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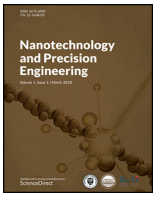

State-of-the-art and recent developments in micro/nanoscale pressure sensors for smart wearable devices and health monitoring systems

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ABSTRACT

Small-sized, low-cost, and high-sensitivity sensors are required for pressure-sensing applications because of their critical role in consumer electronics, automotive applications, and industrial environments. Thus, micro/nanoscale pressure sensors based on micro/nanofabrication and micro/nanoelectromechanical system technologies have emerged as a promising class of pressure sensors on account of their remarkable miniaturization and performance. These sensors have recently been developed to feature multifunctionality and applicability to novel scenarios, such as smart wearable devices and health monitoring systems. In this review, we summarize the major sensing principles used in micro/nanoscale pressure sensors and discuss recent progress in the development of four major categories of these sensors, namely, novel material-based, flexible, implantable, and self-powered pressure sensors.

1. Introduction

A pressure sensor is a transducer that converts an external pressure stimulus into an electrical or other identifiable output signal according to certain rules.[1] Over the last several decades, the role of pressure sensing in daily life has escalated, leading to the rapid growth of its market size. According to a recent study, the global market for pressure sensors is expected to increase to $15.97 billion by the year 2028 from $8.8 billion in 2018. The major pressure-sensor suppliers in the global market include Bosch, Denso, Sensata, and Amphenol.

Conventional pressure-sensing devices are mainly based on macroscale diaphragm configurations, the deformation of which indicates the applied pressure. Such sensors provide the advantages of high stability and large dynamic range, but their bulky size limits their further application. Given rapid developments in micro/nanofabrication and micro/nanoelectromechanical system (M/NEMS) technologies, micro/nanoscale pressure sensors based on various measurement principles, *e.g.*, piezoresistive, capacitive, piezoelectric, and resonant transduction,[2–6] have received increased research attention. CMOS compatibility and wafer-scale fabrication have enabled the development of a new generation of pressure sensors with high sensitivity, low cost, and small size to address the needs of current applications. Thus far, a number of micro/nanoscale pressure sensors have been successfully used in consumer electronics devices, automotive applications, and industrial environments.[7] In addition, some specific sensors have been demonstrated to be capable of operating in extreme conditions, such as those applied in the aerospace, marine, and oil industries, with excellent performance and robustness.[8–12]

Advances in nanomaterials, microelectronics, and flexible electronics have allowed the application of micro/nanoscale pressure sensors to a wider range of scenarios, such as smart wearable devices and health monitoring systems.[13,14] In smart wearable devices, a pressure sensor, especially a pressure sensor matrix, can be used to indicate tactile signals on human skin; this feature is the main principle behind the so-called "electronic skin" (*E*-skin).[15] The applications of E-skins are mainly focused on soft robotics, artificial prosthetic replacement, and medical diagnostics, which present challenges to current micro/nanoscale pressure sensors, such as the entire flexibility, easy integration and self-healing properties of the device. In health monitoring systems, pressure is a major sign of life because pressure variations in physiology may induce deteriorating actions on body tissues.[16] Therefore, micro/nanoscale pressure sensors are also increasingly used in mobile biological monitoring and *in vivo* pressure measurements.[17–19] These sensors must meet increasing demands, including implantation ability, biocompatibility, self-power, and wireless transmission.

Great advances have been achieved in the development of micro/nanoscale pressure sensors for the past few years. In this review, we provide a brief introduction of recent progress in micro/nanoscale pressure sensors applicable to wider usage. First, an overview of

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fundamental pressure-sensing principles, including piezoresistivity, capacitance, piezoelectricity, and resonance, is discussed. Next, we present recent advancements in four major categories of micro/nanoscale pressure sensors, namely, novel material-based, flexible, implantable, and self-powered pressure sensors. Finally, we conclude this review and outline perspectives on the development of micro/nanoscale pressure sensors.

2. Pressure-sensing principles

2.1. Piezoresistivity

The discovery of the piezoresistive effect can be dated back to 1856 by Lord Kelvin.[20] Several decades afterward, Smith et al.[21] investigated the piezoresistive effect in semiconductors (*e.g.*, silicon and germanium) and contributed to significant developments in miniaturized piezoresistive sensors. Thus far, these sensors have become one of the most well-known and widely used approaches in sensing applications, such as force, displacement, flow, and pressure sensing.[22] The basic principle of a piezoresistive pressure sensor is conversion of the pressure stimulus exerted on the device into a resistance variation that can be recorded. A piezoresistive pressure sensor typically consists of a sandwich structure with a piezoresistive material layer intercalated between a pair of parallel electrodes. The piezoresistive layer should offer outstanding electrical and mechanical properties and can be designed as beam, cantilever, or diaphragm for specific needs. Piezoresistive pressure sensors based on this simple structure and mechanism allow facile fabrication, high sensitivity, short response times, and easy circuit interfacing. However, the high temperature coefficient of piezoresistivity limits the performance of these sensors, which means these devices require temperature compensation techniques.[1,23]

2.2. Capacitance

A typical capacitive pressure sensor converts applied pressure into a capacitance variation by using a parallel electrode capacitor. In a typical configuration, one electrode of the capacitor is deflected under pressure stimuli while the other electrode is fixed. The device capacitance follows the equation $C = \varepsilon_0 \varepsilon_r A / d$, where ε_0 and ε_r respectively represent the permittivities of the vacuum and dielectric material between the capacitor electrodes and A and d respectively represent the overlap area and distance between two electrodes. Deflection of the electrode leads to a change in d (compression force) or A (shear force), resulting in variations in capacitance that can be measured by a capacitance bridge circuit.[24] Similar to piezoresistive pressure sensors, capacitive pressure sensors present the advantages of simple structure, easy fabrication, high sensitivity, and low cost. In addition, this type of sensor enables high-temperature adaptability, which satisfies requirements for application to harsh conditions. Nevertheless, nonlinear output signals and parasitic capacitance remain significant issues for capacitive pressure sensors.

2.3. Piezoelectricity

The piezoelectric effect was first described by the Curie brothers in 1880. When a piezoelectric material is under external stress, its two surfaces become positively and negatively charged.[25] This phenomenon has been used to develop piezoelectric pressure sensors in which pressure stimuli are directly converted into electrical potential variations. PZT thin films are conventionally used as active materials, usually sandwiched between two electrodes, in micro piezoelectric pressure sensors. ZnO has also been reported as a promising material for piezoelectric pressure-sensing devices.[26] These miniaturized sensors offer properties similar to those of sensors based on microfabrication technology described earlier. Indeed, they are especially suitable for dynamic pressure-sensing applications because of their impulsive output signals.[14]

2.4. Resonance

The current resonant devices are widely used in the sensing field on account of their improved sensitivity and reliability. When these devices are used as pressure sensors, pressure-induced stresses change their natural frequencies. Compared with conventional pressure sensors, resonant pressure sensors have been demonstrated to enable higher sensitivity and precision because their frequency signals are more immune to environmental noises.[1]

Surface acoustic wave resonators (SAWs),[27–29] lamb wave resonators (LWRs),[30] and film bulk acoustic wave resonators (FBARs)[31–33] are three representative resonators used in pressure-sensing applications. The propagation speed and wavelength of SAWs are the main parameters affecting sensor frequency variations.[34] When pressure is applied to the surface of a sensor, the SAW propagation speed changes correspondingly. This pressure–frequency relationship forms the sensing mechanism of a typical SAW pressure sensor.[35] The sensing mechanism of LWR and FBAR pressure sensors is determined by pressure-induced deformations and elasticity variations, which affect either the dimensions of the resonance cavity or the propagation velocity and lead to resonant frequency variations.[33,36] Miniaturization of resonant sensor interface circuits has recently become a research hotspot. In 2015, Nagaraju et al.[32] proposed an extremely miniaturized low-power sensor interface IC for FBAR pressure sensors (Fig. 1a). Here, a hermetically sealed reference FBAR was used to eliminate temperature drifts, and a resolution of 0.037 psi was measured. In 2017, Zhang et al.[33] proposed a high-performance FBAR pressure sensor in which the sensor chip was packaged into an oscillator circuit (Fig. 1b). The sensitivity and linearity of this sensor were improved by using a partially etched support film configuration, and a sensitivity of -0.69 ppm hPa^{-1}, which is 19% higher than previous results, was obtained.

3. Recent advances in micro/nanoscale pressure sensors

3.1. Novel materials based pressure sensors

3.1.1. 2D materials

Since the discovery of graphene in 2004,[37] 2D nanomaterials have attracted wide research interest due to their unique 2D nature-based physical and chemical properties. Graphene pressure sensors, which take advantage of the electrical, mechanical, and piezo-electrical properties of the bulk material, are of particular interest in this field.[38] The Young's modulus of graphene film is approximately 1 TPa.[39] The electronic band structure and conduction properties of graphene vary strongly with the applied pressure, and this principle constitutes the sensing mechanism of a graphene-based piezoresistive pressure sensor.[40] Over the last decade, a variety of these sensors with different design strategies have been developed, and promising results have been obtained.[40–42] Attention has recently been focused on graphene-based nanocomposites, such as graphene/polyurethane nanocomposites,[43] graphene/nanowires,[44,45] and graphene/carbon nanotubes (CNTs), in efforts to improve the sensing performance of these sensors.[46] Researchers have found that the synergistic effect between graphene and nanomaterials results in a network with high conductivity and, thus, enhanced sensitivity.[45] Furthermore, inherently flexible graphene-based nanocomposites are ideal materials for E-skins and other wearable devices. Graphene paper,[47] porous graphene sponges,[48] and graphene/PDMS sponges[49] have been proven to be promising materials for flexible pressure sensors (Fig. 2).

