, which need signal decoupling and delicate circuit design. Interestingly, electric signal exhibits positive and negative gradient in response to the same trend of pressure and temperature stimuli. Given that, resistive-based pressure and temperature sensors are widely studied and fabricated due to easy readout and relatively intuitive distinguishability. Besides, conjuncted pyro-piezoelectric[78], capacitive[79], and frequency response-based[80] sensors are introduced briefly in this section.

For simultaneous pressure and temperature detection, a resistive mechanism can be utilized. For instance, Wang *et al.* developed a flexible and multifunctional resistive sensor integrating uniform conductive coating PEDOT: PSS and AgNP layers with an interlaced nanofibrous structure through a large-scale and cost-efficient strategy[74]. Due to structural design, the multilevel sensing paths comprising both interlaminar and intrastratal signal transmissions fulfill the simultaneous and precise detection of pressure-temperature stimuli without interference, as seen in Figure 9A. Kim *et al.* made a micro-pyramid patterned PEDOT: PSS/AgNPs/PU film along with dogbone-shaped PEDOT: PSS/AgNPs/PI film by inkjet printing to implement pressure and temperature distinguishable detecting[75], which could show the opposite resistance change with different temperature trends, as illustrated in Figure 9B.

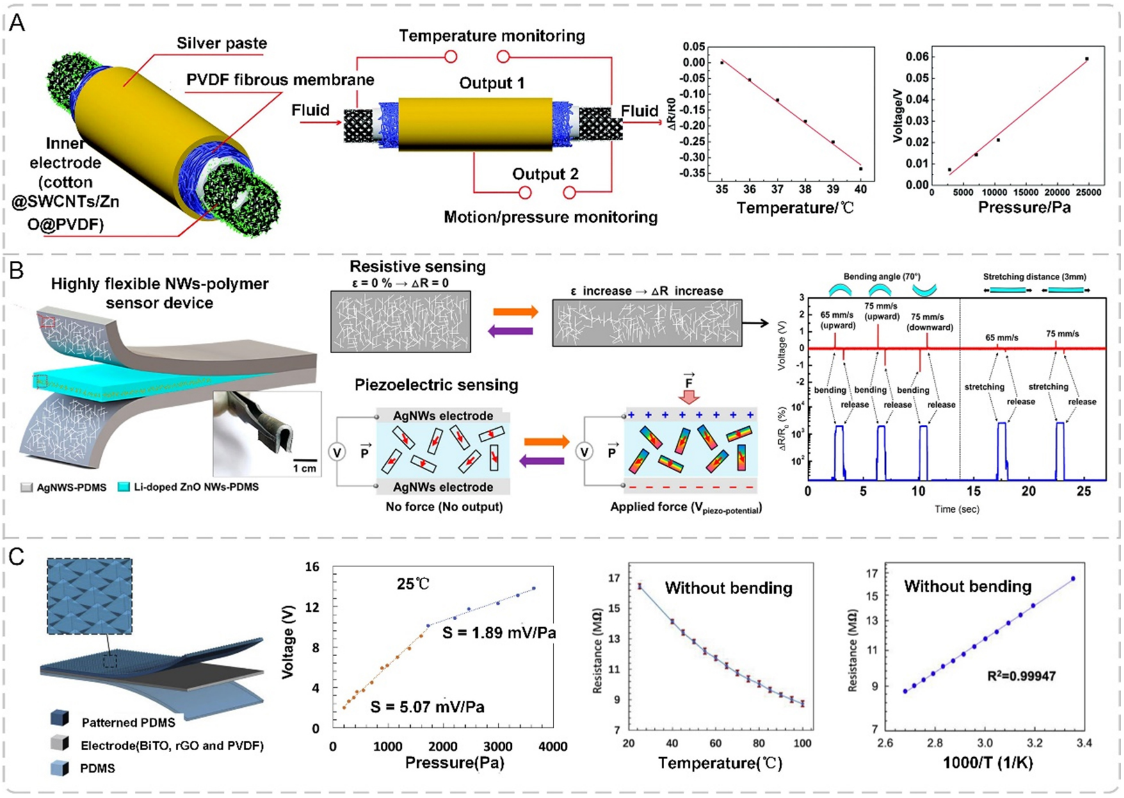

Figure 7. Typical piezoelectric/triboelectric and thermoresistive sensors. (A) A strong and flexible electronic vessel for real-time monitoring of temperature, motions, and flow. Reproduced with permission[27]. Copyright 2017, Royal Society of Chemistry. (B) Ferroelectric zinc oxide nanowire embedded flexible sensor for motion and temperature sensing. Reproduced with permission[71]. Copyright 2017, American Chemical Society. (C) Tactile electronic skin to simultaneously detect and distinguish between temperature and pressure based on a triboelectric nanogenerator. Reproduced with permission[23]. Copyright 2020, Elsevier B.V.