MXenes are an emerging family of 2D materials with potential applications in pressure sensing. These 2D materials were first synthesized by Naguib et al.[50] and have the chemical formula $\mathrm{M}_{n+1}\mathrm{X}_n\mathrm{T}_x$, where M is a transition metal, X is C and/or N, and T is a surface functional group.[51]

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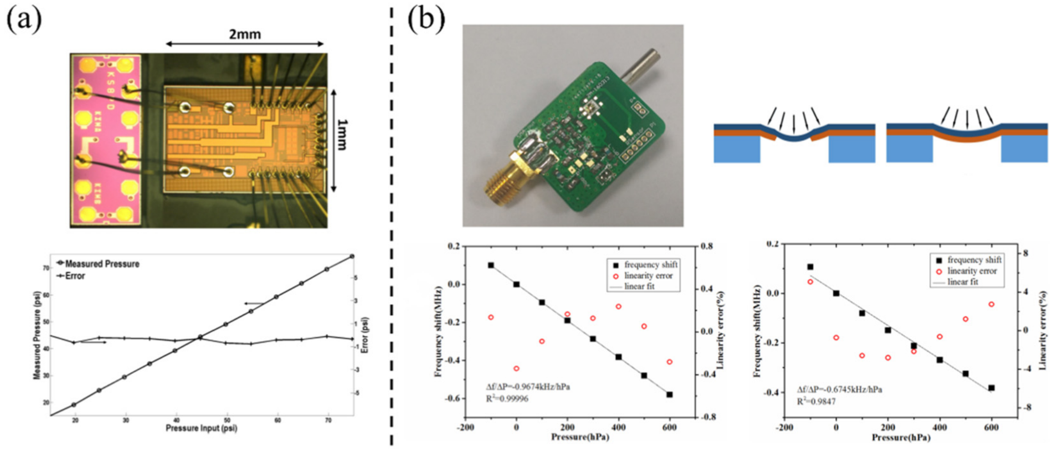

Fig. 1. Miniaturization of resonant pressure sensor interface circuits. (a) Micrograph of a miniaturized sensor interface IC for the FBAR pressure sensor and calibration curve of the sensor. The interface IC is fabricated by using a 130 nm CMOS process. The maximum error is ±0.53 psi.[32] (b) Photograph of a Colpitts oscillator circuit packaged with an FBAR chip and the schematic and sensing performance (linear relationship) of FBARs using and not using the partially etched support film configuration. The partially etched support layer concentrates the induced pressure in the resonator area, leading to high sensitivity.[33]

MXenes exhibit excellent characteristics, such as high electrical conductivity, large specific surface areas, and good hydrophilicity,[51] and have been used for energy storage,[52] catalysis,[53] and water desalination.[54] The wide layer distance of multilayered MXenes enables easy control by an external pressure, thus indicating that MXenes may also be a promising material for piezoresistive pressure sensors. In 2017, Ma et al.[55] first reported a flexible piezoresistive pressure sensor based on multilayered Ti_3C_2–MXene with interdigital electrodes (Fig. 3). This sensor showed high sensitivity below 5 kPa and relatively low sensitivity above 5 kPa, which is due to the compression limit of MXene layers. This achievement was followed by a series of reports on piezoresistive pressure sensors using MXene-based materials, such as MXene/rGO aerogels,[56] porous MXene-sponge networks,[57] MXene–textile networks,[58] MXene nanosheets,[59] and MXene/polymer composites.[60] These devices provide low detection limits, fast response times, and good reproducibility and, hence, show advantages in the real-time monitoring of weak pressure signals, such as subtle human activities.

3.1.2. Carbon nanotubes

Since their discovery in 1991, CNTs have attracted considerable interest due to their outstanding mechanical and electrical properties.[61] CNTs have high elasticity and can be bent to very large angles without breakage.[62] The Young's modulus of single-walled carbon nanotubes (SWNTs) was estimated to be approximately 1 TPa.[63] CNTs have been proven to be potential materials for pressure-sensing applications in numerous studies.[64–66] Over the last few years, advances in flexible electronics have produced a new type of CNT/PDMS composite material-based pressure sensors that can work as artificial *E*-skins to monitor human physiological signals.[67] Such devices, including capacitive sensors and resistive sensors, exhibit ultrahigh sensitivity to human motions and good stability under most operating conditions.[67–69]

Flexible arrays capable of covering complex surfaces have emerged as a novel development in CNT-based pressure sensors. In 2017, Zhan et al.[70] proposed a 4 × 4 array of piezoresistive pressure sensors using

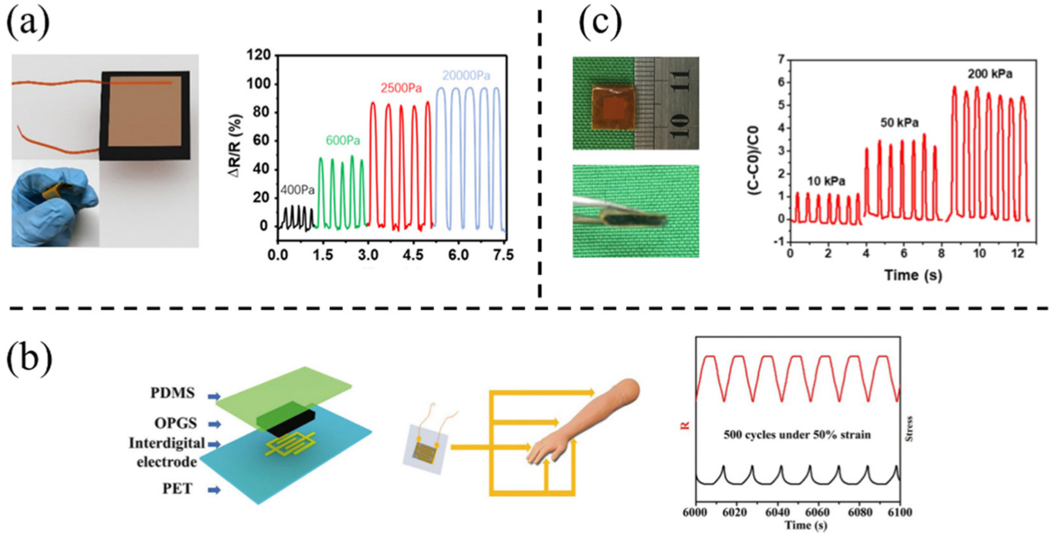

Fig. 2. Graphene-based flexible pressure sensors. (a) Photograph of a graphene paper pressure sensor and its responses at different pressures. The sensor shows stable responses at each tested pressure, and these responses increase appreciably over a small pressure range.[47] (b) Schematic and sensing performance of a porous graphene sponge pressure sensor. The sensor is fabricated by using a sandwich structure packaged by a PDMS layer, 3D porous graphene sponges, an interdigital electrode, and PET film. The sensor shows good stability after 500 cycles of loading/unloading under 50% strain.[48] (c) Photograph of a graphene/PDMS sponge pressure sensor and its responses at different pressures. The sensor is fabricated by folding a flexible substrate with copper electrodes and using a graphene/PDMS sponge as the dielectric layer. The sensor shows stable responses over seven pressure–relaxation cycles under each test pressure.[49]

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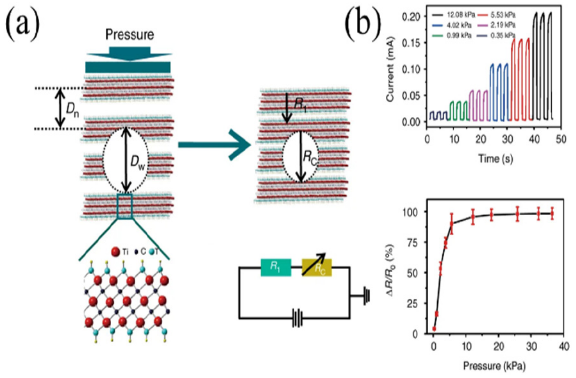

Fig. 3. An MXene-based piezoresistive pressure sensor. (a) Working principle of the sensor. The distances between MXene interlayers decrease under an applied pressure, and the internal resistance R_C is reduced. The wide distance (D_w) between two interlayers can easily be compressed, whereas the narrower distance (D_n) between two lattices cannot. As a result, the partial resistivity R_1 of the MXene device is nearly unchanged under pressure.[55] (b) I–T curves of the sensor at different pressures. The sensor response first increases significantly as a function of pressures below 5 kPa and then slightly increases at pressures above 5 kPa due to the compression limit of narrower distances between two lattices.[55]

an SWNT/tissue paper composite (Fig. 4a). The sensing array was able to simultaneously monitor the pressure and position of human physiological signals with high sensitivity, low energy consumption, and fast response times. In another work, Nela et al.[71] demonstrated a sensing array of 16 × 16 CNT thin-film transistors (TFTs) working as *E*-skins (Fig. 4b). The response time of this device was much faster than that of human skin (<30 ms), and the sensing accuracy was not compromised on both flat and curved surfaces. Novel sensing structures with excellent features, including CNT network-covered pyramidal microstructures,[72] CNT microwires,[73] and wrinkled CNT films,[74] have also been demonstrated in pressure sensors.

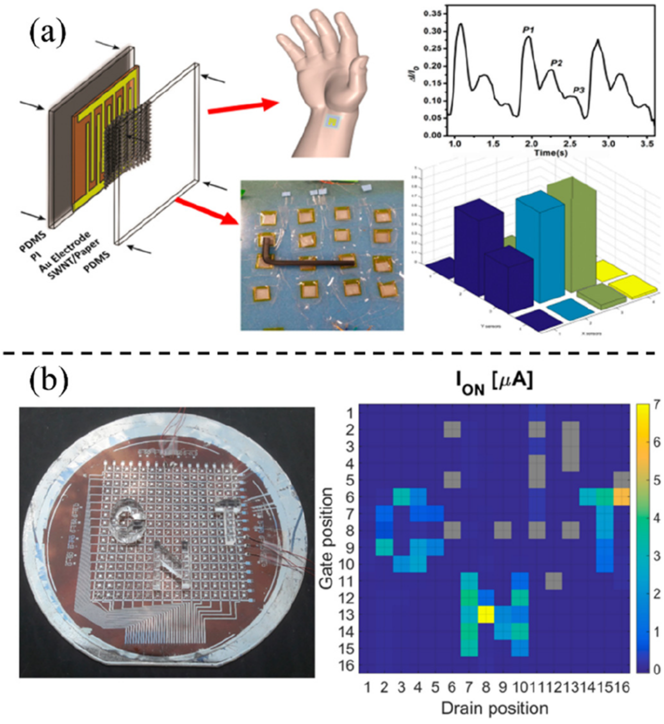

Fig. 4. CNT-based flexible pressure sensor arrays. (a) Schematic and sensing performance of a 4 × 4 array of piezoresistive pressure sensors using an SWNT/tissue paper composite. The composite is assembled onto Au interdigital electrodes on a polyimide (PI) layer, and PDMS layers are used to seal the sensor and provide mechanical support. The pressure sensor could be mounted on a human wrist for heart pulse sensing.[70] (b) Schematic and pressure mapping of a 16 × 16 array of CNT TFTs fabricated into an *E*-skin. CNT TFTs are fabricated on a flexible PI film and laminated on a Si handling wafer using PDMS and epoxy.[71]

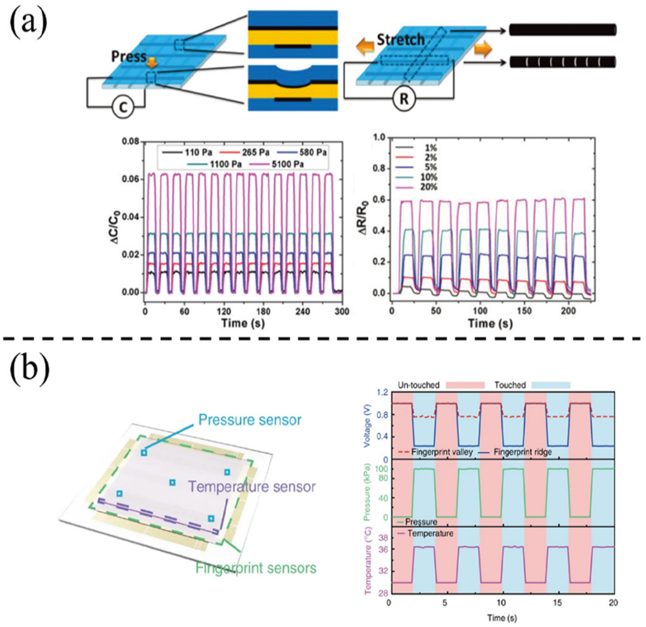

Fig. 5. Multifunctional sensor array using metal nanowires. (a) Schematic and sensing performance of an *E*-skin sensor capable of simultaneously monitoring pressure and strain. When pressure is applied on a sensing pixel, the thickness of the dielectric layer decreases, which induces an increase in capacitance. When the sensor is stretched, the plane strain component parallel to the pre-cracked fibers results in an increase in crack density, which causes a linear increase in resistance.[84] (b) Schematic and sensing performance of a fingerprint sensor array capable of simultaneously monitoring pressure and temperature. All transparent sensors for the fingerprint, pressure, and temperature are located in the central transparent region inside outer bezel areas to interconnect these sensors to the readout circuit using Cr/Au electrodes. When a finger touches the device, an additional voltage drop of approximately 500 mV is generated in the ridge area (blue line) compared with that in the valley area (red line). FETs monitor the tactile pressure (green line), and the temperature sensor detects the temperature of the finger skin each time the finger makes contact with it (purple line).[85]

3.1.3. Metal nanowires

Given their outstanding electrical, optical, and physical properties, metal nanowires have attracted attention as elements of flexible

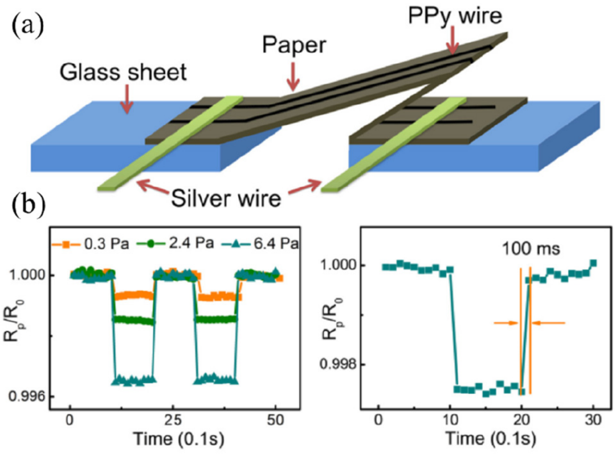

Fig. 6. PPy-coated paper based piezoresistive pressure sensor. (a) Schematic of the sensor. The zigzag layout is inspired by the concept of leaves fluttering in the wind. The inherent flexibility of the paper and conducting polymers allows the PPy-coated paper to serve as a flexible sensor possessing good bendability and stability.[88] (b) Response of the sensor to pressure. The CPFP sensor can easily map pressures with only 1 Pa difference, and the response time is as low as 100 ms.[88]

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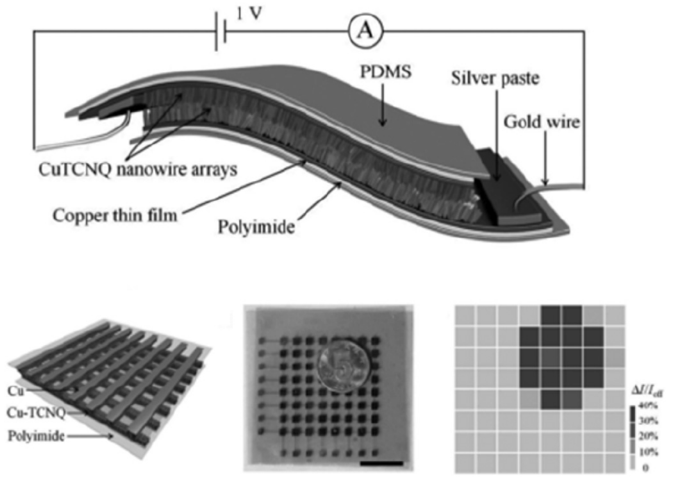

Fig. 7. Schematic and sensing performance of a resistive pressure sensor based on MOF-derived nanowire arrays. The conducting path of the sensor is constructed by numerous mechanical contacts between the nanowire arrays. A metal coin is left on the sensor arrays, and the pressure distributions are revealed through current mapping of these arrays. The sensor arrays are able to give spatially resolved pressure change information.[90]

conductors, transparent film heaters, and photovoltaic systems.[75,76] The excellent mechanical properties[77] of metal nanowires also make them an ideal material for strain and pressure sensors, especially those requiring flexibility. In 2014, Gong et al.[78] demonstrated an ultrathin gold nanowire (AuNW)-based flexible pressure sensor. Here, the AuNWs were deposited onto tissue papers, which were then sandwiched between a PDMS layer and an interdigitated electrode array-patterned PDMS layer. External pressures facilitate contact between the AuNWs and electrodes, resulting in an increase in current. The method provided a low-cost way to develop wearable pressure-sensing devices with relatively high performance (detection limit, 13 Pa) and proved the potential use of metal nanowires for pressure sensing. Flexible pressure sensors using silver nanowires (AgNWs)[79–82] and copper nanowires[83] have also attracted research interest.

Several reports on multifunctional sensor arrays using metal nanowires have been published. In 2017, Cheng et al.[84] reported an *E*-skin sensor capable of simultaneously monitoring multiple parameters, including pressure and strain. This sensor was based on an elastic AgNW composite fiber electrode and could independently be operated in capacitive mode for pressure detection and resistive mode for strain detection (Fig. 5a). In 2018, An et al.[85] developed a fingerprint sensor array integrated with AgNW composite-based pressure-sensitive FETs and polymer-based temperature-sensitive resistors (Fig. 5b). These two devices enabled the multifunctional detection of different stimuli and, thus, greatly expanded the application fields of this type of sensors.

3.1.4. Other novel materials

Besides the materials described above, conducting polymer (CP) and metal–organic framework (MOF)-derived nanostructured materials have also been studied as potential materials for pressure-sensing applications. CPs are mainly used as the active layer in piezoresistive pressure sensors for wearable electronics. Conventional piezoresistive sensors using composites of insulating polymers (*e.g.*, PDMS) and conductive additives are limited by their bulk mechanical properties and, consequently, offer poor sensitivity and slow response times.[86] By contrast, piezoresistive sensors using CPs, especially polypyrrole (PPy), provide high sensitivity and fast response times due to the conductive and elastic properties of the active layer.[87] In 2018, Zang et al.[88] reported a piezoresistive pressure sensor based on PPy-coated paper (Fig. 6). The device showed a detection limit of 0.3 Pa and a response time of approximately 100 ms and provided a facile and low-cost method to fabricate high-performance pressure sensors.

MOFs are a family of crystalline nanoporous materials with large surface areas and high porosity. These materials have received worldwide attention for their potential applications in gas separation, chemical sensing, and heterogeneous catalysis.[89] In particular, MOFs can be used as precursors/templates to prepare nanostructured materials with large pore volumes and surface areas and excellent electrical stability. Fu et al.[90] first proposed a resistive pressure sensor based on MOF-derived nanowire arrays, the sensing mechanism of which was attributed to mechanical contact between two opposite nanowire arrays (Fig. 7). In another work, Zhao et al.[91] demonstrated a multifunctional sensor using MOF-derived porous carbon to have high performance in pressure and temperature sensing due to its porous structures and rough surface.