Besides a resistive mechanism, other mechanisms can also be used to construct pressure and temperature sensors with SEOS systems. First of all, piezoelectricity and thermo/pyroelectricity are special mechanisms for monitoring pressure and temperature. For instance, Song *et al.* demonstrated a ferroelectric BaTiO$_3$-based pyro-piezoelectric sensor system to detect temperature and pressure simultaneously[78], in which no interference appears in the output voltage signals, as shown in Figure 9C. Moreover, capacitance response sensing is mentioned in Figure 9D. Lei *et al.* designed a multifunctional and mechanically compliant skin-like sensor by utilizing 3D-printed thermo-responsive hydrogel[79]. This capacitive-based pressure and temperature sensor shows a stable and sensitive response allowing wide applications in tactile sensing. Additionally, an innovative flexible multifunctional microsensor is proposed by Cao *et al.*[80], which could tactfully transform the urgent threat of electromagnetic radiation into integrating self-powered functions thanks to the deep insight into the variable-temperature electromagnetic response, as illustrated in Figure 9E.

MANUFACTURING METHODS FOR PRESSURE AND TEMPERATURE SENSORS

Having discussed three perspectives of pressure and temperature sensor design, namely material selection, mechanism integration, and structural design, manufacturing methods are comprehensively outlined in this section, which means that the theoretical analysis and design are completed while the design scheme is summarized and demonstrated by the manufacturing methods. Over decades, plenty of manufacturing methods have been adopted, combined, and developed to fabricate high-performance flexible pressure and