3.2. Flexible pressure sensors

Due to rapid developments in electronic sensing technologies and organic electronic technologies, wearable sensors have been widely developed over the last several decades.[92–94] Flexible pressure sensors are of particular interest and importance in wearable electronics owing to their broad application prospects in human-machine interfaces,[95,96] *E*-skins,[97,98] robotics,[99,100] and health care systems.[13,101] An ideal flexible pressure sensor should have the advantages of high sensitivity, fast

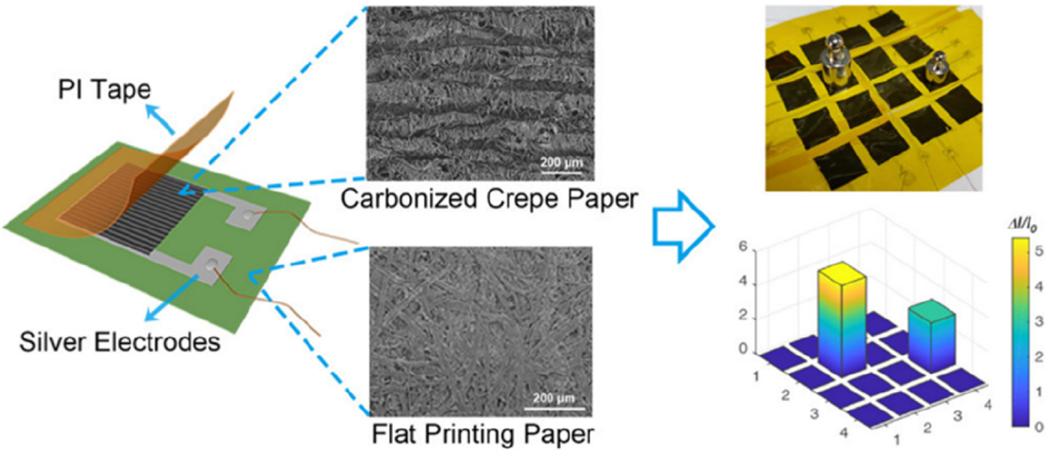

Fig. 8. Schematic and sensing performance of a flexible resistive pressure sensor based on printing paper patterned with Ag interdigital electrodes. The flexible and sensitive resistive pressure sensor is composed of carbonized crepe paper (CCP) as the active material and printing paper as the substrate. The conductive CCP and interdigitated electrodes on printing paper are combined and encapsulated by PI tape to prepare the pressure sensor. Weights of 1 and 2 g lying on the sensor array are immediately illustrated by the pixel bars using different heights in the 3D bar graph.[103]

Fig. 9. Schematic of the rehealability and recyclability of an E-skin. When moderately damaged, the E-skin can be rehealed. The rehealed E-skin can restore mechanical and electrical properties to levels comparable with those of the original device. When severe damage occurs or the device is no longer needed, the whole E-skin can be completely recycled, leaving no waste. Once recycled, a short-oligomer/precursor solution and Ag nanoparticles that can be used to make new materials and devices are obtained.[105]

responses, strong robustness, low cost, and long lifetime to meet the demands of these emerging technologies. Indeed, establishing compatibility between flexible pressure sensors and the array upon integration has become a major challenge for further development because large-area measurements, which can provide comprehensive information about the test object, are also needed in these applications.

Flexible pressure sensors are composed of three key parts: sensing materials, electrodes, and substrates.[14] Advances in flexible sensing materials (*e.g.*, graphene, MXenes or nanocomposites) and electrodes were discussed in the aforementioned sections. Rubbery polymers for flexible substrates, including PDMS, polyethylene terephthalate (PET), and PI, are widely discussed in the literature because of their excellent flexibility, stability, and mechanical properties.[13] In fact, paper substrates have attracted considerable research attention because of their unique properties of low cost and easy realization.[102] For instance, Chen et al.[103] proposed a flexible resistive pressure sensor based nearly completely on paper in 2017 (Fig. 8). The substrate of the sensor was printing paper patterned with Ag interdigital electrodes *via* the screen-printing technique, and the sensing material was formed by using carbonized crepe paper. Experimental results showed that the paper-based sensor offers excellent performance (detection limit, 0.9 Pa; response time, <30 ms) and good durability (over 3000 cycles). Gao et al.[104] reported a paper-based resistive pressure sensor that could be used as an *E*-skin to monitor applied pressure signals. Despite these achievements, however, the high hygroscopicity and weak mechanical strength of paper-based materials pose considerable challenges that must be overcome for practical applications.

Self-healing is a new trend in flexible pressure-sensing devices. Given the advantages presented by the specific association/dissociation of molecular bonds, self-healing materials, especially *E*-skins, are able to repeatedly heal damage and recover mechanical and electrical properties to extend the service life of sensing devices.[97] In 2018, Zou et al.[105] proposed a covalent thermoset nanocomposite-based rehealable *E*-skin capable of monitoring pressure, temperature, flow, and humidity (Fig. 9). The self-healing material of this device was composed of dynamic covalent thermoset polyimine-doped Ag nanoparticles. The self-healing process of the *E*-skin was achieved by new oligomers/polymers growing across the damage site to mimic the healing process of injured skin. Moreover, the mechanical and electrical properties of the device could be restored after the self-healing process.

3.3. Implantable pressure sensors

Implantable pressure sensors that are small in size, light in weight, and compatible with body tissues are extremely necessary to realize the real-time monitoring of physiological parameters in the human body for clinical medicine. Research on implantable pressure sensors has extended to various aspects of health, including blood pressure (monitoring of hypertension and heart failure),[106–108] intraocular pressure (detection of glaucoma),[109–111] intracranial pressure (monitoring of intracranial hypertension),[112–114] and bladder pressure (detection of urinary incontinence).[115] However, several challenges in designing and developing implantable devices for *in vivo* pressure measurements remain; these challenges include packaging of devices, long-term accuracy of signals, biocompatibility of materials, wireless transmission of data, and external power.

MEMS sensors based on micromachining technology provide new opportunities for developing miniaturized and low energy-consuming implantable pressure-sensing devices. MEMS sensors can leverage advances in biocompatible packaging[116] and wireless data and power transmission,[117] leading to improvements in conventional implantable pressure sensors. Capacitive and piezoresistive sensors using deformable membrane structures are the two main types of MEMS-based implantable pressure sensors. For instance, Chen et al.[118] demonstrated a capacitive implantable pressure sensor using a gold–PI diaphragm configuration in 2017 (Fig. 10). Here, a medical-grade stainless steel substrate was utilized to ensure the complete biocompatibility of the device. The capacitive structure comprised an air-filled cavity microfabricated on the substrate and a gold-PI diaphragm that seals

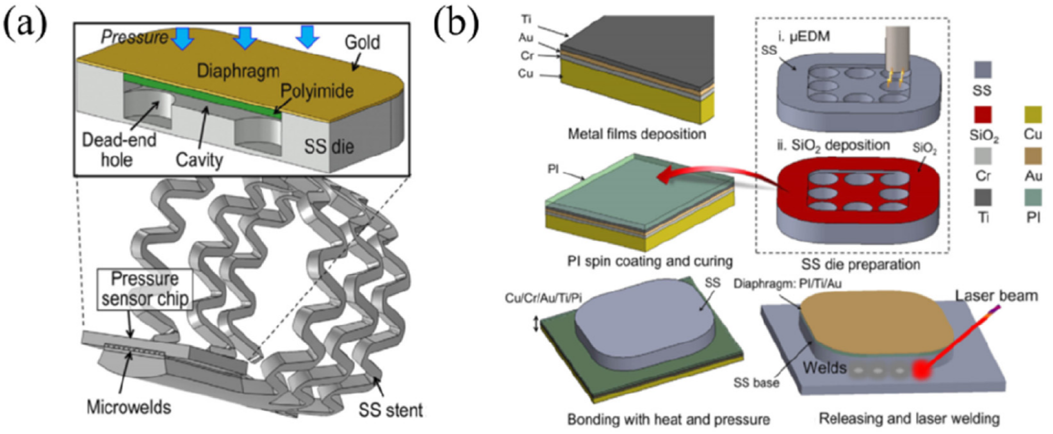

Fig. 10. (a) Cross-sectional structure and (b) fabrication process of an implantable pressure sensor based on a gold–PI diaphragm configuration. The sensor comprises a stainless-steel (SS) chip micromachined to have a square cavity serving as one of the capacitive electrodes and a gold–PI multilayer diaphragm that hermetically seals the cavity while acting as another capacitive electrode to deflect external pressure. The capacitive structure is constructed by heat-assisted bonding of the PI side of the diaphragm to the SS chip.[118]