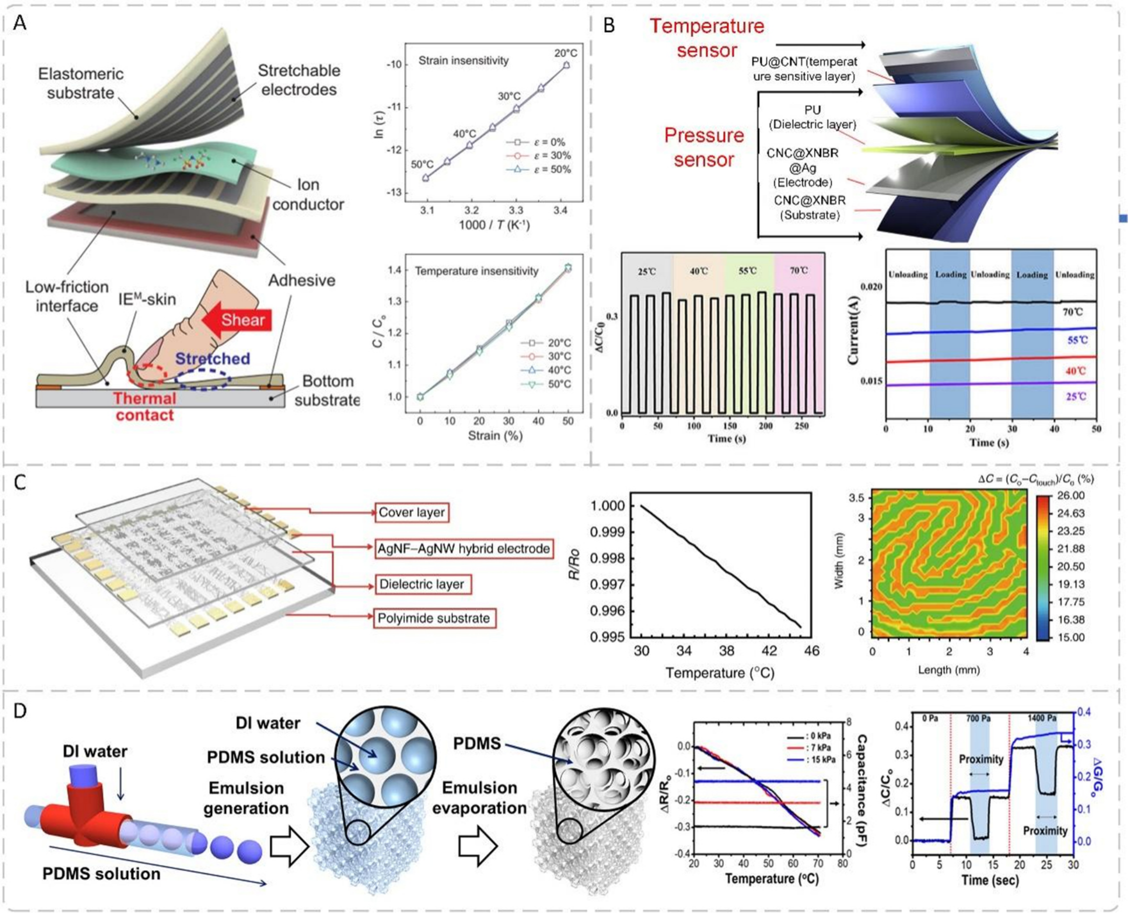

Figure 8. Typical piezo-capacitive and thermoresistive sensors. (A) Artificial multimodal receptors based on ion relaxation dynamics. Reproduced with permission[24]. Copyright 2020, American Association for the Advancement of Science. (B) A self-healable bifunctional electronic skin. Reproduced with permission[72]. Copyright 2020, American Chemical Society. (C) Transparent and flexible fingerprint sensor array with multiplexed detection of tactile pressure and skin temperature. Reproduced with permission[73]. Copyright 2018, Springer Nature. (D) Highly ordered 3D microstructure-based electronic skin capable of differentiating pressure, temperature, and proximity. Reproduced with permission[77]. Copyright 2018, American Chemical Society.

temperature sensors. In summary, manufacturing methods cover coating (spray-coating, spin-coating), photolithography, etching, self-assembly, doctor-blading, electrospinning, chemical vapor deposition, additive manufacturing, and printing (screen printing, inkjet printing, gravure printing, flexography printing)[3,81-83]. Among all the manufacturing methods, the printing process, including contact and non-contact printing, is widely favored, by which inorganic nanomaterials can be deposited onto any material substrate by solution. It is not limited by the nature of the substrate and surface morphology, as shown in Figure 10. In this section, we mainly generalize printing methods for flexible pressure and temperature sensors, which contain contact printing (gravure printing, gravure-offset printing, flexography printing) and non-contact printing (screen printing, inkjet printing, slot-die coating)[82,83].

Gravure printing is capable of transferring functional inks by forming physical contact of the engraved structures with the soft substrate, which provides a high print resolution. This printing method is suited for fabrication that needs relatively high resolution, such as organic flexible light Emitting Diodes (LEDs) and photovoltaic devices[84]. In regard to gravure-offset printing, it is an enhanced version of gravure printing, in which an elastic blanket is added to prevent damage from direct contact with the substrate[83,89]. Unlike the

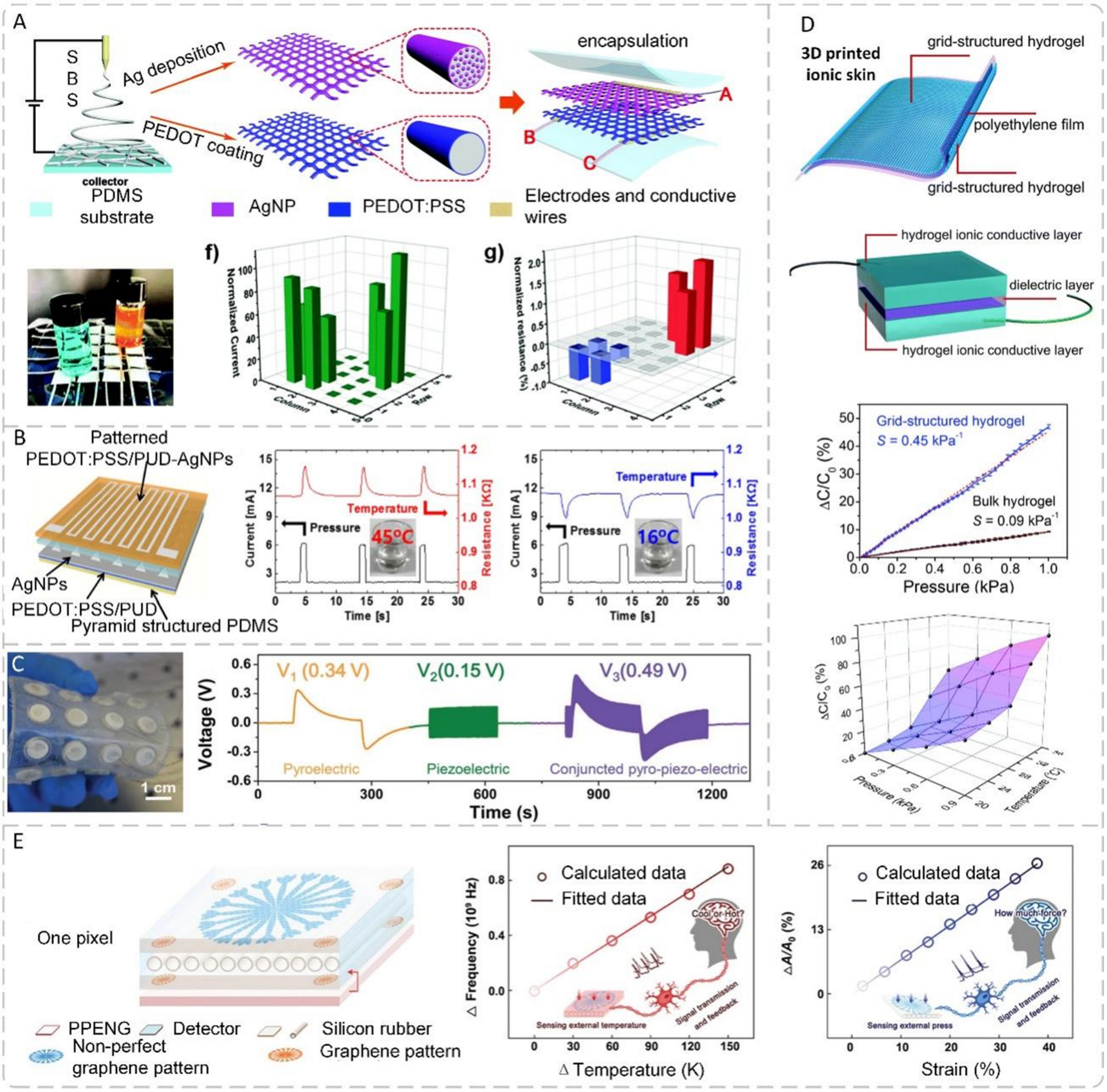

Figure 9. Typical pressure and temperature sensors based on the SEOS mechanism. (A) A flexible bimodal sensor based on an electrospun nanofibrous structure for simultaneous pressure–temperature detection. Reproduced with permission[74]. Copyright 2019, Royal Society of Chemistry. (B) Low-voltage, high-sensitivity, and high-reliability bimodal sensor array with fully inkjet-printed flexible conducting electrode for low power consumption electronic skin. Reproduced with permission[75]. Copyright 2017, Elsevier B.V. (C) Conjuncted pyro-piezoelectric effect for self-powered simultaneous temperature and pressure sensing. Reproduced with permission[78]. Copyright 2019, John Wiley & Sons, Inc. (D) A multifunctional skin-like sensor based on a 3D printed thermo-responsive hydrogel. Reproduced with permission[79]. Copyright 2017, Royal Society of Chemistry. (E) Variable-temperature electron transport and dipole polarization turning flexible multifunctional microsensors beyond electrical and optical energy. Reproduced with permission[80]. Copyright 2020, John Wiley & Sons, Inc.

gravure printing method, the flexible substrate of flexographic printing is often made of rubber or a photopolymer. In addition, the roll-to-roll mode is widely used in flexographic printing due to its ease and speed of fabrication[82,85].

In terms of non-contact printing, screen printing is the most preferred and adopted printing method, in which the mesh and squeegee are the essential components. The working process can be described as follows: the ink is squeezed out from the squeegee through the open mesh, and it finally forms the desired