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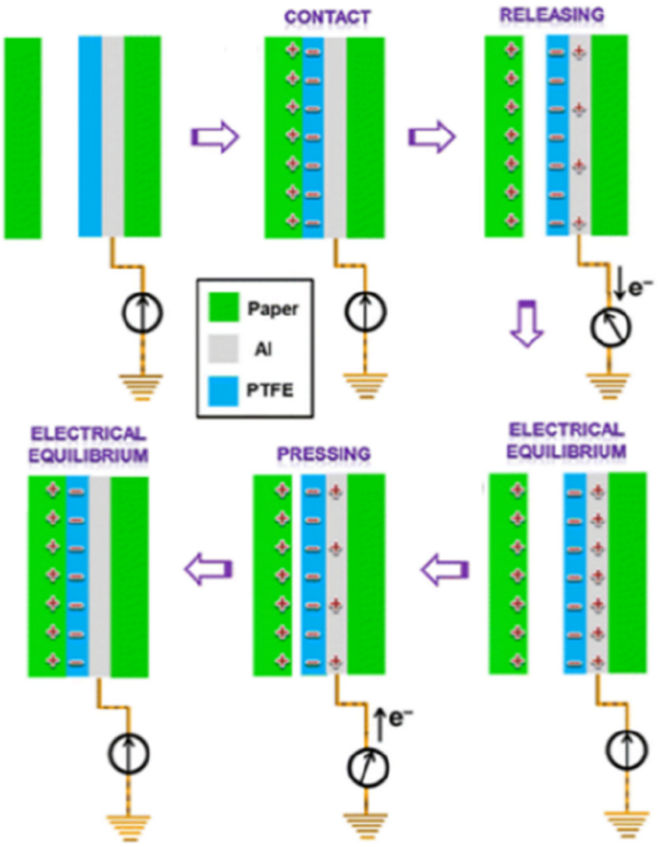

Fig. 11. Working mechanism of a TENG device. The operating principle of TENG is based on the periodic contact and separation of two materials with contrasting triboelectric polarities. Contact between these materials produces triboelectric charged surfaces. During contact and separation, potential differences are created and contribute to the flow of electrons between the back conductive electrodes to generate electric outputs.[123]

the cavity and serves as the capacitive electrode. Deflection of the diaphragm by an applied pressure resulted in capacitance variations between the Au side of the diaphragm and the substrate. Unfortunately, these membrane-based sensors usually offer high sensitivity and biostability but suffer from long-term stability issues due to material fatigue of the membrane substrate.[119] Thus, this issue must be further overcome in the next stages of development.

3.4. Self-powered pressure sensors

Harvesting energy directly from the environment may efficiently solve the threat of global energy exhaustion.[120,121] Hence, self-powered pressure sensors have been extensively studied in recent years. Since mechanical energy is an easily available energy resource in daily life, the use of the triboelectric effect, which converts mechanical energy into electricity, is of vital importance for a self-powered device. Triboelectric generators are the most widely used devices for producing energy in self-powered systems. For instance, Fan et al.[122] and Yang et al.[123] proposed two types of triboelectric nanogenerator (TENG) devices based on a micropatterned plastic film substrate and paper substrate, respectively, for use as self-powered pressure sensors. The self-powering mechanism of TENG is based on the collection of mechanical energy from human motion (Fig. 11). When pressure is applied to a TENG, the deformation of the device leads to a change in electric outputs. Following these works, several researchers have attempted to improve the performance of triboelectric effect-based devices using various materials, including graphene oxide,[124] polymer sponges,[125] and nanofibers.[126,127] These devices present the advantage of simple and low-cost preparation and show potential for scaling up for large-scale production.

Self-powered sensing arrays based on triboelectric effects have been proposed. In 2013, Lin et al.[128] first proposed a 6 × 6 array of triboelectric active sensors for pressure detection. Here, each sensor consisted of a PDMS membrane with pyramidal microstructures, and an Al film assembled with Ag nanowire/nanoparticle composite was applied to improve the triboelectric effect. Spatial pressure mapping could be achieved by integrating multiple sensors into a sensing array. Self-powered pressure sensor arrays based on the triboelectric effect have been proposed to meet the demands of practical applications. In 2017, for example, Ma et al.[129] reported a self-powered *E*-skin consisting of a network of triboelectric pressure sensors using PDMS layers and carbon fiber electrodes (Fig. 12). This device could be assembled on a finger or beetle for pressure monitoring with an ultra-high resolution of 127 × 127 dpi. In the same year, Yuan et al.[130] proposed a self-powered flexible triboelectric sensing array for touch-screen applications. This sensing array was constructed using films of PDMS, fluoroethylene–fluoropropylene copolymer, and a PET substrate sandwiched between two ITO electrodes. The sensing array was capable of sensing real-time touch, mapping spatial pressure distributions, and tracking touch movements.

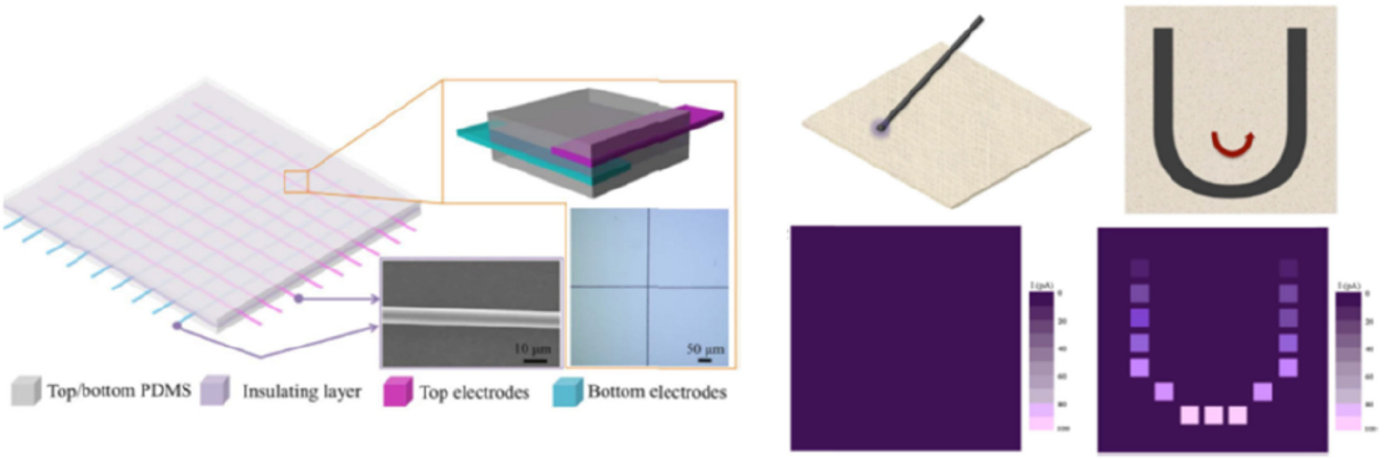

Fig. 12. Schematic of the structure and performance of a self-powered E-skin consisting of triboelectric pressure sensors using PDMS layers and carbon fiber electrodes. The top inset shows an enlarged diagram of one pixel, the bottom-left inset shows an SEM image of a single carbon fiber, and the bottom-right inset shows a micrograph of one pixel. A tip is controlled by a linear motor to press the pixels of the device with variable forces. Real-time mapping of the pressure trajectory could be easily achieved.[129]

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4. Conclusions

Micro/nanoscale pressure sensors have been extensively developed and studied over the years due to their increased miniaturization and performance. In this review, the sensing principles of current pressure-sensing devices were summarized, and recent advances in the development of micro/nanoscale pressure sensors with respect to emerging markets, including novel material-based, flexible, implantable, and self-powered pressure sensors, were discussed.

Although progress has been made in these areas, further work and research should be conducted to tackle the remaining challenges in practical applications and commercial exploitation. Considering the scenarios associated with smart wearable devices and health monitoring systems, the development trends of micro/nanoscale pressure sensors may focus on the following issues. First, while various pressure-sensitive materials have been investigated for implementation in micro/nanoscale pressure sensors, realization of an active material for repeatable and uniform mass-production remains a challenge. Second, construction of a versatile pressure sensor array with small pixel sizes and large coverage areas is necessary for sensor network-related applications (*e.g.*, *E*-skins). The current approach integrates individual sensors capable of monitoring other factors, such as temperature, humidity, and flow.[105] Therefore, crosstalk between sensors and interactions between environmental factors should be considered in the design of these materials and sensors. Third, further development of highly sensitive pressure sensors for health monitoring is necessary. Current implantable and self-powered pressure sensors provide potential solutions for future *in vivo* applications. However, more research work should be dedicated to the realization of high sensing performance, miniaturized circuit components, and effective wireless transmission. Overall, considering the rapid development and advancement of micro/nanoscale pressure sensors, commercialization of these devices and their use in wider applications may be expected in the near future.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