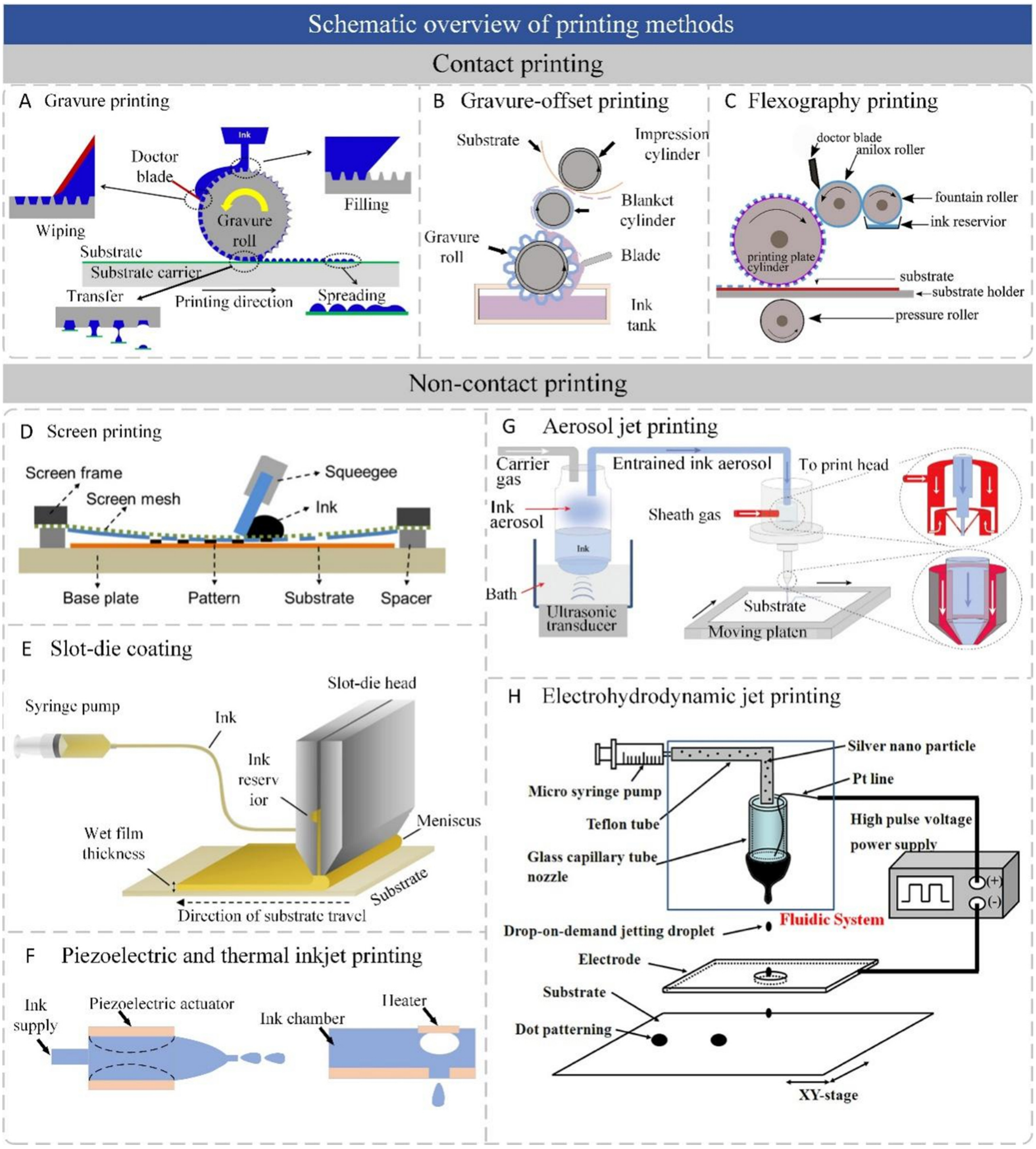

Figure 10. A brief summary of contact and non-contact printing methods. (A) Gravure printing. Reproduced with permission[84]. Copyright 2016, IOP publishing. (B) Gravure-offset printing. (C) Flexography printing. Reproduced with permission[85]. Copyright 2020, Elsevier B.V. (D) Screen printing. Reproduced with permission[86]. Copyright 2019, American Chemical Society. (E) Slot-die coating. Reproduced with permission[87]. Copyright 2020, Elsevier B.V. (F) Piezoelectric (left) and thermal (right) inkjet printing. (G) Aerosol jet printing. Reproduced with permission[29]. Copyright 2020, Springer Nature. (H) Electrohydrodynamic jet printing. Reproduced with permission[88]. Copyright 2008, AIP publishing.

patterns. The major problem of screen printing is low printing speed that restricts applications in mass production[82,86]. It is worth mentioning that slot die coating is a direct way of roll-to-roll printing, where ink solution is coated on the substrate through a uniform flow of solution and adjustment of distance and speed between the slot die and moving substrate[83,87]. Another popular non-contact printing is inkjet printing, which can be divided into continuous printing and on-demand printing, as shown in Figure 11. When continuous inkjet printing, the nozzles continuously inject ink into the substrate, after which only the

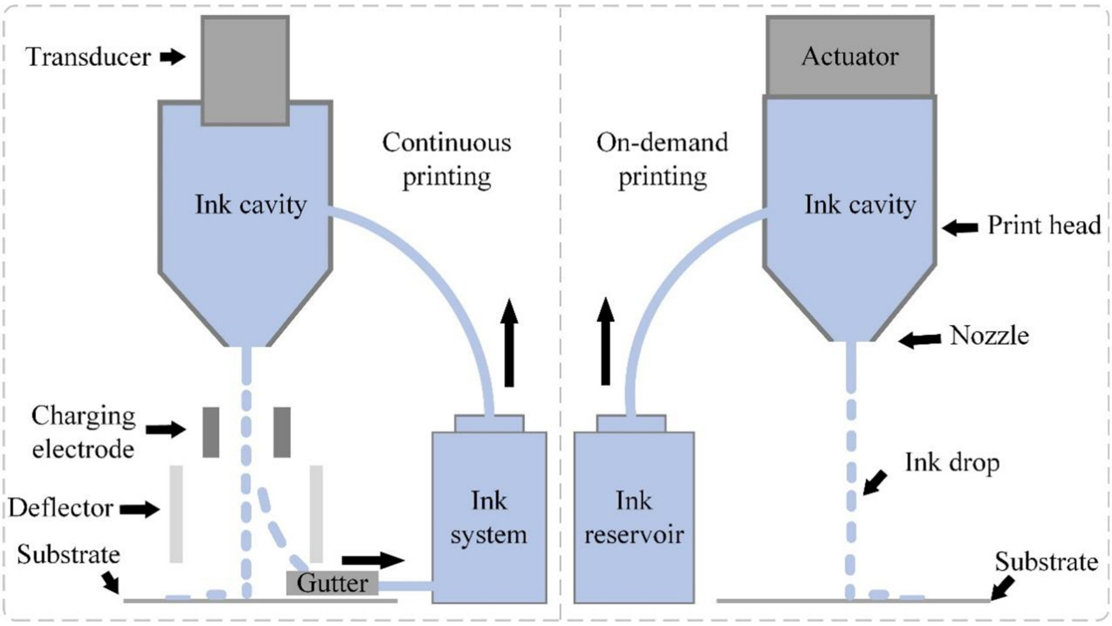

Figure 11. A comparison between continuous and on-demand inkjet printing.

desired droplets are deposited onto the substrate to form a pattern, and the excess ink is recycled. Due to the complexity of the installation, continuous inkjet printing is gradually being phased out while on-demand printing is flourishing. On-demand printing technology is used more widely because the nozzles are only inked where they are needed by controlling electrical signals, so there is no need to install a recovery device, and the equipment is simple and efficient[90]. Today, there are several mainstream on-demand printing technologies for multifunctional sensor fabrication, which can be classified into piezoelectric inkjet printing, thermal inkjet printing, aerosol jet printing (AJP), and electrohydrodynamic jet printing (EHD)[29,88,90].

Admittedly, multiple advanced printing methods have demonstrated potential in flexible sensor fabrication. In contrast to other methods, printing methods are capable of realizing high resolution and complex desired patterns of sensors. As mentioned above, flexible e-skin sensors require complex geometries to be designed, especially for conductive interconnects, but traditional methods are difficult to provide desired high-precision fabrication, such as serpentine design. Printing methods improve the feasibility of complex patterned processing on flexible substrates, which means revolutionary advances for flexible electronics. Besides the benefits on complex fabrication, printing methods can also exclude cumbersome processing[83-90]. For instance, a typical additive manufacturing method, inkjet printing, only deposits ink materials directly and precisely on the substrate to form complicated structures without the necessary steps, including film deposition, photolithography, and etching. In a nutshell, a number of printing methods offer the possibility of cost-effective production of large-area flexible sensors. Herein, a brief summary about printed sensors towards e-skin is shown in Figure 12. Figure 12A shows a fully printed flexible sensor using a screen printing method with the trifunctional bottom electrode layer for pressure, temperature, and proximity sensing[91]. A flexible multifunctional sensor is illustrated in Figure 12B, which allows for stretching on human skin to monitor for temperature, acceleration, and electrocardiograms (ECG). It is worth mentioning that a kirigami structure is designed and fabricated elaborately by the printing method[92]. Figure 12C shows a fully printed high-sensitivity multifunctional electronic whisker (E-whisker) integrated with strain and temperature sensors using the inkjet printing method. It can be demonstrated in macroscale electrical applications[93].