1. Eaton WP, Smith JH. Micromachined pressure sensors: review and recent developments. Smart Mater Struct 1997;6(5):530-9. https://doi.org/10.1088/0964-1726/6/5/004.
2. Akar O, Akin T, Najafi K. A wireless batch sealed absolute capacitive pressure sensor. Sensors Actuators A Phys 2001;95(1):29-38. https://doi.org/10.1016/S0924-4247(01)00753-1.
3. Knite M, Teteris V, Kiploka A, et al. Polyisoprene-carbon black nanocomposites as tensile strain and pressure sensor materials. Sensors and Actuators, A: Physical 2004;110:142-9. https://doi.org/10.1016/j.sna.2003.08.006.
4. Lim HC, Schulkin B, Pulickal MJ, et al. Flexible membrane pressure sensor. Sensors Actuators, A Phys 2005;119(2):332-5. https://doi.org/10.1016/j.sna.2004.10.012.
5. Shirinov AV, Schomburg WK. Pressure sensor from a PVDF film. Sensors Actuators A Phys 2008;142(1):48-55. https://doi.org/10.1016/j.sna.2007.04.002.
6. Zhou J, Gu Y, Fei P, et al. Flexible piezotronic strain sensor. Nano Lett 2008;8(9):3035-40. https://doi.org/10.1021/nl802367t.
7. Eswaran P, Malarvizhi S. MEMS capacitive pressure sensors: a review on recent development and prospective. Int J Eng Technol 2013;5(3):2734-46.
8. Clowes J, Edwards J, Grudinin I, et al. Low drift fibre optic pressure sensor for oil field downhole monitoring. Electron Lett 1999;35(11):926. https://doi.org/10.1049/el:19990646.
9. Zhao LB, Zhao YL, Jiang ZD. Design and fabrication of a piezoresistive pressure sensor for ultra high temperature environment. J Phys Conf Ser 2006;48(1):178-83. https://doi.org/10.1088/1742-6596/48/1/033.
10. Mohammadi AR, Bennington CPJ, Chiao M. A hybrid capacitive pressure and temperature sensor fabricated by adhesive bonding technique for harsh environment of kraft pulp digesters. Microsyst Technol 2011;17(1):149-60. https://doi.org/10.1007/s00542-010-1195-5.
11. San H, Zhang H, Zhang Q, et al. Silicon–glass-based single piezoresistive pressure sensors for harsh environment applications. J Micromech Microeng 2013;23(7), 075020. https://doi.org/10.1088/0960-1317/23/7/075020.
12. Yang J. A harsh environment wireless pressure sensing solution utilizing high temperature electronics. Sensors (Switzerland) 2013;13(3):2719-34. https://doi.org/10.3390/s130302719.
13. Zang Y, Zhang F, Di CA, et al. Advances of flexible pressure sensors toward artificial intelligence and health care applications. Mater Horizons 2015;2(2):140-56. https://doi.org/10.1039/c4mh00147h.
14. Huang Y, Fan X, Chen SC, et al. Emerging technologies of flexible pressure sensors: materials, modeling, devices, and manufacturing. Adv Funct Mater 2019;29(12):1-24. https://doi.org/10.1002/adfm.201808509.
15. Hammock ML, Chortos A, Tee BCK, et al. 25th anniversary article: the evolution of electronic skin (E-skin): a brief history, design considerations, and recent progress. Adv Mater 2013;25(42):5997-6038. https://doi.org/10.1002/adma.201302240.
16. Clausen I, Glott T. Development of clinically relevant implantable pressure sensors: perspectives and challenges. Sensors (Switzerland) 2014;14(9):17686-702. https://doi.org/10.3390/s140917686.
17. Hu F, Xiao Y, Hao Q. Congestion-aware, loss-resilient bio-monitoring sensor networking for mobile health applications. IEEE J Sel Areas Commun 2009. https://doi.org/10.1109/JSAC.2009.090509.
18. Nakamura M, Nakamura J, Lopez G, et al. Collaborative processing of wearable and ambient sensor system for blood pressure monitoring. Sensors 2011. https://doi.org/10.3390/s110706760.
19. Lakhal K. Noninvasive continuous blood pressure monitoring. Anesth Analg 2018. https://doi.org/10.1213/00000539-900000000-96395.
20. Thomson W. On the electro-dynamic qualities of metals:—effects of magnetization on the electric conductivity of nickel and of iron. Proc R Soc London 1857;8:546-50. https://doi.org/10.1098/rspl.1856.0144.
21. Smith CS. Piezoresistance effect in germanium and silicon. Phys Rev 1954;94(1):42-9. https://doi.org/10.1103/PhysRev.94.42.
22. Li J, Bao R, Tao J, et al. Recent progress in flexible pressure sensor arrays: from design to applications. J Mater Chem C 2018;6(44):11878-92. https://doi.org/10.1039/c8tc02946f.
23. Fiorillo AS, Critello CD, Pullano AS. Theory, technology and applications of piezoresistive sensors: a review. Sensors Actuators A Phys 2018;281:156-75. https://doi.org/10.1016/j.sna.2018.07.006.
24. Balavalad KB, Sheeparamatti BG. Sensors & transducers a critical review of MEMS capacitive pressure sensors. Sensors & Tranducers 2015;187(4):120-8.
25. Akiyama M, Morofuji Y, Kamohara T, et al. Flexible piezoelectric pressure sensors using oriented aluminum nitride thin films prepared on polyethylene terephthalate films. J Appl Phys 2006;100(11). https://doi.org/10.1063/1.2401312.
26. Kuoni A, Holzherr RL, Boillat M, et al. Polyimide membrane with ZnO piezoelectric thin film pressure transducers as a differential pressure liquid flow sensor. J Micromech Microeng 2003;13(4):S103-7. https://doi.org/10.1088/0960-1317/13/4/317.
27. Wang WN, Fan Q. Tire pressure monitoring system and wireless passive surface acoustic wave sensor. Appl Mech Mater 2014;536–537:333-7. https://doi.org/10.4028/www.scientific.net/AMM.536-537.333.
28. Mu X, Kropelnicki P, Wang Y, et al. Dual mode acoustic wave sensor for precise pressure reading. Appl Phys Lett 2014;105(11), 113507. https://doi.org/10.1063/1.4896025.
29. Della Lucia F, Zambrozi P, Frazatto F, et al. Design, fabrication and characterization of SAW pressure sensors for offshore oil and gas exploration. Sensors Actuators A Phys 2015;222:322-8. https://doi.org/10.1016/j.sna.2014.12.011.
30. Kropelnicki P, Muckensturm KM, Mu XJ, et al. CMOS-compatible ruggedized high-temperature Lamb wave pressure sensor. J Micromech Microeng 2013;23(8), 085018. https://doi.org/10.1088/0960-1317/23/8/085018.
31. Anderås E, Katardjiev I, Yantchev VM. Tilted c-axis thin-film bulk wave resonant pressure sensors with improved sensitivity. IEEE Sensors J 2012;12(8):2653-4. https://doi.org/10.1109/JSEN.2012.2199482.
32. Nagaraju M, Sridaran S, Lingley A, et al. A 400μW differential FBAR sensor interface IC with digital readout. 2015 joint conference of the IEEE international frequency control symposium and the European frequency and time forum, FCS 2015 - proceedings. Weinheim, Germany: IEEE; 2015. p. 218-21.
33. Zhang M, Zhao Z, Du L, et al. A film bulk acoustic resonator-based high-performance pressure sensor integrated with temperature control system. J Micromech Microeng 2017;27(4), 045004. https://doi.org/10.1088/1361-6439/aa5e6a.
34. Galipeau DW, Story PR, Vetelino KA, et al. Surface acoustic wave microsensors and applications. Smart Mater Struct 1997;6(6):658-67. https://doi.org/10.1088/0964-1726/6/6/002.

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35. Scholl G, Schmidt F, Wolff U. Surface acoustic wave devices for sensor applications. Phys Status Solidi Appl Res 2001;185(1):47-58. https://doi.org/10.1002/1521-396X(200105)185:1<47::AID-PSSA47>3.0.CO;2-Q.
36. Yantchev V, Katardjiev I. Thin film lamb wave resonators in frequency control and sensing applications: a review. J Micromech Microeng 2013;23(4), 043001. https://doi.org/10.1088/0960-1317/23/4/043001.
37. Novoselov KS, Geim AK, Morozov SV, et al. Electric field in atomically thin carbon films. Science (80-) 2004;306(5696):666-9. https://doi.org/10.1126/science.1102896.
38. Sorkin V, Zhang YW. Graphene-based pressure nano-sensors. J Mol Model 2011;17(11):2825-30. https://doi.org/10.1007/s00894-011-0972-0.
39. Lee C, Wei X, Kysar JW, et al. Measurement of the elastic properties and intrinsic strength of monolayer graphene. Science (80-) 2008;321(5887):385-8. https://doi.org/10.1126/science.1157996.
40. Zhu S-E, Krishna Ghatkesar M, Zhang C, et al. Graphene based piezoresistive pressure sensor. Appl Phys Lett 2013;102(16), 161904. https://doi.org/10.1063/1.4802799.
41. Smith AD, Niklaus F, Paussa A, et al. Electromechanical piezoresistive sensing in suspended graphene membranes. Nano Lett 2013;13(7):3237-42. https://doi.org/10.1021/nl401352k.
42. Sheng L, Liang Y, Jiang L, et al. Bubble-decorated honeycomb-like graphene film as ultrahigh sensitivity pressure sensors. Adv Funct Mater 2015;25(41):6545-51. https://doi.org/10.1002/adfm.201502960.
43. Tung TT, Robert C, Castro M, et al. Enhancing the sensitivity of graphene/polyurethane nanocomposite flexible piezo-resistive pressure sensors with magnetite nano-spacers. Carbon N Y 2016;108:450-60. https://doi.org/10.1016/j.carbon.2016.07.018.
44. Chen Z, Wang Z, Li X, et al. Flexible piezoelectric-induced pressure sensors for static measurements based on nanowires/graphene heterostructures. ACS Nano 2017;11(5):4507-13. https://doi.org/10.1021/acsnano.6b08027.
45. Dong X, Wei Y, Chen S, et al. A linear and large-range pressure sensor based on a graphene/silver nanowires nanobiocomposites network and a hierarchical structural sponge. Compos Sci Technol 2018;155:108-16. https://doi.org/10.1016/j.compscitech.2017.11.028.
46. Jian M, Xia K, Wang Q, et al. Flexible and highly sensitive pressure sensors based on bionic hierarchical structures. Adv Funct Mater 2017;27(9). https://doi.org/10.1002/adfm.201606066.
47. Tao LQ, Zhang KN, Tian H, et al. Graphene-paper pressure sensor for detecting human motions. ACS Nano 2017;11(9):8790-5. https://doi.org/10.1021/acsnano.7b02826.
48. Wang T, Li J, Zhang Y, et al. Highly ordered 3D porous graphene sponge for wearable piezoresistive pressure sensor applications. Chem A Eur J 2019;25(25):6378-84. https://doi.org/10.1002/chem.201900014.
49. Kou H, Zhang L, Tan Q, et al. Wireless wide-range pressure sensor based on graphene/PDMS sponge for tactile monitoring. Sci Rep 2019;9(1):1-7. https://doi.org/10.1038/s41598-019-40828-8.
50. Naguib M, Kurtoglu M, Presser V, et al. Two-dimensional nanocrystals produced by exfoliation of Ti3AlC2. Adv Mater 2011;23(37):4248-53. https://doi.org/10.1002/adma.201102306.
51. Naguib M, Mochalin VN, Barsoum MW, et al. 25th anniversary article: MXenes: a new family of two-dimensional materials. Adv Mater 2014;26(7):992-1005. https://doi.org/10.1002/adma.201304138.
52. Wang X, Kajiyama S, Iinuma H, et al. Pseudocapacitance of MXene nanosheets for high-power sodium-ion hybrid capacitors. Nat Commun 2015;6(1):6544. https://doi.org/10.1038/ncomms7544.
53. Xie X, Chen S, Ding W, et al. An extraordinarily stable catalyst: Pt NPs supported on two-dimensional Ti3C2X2 (X = OH, F) nanosheets for oxygen reduction reaction. Chem Commun 2013;49(86), 10112. https://doi.org/10.1039/c3cc44428g.
54. Srimuk P, Kaasik F, Krüner B, et al. MXene as a novel intercalation-type pseudocapacitive cathode and anode for capacitive deionization. J Mater Chem A 2016;4(47):18265-71. https://doi.org/10.1039/C6TA07833H.
55. Ma Y, Liu N, Li L, et al. A highly flexible and sensitive piezoresistive sensor based on MXene with greatly changed interlayer distances. Nat Commun 2017;8(1):1-7. https://doi.org/10.1038/s41467-017-01136-9.
56. Ma Y, Yue Y, Zhang H, et al. 3D synergistical MXene/reduced graphene oxide aerogel for a piezoresistive sensor. ACS Nano 2018;12(4):3209-16. https://doi.org/10.1021/acsnano.7b06909.
57. Yue Y, Liu N, Liu W, et al. 3D hybrid porous Mxene-sponge network and its application in piezoresistive sensor. Nano Energy 2018;50(March):79-87. https://doi.org/10.1016/j.nanoen.2018.05.020.
58. Li T, Chen L, Yang X, et al. A flexible pressure sensor based on an MXene-textile network structure. J Mater Chem C 2019;7(4):1022-7. https://doi.org/10.1039/c8tc04893b.
59. Guo Y, Zhong M, Fang Z, et al. A wearable transient pressure sensor made with MXene nanosheets for sensitive broad-range human-machine interfacing. Nano Lett 2019;19(2):1143-50. https://doi.org/10.1021/acs.nanolett.8b04514.
60. Hu Y, Zhuo H, Luo Q, et al. Biomass polymer-assisted fabrication of aerogels from MXenes with ultrahigh compression elasticity and pressure sensitivity. J Mater Chem A 2019;7(17):10273-81. https://doi.org/10.1039/c9ta01448a.
61. Iijima S. Helical microtubules of graphitic carbon. Nature 1991;354(6348):56-8. https://doi.org/10.1038/354056a0.
62. Bernholc J, Brenner D, Buongiorno Nardelli M, et al. Mechanical and electrical properties of nanotubes. Annu Rev Mat Res 2002;32(1):347-75. https://doi.org/10.1146/annurev.matsci.32.112601.134925.
63. Yakobson BI, Brabec CJ, Bernholc J. Nanomechanics of carbon tubes: instabilities beyond linear response. Phys Rev Lett 1996;76(14):2511-4. https://doi.org/10.1103/PhysRevLett.76.2511.
64. Stampfer RC, Helbling T, Obergfell D, et al. Fabrication of single-walled carbon-nanotube-based pressure sensors. Nano Lett 2006;6(2):233-7. https://doi.org/10.1021/nl052171d.
65. Wood JR, Wagner HD. Single-wall carbon nanotubes as molecular pressure sensors. Appl Phys Lett 2000;76(20):2883-5. https://doi.org/10.1063/1.126505.
66. Mahar B, Laslau C, Yip R, et al. Development of carbon nanotube-based sensors—a review. IEEE Sensors J 2007;7(2):266-84. https://doi.org/10.1109/JSEN.2006.886863.
67. Lipomi DJ, Vosgueritchian M, BCK T, et al. Skin-like pressure and strain sensors based on transparent elastic films of carbon nanotubes. Nat Nanotechnol 2011;6(12):788-92. https://doi.org/10.1038/nnano.2011.184.
68. Wang X, Gu Y, Xiong Z, et al. Silk-molded flexible, ultrasensitive, and highly stable electronic skin for monitoring human physiological signals. Adv Mater 2014;26(9):1336-42. https://doi.org/10.1002/adma.201304248.
69. Woo S-J, Kong J-H, Kim D-G, et al. A thin all-elastomeric capacitive pressure sensor array based on micro-contact printed elastic conductors. J Mater Chem C 2014;2(22):4415-22. https://doi.org/10.1039/C4TC00392F.
70. Zhan Z, Lin R, Tran VT, et al. Paper/carbon nanotube-based wearable pressure sensor for physiological signal acquisition and soft robotic skin. ACS Appl Mater Interfaces 2017;9(43):37921-8. https://doi.org/10.1021/acsami.7b10820.
71. Nela L, Tang J, Cao Q, et al. Large-area high-performance flexible pressure sensor with carbon nanotube active matrix for electronic skin. Nano Lett 2018;18(3):2054-9. https://doi.org/10.1021/acs.nanolett.8b00063.
72. Huang Z, Gao M, Yan Z, et al. Pyramid microstructure with single walled carbon nanotubes for flexible and transparent micro-pressure sensor with ultra-high sensitivity. Sensors Actuators, A Phys 2017;266:345-51. https://doi.org/10.1016/j.sna.2017.09.054.
73. Zhou J, Xu X, Yu H, et al. Deformable and wearable carbon nanotube microwire-based sensors for ultrasensitive monitoring of strain, pressure and torsion. Nanoscale 2017;9(2):604-12. https://doi.org/10.1039/c6nr08096k.
74. Park SJ, Kim J, Chu M, et al. Flexible piezoresistive pressure sensor using wrinkled carbon nanotube thin films for human physiological signals. Adv Mater Technol 2018;3(1):1-7. https://doi.org/10.1002/admt.201700158.
75. Bell AP, Fairfield JA, McCarthy EK, et al. Quantitative study of the photothermal properties of metallic nanowire networks. ACS Nano 2015;9(5):5551-8. https://doi.org/10.1021/acsnano.5b01673.
76. Sannicolo T, Lagrange M, Cabos A, et al. Metallic nanowire-based transparent electrodes for next generation flexible devices: a review. Small 2016;12(44):6052-75. https://doi.org/10.1002/smll.201602581.
77. McCarthy EK, Bellew AT, Sader JE, et al. Poisson's ratio of individual metal nanowires. Nat Commun 2014;5(1):4336. https://doi.org/10.1038/ncomms5336.
78. Gong S, Schwalb W, Wang Y, et al. A wearable and highly sensitive pressure sensor with ultrathin gold nanowires. Nat Commun 2014;5:3132. https://doi.org/10.1038/ncomms4132.
79. Yao S, Zhu Y. Wearable multifunctional sensors using printed stretchable conductors made of silver nanowires. Nanoscale 2014;6(4):2345-52. https://doi.org/10.1039/c3nr05496a.
80. Amjadi M, Pichitpajongkit A, Lee S, et al. Highly stretchable and sensitive strain sensor based on silver nanowire-elastomer nanocomposite. ACS Nano 2014;8(5):5154-63. https://doi.org/10.1021/nn501204t.
81. Ge J, Sun L, Zhang FR, et al. A stretchable electronic fabric artificial skin with pressure-, lateral strain-, and flexion-sensitive properties. Adv Mater 2016;28(4):722-8. https://doi.org/10.1002/adma.201504239.
82. Wei Y, Chen S, Dong X, et al. Flexible piezoresistive sensors based on "dynamic bridging effect" of silver nanowires toward graphene. Carbon N Y 2017;113:395-403. https://doi.org/10.1016/j.carbon.2016.11.027.
83. Tang Y, Gong S, Chen Y, et al. Manufacturable conducting rubber ambers and stretchable conductors from copper nanowire aerogel monoliths. ACS Nano 2014;8(6):5707-14. https://doi.org/10.1021/nn502702a.
84. Cheng Y, Wang R, Zhai H, et al. Stretchable electronic skin based on silver nanowire composite fiber electrodes for sensing pressure, proximity, and multidirectional strain. Nanoscale 2017;9(11):3834-42. https://doi.org/10.1039/c7nr00121e.
85. An BW, Heo S, Ji S, et al. Transparent and flexible fingerprint sensor array with multiplexed detection of tactile pressure and skin temperature. Nat Commun 2018;9(1):1-10. https://doi.org/10.1038/s41467-018-04906-1.
86. Zhong W, Liu Q, Wu Y, et al. A nanofiber based artificial electronic skin with high pressure sensitivity and 3D conformability. Nanoscale 2016;8(24):12105-12. https://doi.org/10.1039/c6nr02678h.
87. Pan L, Chortos A, Yu G, et al. An ultra-sensitive resistive pressure sensor based on hollow-sphere microstructure induced elasticity in conducting polymer film. Nat Commun 2014;5:1-8. https://doi.org/10.1038/ncomms4002.
88. Zang X, Jiang Y, Wang X, et al. Highly sensitive pressure sensors based on conducting polymer-coated paper. Sens Actuators B 2018;273(June):1195-201. https://doi.org/10.1016/j.snb.2018.06.132.
89. Farrusseng D. *Metal-organic frameworks: applications from catalysis to gas storage.* 2011. https://doi.org/10.1002/9783527635856.
90. Fu X, Dong H, Zhen Y, et al. Solution-processed large-area nanocrystal arrays of metal-organic frameworks as wearable, ultrasensitive, electronic skin for health monitoring. Small 2015;11(27):3351-6. https://doi.org/10.1002/smll.201402890.
91. Zhao XH, Ma SN, Long H, et al. Multifunctional sensor based on porous carbon derived from metal-organic frameworks for real time health monitoring. ACS Appl Mater Interfaces 2018;10(4):3986-93. https://doi.org/10.1021/acsami.7b16859.
92. Patel S, Park H, Bonato P, et al. A review of wearable sensors and systems with application in rehabilitation. J Neuroeng Rehabil 2012;9(1). https://doi.org/10.1186/1743-0003-9-21.