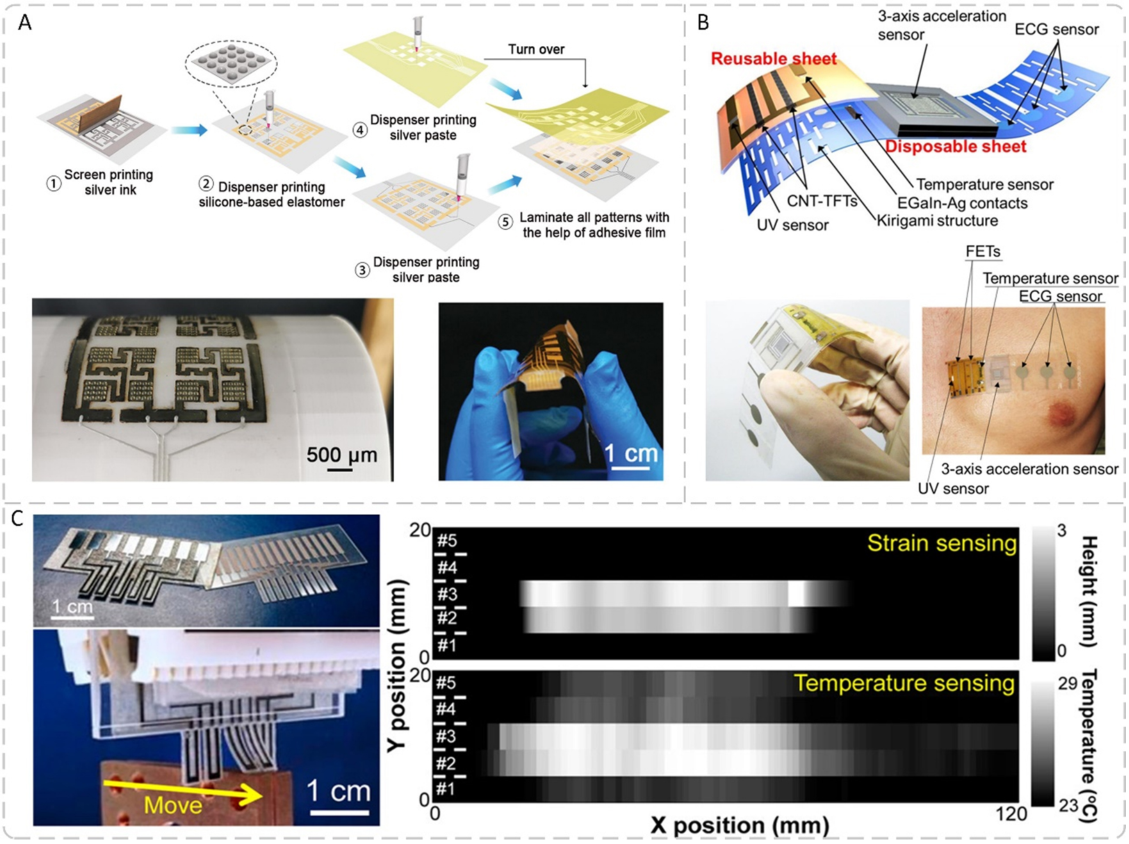

Figure 12. Typical printed sensors towards e-skin. (A) A fully printed flexible sensor sheet for simultaneous proximity-pressure-temperature detection. Reproduced with permission[91]. Copyright 2021, John Wiley & Sons, Inc. (B) Printed multifunctional flexible device with an integrated motion sensor for health care monitoring. Reproduced with permission[92]. Copyright 2016, American Association for the Advancement of Science. (C) Fully printed, highly sensitive multifunctional artificial electronic whisker arrays integrated with strain and temperature sensors. Reproduced with permission[93]. Copyright 2014, American Chemical Society.

SUMMARY AND FUTURE PROSPECTS

In this review, we have summarized the recent advances of flexible pressure and temperature sensors towards e-skin from four perspectives containing material selection, mechanism integration, structural design, and manufacturing methods. In particular, it is fundamental to clarify the relationship between them. Excellent materials can ensure the stability and effectiveness of mechanism integration since advanced material technology provides an important theoretical basis, especially sizzling carbon-based material technology. Various mechanism-integrated approaches offer innovative insights for the structural design of sensing systems in which crosstalk from different types of signals should be avoided by delicate means. Choosing the fitting manufacturing methods is vital for the whole design, which is reflected in the tradeoff between manufacturing accuracy and cost. In short, the flexible large-area arrays integrated with pressure and temperature detection towards e-skin will undoubtedly be potential in various applications, including soft bionic robots[94 -96], virtual reality[97], human-machine interface[97], wearable electronics[98,99], and intelligent medical treatment[100].