Please cite this article as: Y. Chang, J. Zuo, H. Zhang, et al., State-of-the-art and recent developments in micro/nanoscale pressure sensors for smart wearable devi..., , https://doi.org/10.1016/j.npe.2019.12.006

93. Pang C, Lee C, Suh KY. Recent advances in flexible sensors for wearable and implantable devices. J Appl Polym Sci 2013;130(3):1429-41. https://doi.org/10.1002/app.39461.
94. Nag A, Mukhopadhyay SC, Kosel J. Wearable flexible sensors: a review. IEEE Sensors J 2017;17(13):3949-60. https://doi.org/10.1109/JSEN.2017.2705700.
95. Jung S, Kim JH, Kim J, et al. Reverse-micelle-induced porous pressure-sensitive rubber for wearable human-machine interfaces. Adv Mater 2014;26(28):4825-30. https://doi.org/10.1002/adma.201401364.
96. Wu X, Han Y, Zhang X, et al. Large-area compliant, low-cost, and versatile pressure-sensing platform based on microcrack-designed carbon black@polyurethane sponge for human–machine interfacing. Adv Funct Mater 2016;26(34):6246-56. https://doi.org/10.1002/adfm.201601995.
97. Tee BCK, Wang C, Allen R, et al. An electrically and mechanically self-healing composite with pressure- and flexion-sensitive properties for electronic skin applications. Nat Nanotechnol 2012;7(12):825-32. https://doi.org/10.1038/nnano.2012.192.
98. Wang C, Hwang D, Yu Z, et al. User-interactive electronic skin for instantaneous pressure visualization. Nat Mater 2013;12(10):899-904. https://doi.org/10.1038/nmat3711.
99. Maiolino P, Maggiali M, Cannata G, et al. A flexible and robust large scale capacitive tactile system for robots. IEEE Sensors J 2013;13(10):3910-7. https://doi.org/10.1109/JSEN.2013.2258149.
100. Lu N, Kim DH. Flexible and stretchable electronics paving the way for soft robotics. Soft Robot 2014;1(1):53-62. https://doi.org/10.1089/soro.2013.0005.
101. Schwartz G, BCK T, Mei J, et al. Flexible polymer transistors with high pressure sensitivity for application in electronic skin and health monitoring. Nat Commun 2013;4. https://doi.org/10.1038/ncomms2832.
102. Zhang Y, Zhang L, Cui K, et al. Flexible electronics based on micro/nanostructured paper. Adv Mater 2018;30(51):1-39. https://doi.org/10.1002/adma.201801588.
103. Chen S, Song Y, Xu F. Flexible and highly sensitive resistive pressure sensor based on carbonized crepe paper with corrugated structure. ACS Appl Mater Interfaces 2018;10(40):34646-54. https://doi.org/10.1021/acsami.8b13535.
104. Gao L, Zhu C, Li L, et al. All paper-based flexible and wearable piezoresistive pressure sensor. ACS Appl Mater Interfaces 2019;11(28):25034-42. https://doi.org/10.1021/acsami.9b07465.
105. Zou Z, Zhu C, Li Y, et al. Rehealable, fully recyclable, and malleable electronic skin enabled by dynamic covalent thermoset nanocomposite. Sci Adv 2018;4(2):1-9. https://doi.org/10.1126/sciadv.aaq0508.
106. Murphy OH, Bahmanyar MR, Borghi A, et al. Continuous in vivo blood pressure measurements using a fully implantable wireless SAW sensor. Biomed Microdevices 2013;15(5):737-49. https://doi.org/10.1007/s10544-013-9759-7.
107. Starr P, Bartels K, Agrawal CM, et al. A thin-film pressure transducer for implantable and intravascular blood pressure sensing. Sensors Actuators A Phys 2016;248:38-45. https://doi.org/10.1016/j.sna.2016.06.035.
108. Kim S, Park J, So S, et al. Characteristics of an implantable blood pressure sensor packaged by ultrafast laser microwelding. Sensors (Switzerland) 2019;19(8). https://doi.org/10.3390/s19081801.
109. Melki S, Todani A, Cherfan G. An implantable intraocular pressure transducer initial safety outcomes. JAMA Ophthalmol 2014;132(10):1221-5. https://doi.org/10.1001/jamaophthalmol.2014.1739.
110. Mariacher S, Ebner M, Januschowski K, et al. Investigation of a novel implantable suprachoroidal pressure transducer for telemetric intraocular pressure monitoring. Exp Eye Res 2016;151:54-60. https://doi.org/10.1016/j.exer.2016.07.016.
111. Mariacher S, Ebner M, Hurst J, et al. Implantation and testing of a novel episcleral pressure transducer: a new approach to telemetric intraocular pressure monitoring. Exp Eye Res 2018;166(October 2017):84-90. https://doi.org/10.1016/j.exer.2017.10.020.
112. Kawoos U, McCarron RM, Auker CR, et al. Advances in intracranial pressure monitoring and its significance in managing traumatic brain injury. Int J Mol Sci 2015;16(12):28979-97. https://doi.org/10.3390/ijms161226146.
113. Zhang X, Medow JE, Iskandar BJ, et al. Invasive and noninvasive means of measuring intracranial pressure: a review. Physiol Meas 2017;38(8):R143-82. https://doi.org/10.1088/1361-6579/aa7256.
114. Harary M, Dolmans RGF, Gormley WB. Intracranial pressure monitoring—review and avenues for development. Sensors (Switzerland) 2018;18(2):3-7. https://doi.org/10.3390/s18020465.
115. Dakurah MN, Koo C, Choi W, et al. Implantable bladder sensors: a methodological review. Int Neurourol J 2015;19(3):133-41. https://doi.org/10.5213/inj.2015.19.3.133.
116. Chen Y, Kim YS, Tillman BW, et al. Advances in materials for recent low-profile implantable bioelectronics. Materials (Basel) 2018;11(4):1-24. https://doi.org/10.3390/ma11040522.
117. Lee J, Jang J, Song YK. A review on wireless powering schemes for implantable microsystems in neural engineering applications. Biomed Eng Lett 2016;6(4):205-15. https://doi.org/10.1007/s13534-016-0242-2.
118. Chen X, Brox D, Assadsangabi B, et al. A stainless-steel-based implantable pressure sensor chip and its integration by microwelding. Sensors Actuators A Phys 2017;257:134-44. https://doi.org/10.1016/j.sna.2017.01.017.
119. Yu L, Kim BJ, Meng E. Chronically implanted pressure sensors: challenges and state of the field. Sensors (Switzerland) 2014;14(11):20620-44. https://doi.org/10.3390/s141120620.
120. Brown KS. ENERGY: bright future–or brief flare–for renewable energy? Science (80-) 1999;285(5428):678-80. https://doi.org/10.1126/science.285.5428.678.
121. Tian B, Zheng X, Kempa TJ, et al. Coaxial silicon nanowires as solar cells and nanoelectronic power sources. Nature 2007;449(7164):885-9. https://doi.org/10.1038/nature06181.
122. Fan FR, Lin L, Zhu G, et al. Transparent triboelectric nanogenerators and self-powered pressure sensors based on micropatterned plastic films. Nano Lett 2012;12(6):3109-14. https://doi.org/10.1021/nl300988z.
123. Yang PK, Lin ZH, Pradel KC, et al. Paper-based origami triboelectric nanogenerators and self-powered pressure sensors. ACS Nano 2015;9(1):901-7. https://doi.org/10.1021/nn506631t.
124. Guo H, Li T, Cao X, et al. Self-sterilized flexible single-electrode triboelectric nanogenerator for energy harvesting and dynamic force sensing. ACS Nano 2017;11(1):856-64. https://doi.org/10.1021/acsnano.6b07389.
125. Parida K, Bhavanasi V, Kumar V, et al. Self-powered pressure sensor for ultra-wide range pressure detection. Nano Res 2017;10(10):3557-70. https://doi.org/10.1007/s12274-017-1567-6.
126. Lin MF, Xiong J, Wang J, et al. Core-shell nanofiber mats for tactile pressure sensor and nanogenerator applications. Nano Energy 2018;44(December 2017):248-55. https://doi.org/10.1016/j.nanoen.2017.12.004.
127. Garcia C, Trendafilova I, Guzman de Villoria R, et al. Self-powered pressure sensor based on the triboelectric effect and its analysis using dynamic mechanical analysis. Nano Energy 2018;50(May):401-9. https://doi.org/10.1016/j.nanoen.2018.05.046.
128. Lin L, Xie Y, Wang S, et al. Triboelectric active sensor array for self-powered static and dynamic pressure detection and tactile imaging. ACS Nano 2013;7(9):8266-74. https://doi.org/10.1021/nn4037514.
129. Ma M, Zhang Z, Liao Q, et al. Self-powered artificial electronic skin for high-resolution pressure sensing. Nano Energy 2017;32(January):389-96. https://doi.org/10.1016/j.nanoen.2017.01.004.
130. Yuan Z, Zhou T, Yin Y, et al. Transparent and flexible triboelectric sensing array for touch security applications. ACS Nano 2017;11(8):8364-9. https://doi.org/10.1021/acsnano.7b03680.

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