Meanwhile, the flexible sensing system is confronted with progress and challenges from the advanced material combination, innovative mechanism integration, novel structure design, and high-level manufacturing methods. New functional materials play a pivotal role in the design of flexible pressure and temperature sensors. Given the application of sensors in the field of e-skin, materials need to have basic properties, such as non-toxic, antibacterial, highly flexible, and highly biocompatible, and additional properties, such as hydrophobicity and breathability, in order to fit the human skin to a high degree during long wear. In addition, green materials for use in electronic devices are highly sought after, and their biodegradable properties meet the requirements for sustainability. With regard to the integration of multiple sensing, the traditional combination of capacitive, resistive, and potential detection is still the mainstream design approach for flexible pressure and temperature sensors, but nonelectrical signals, such as optical, electromagnetic, frequency-based, and biochemical detection, also provide new ideas for the integration of multiple mechanisms, which are highly relevant to the application scenario. Interestingly, natural flora and fauna can also provide valuable design guidance for sensing mechanisms and structures. Structural design is the most direct aspect of sensor uniqueness. Flexible pressure and temperature e-skin sensors are used in a wide range of applications, including, but not limited to, underwater operations, medical treatment, emergency rescue, and many more, so the exploration of structural diversity is essential. Several interesting bionic structures have now been proposed and applied to sensor design. Finally, high-level manufacturing methods can empower flexible sensors. Large-scale, highly processable, and cost-effective manufacturing methods can produce highly flexible, thin, and light e-skin sensors that are highly compatible with the desired structure, but the greatest challenges exist in the stable mechanical and electrical connections along with device packaging under the complex heterogeneous integration, which is essential for the stability and durability of sensors[101].

Facing huge opportunities, flexible pressure and temperature sensors towards e-skin are greatly desired to overcome several bottlenecks containing crosstalk between two responsive signals, integrated transistor circuit implementation, and self-powered supply requirements. Firstly, crosstalk between temperature and pressure apparently has an impact on the overall performance, especially temperature changes that influence the properties of active materials with unavoidable disturbances to the pressure output. Two different methods, namely sensing mechanism and output data processing, have been discussed to solve this problem. The DEOS system-based two types of mechanisms can effectively alleviate signal crosstalk, and machine learning algorithms are also researched for distinctions from one mixed output electric signal[3]. Secondly, flexible sensors integrated transistor circuits show promising research space as a vital element of sensors in interdisciplinary fields. With the integrated readout circuit, pressure and temperature sensing data can be monitored in a real-time fashion. In addition, communication with the upper computer is so necessary in many situations that a wireless transceiver module is integrated into the circuit. However, several problems, including the extra signal noise and flexible circuit fabrication, need to be taken seriously during the design and manufacturing process of circuits[96,100]. Thirdly, the issue of energy supply for sensing systems is essential, which drives more and more researchers to pursue kinds of clean energy for sensing systems. Interestingly, hybrid nanogenerators provide a solution for flexible pressure and temperature sensing arrays. Based on similar mechanisms with sensing, it is relatively achievable to integrate nano-scale energy harvesters with sensing systems, which embody tremendous latent capacity in wearable electronics[98]. Additionally, the low-power performance of the sensing element is also worthy of attention as a method of alleviating design sophistication on energy supply issues. Currently, e-skin with intelligent sensing capabilities is being explored. High-precision sensor arrays are only at the forefront of the vast e-skin system, and to truly realize the sensory capabilities of human skin requires the integration and penetration of multiple disciplines, such as the integration of high-speed data collectors and machine learning to assist in sensing contact surface material properties to process complex information, highlighting the wide range of applications for flexible e-skins in the fields of flexible prosthetics[102], haptic perception[103], and text recognition[104]. Therefore, challenges co-exist with opportunities in the design of flexible pressure and temperature sensors towards e-skin. Besides pressure and temperature, other tactile parameters containing proximity, humidity, sound, magnetic field, and some biochemical signals are expected to be detected in a highly integrated multifunctional flexible sensing system equipped with a self-powered supply and data transmission circuit.

All in all, scientific research on flexible pressure and temperature sensors, the basic element of multifunctional sensors towards e-skin, is a subject worthy of in-depth discussion and study, in which multiple engineering applications in wearable electronics, intelligent medical treatment, and virtual and augmented reality can propel the development of technology to help humanity more effectively.

DECLARATIONS

Authors' contributions

Conceptualization, investigation, writing original draft: Tian S
Investigation, writing review, editing: Wang Y (Yilin Wang), Deng H
Writing, review, editing: Wang Y (Yan Wang)
Conceptualization, supervision, project administration, writing, review, editing: Zhang X

Availability of data and materials

Not applicable.

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Conflicts of interest

All authors declared that there are no conflicts of interest.

Ethical approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

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