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TOPICAL REVIEW

Progress in micro/nano sensors and nanoenergy for future AIoT-based smart home applications

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Abstract

Self-sustainable sensing systems composed of micro/nano sensors and nano-energy harvesters contribute significantly to developing the internet of things (IoT) systems. As one of the most promising IoT applications, smart home relies on implementing wireless sensor networks with miniaturized and multi-functional sensors, and distributed, reliable, and sustainable power sources, namely energy harvesters with a variety of conversion mechanisms. To extend the capabilities of IoT in the smart home, a technology fusion of IoT and artificial intelligence (AI), called the artificial intelligence of things (AIoT), enables the detection, analysis, and decision-making functions with the aids of machine learning assisted algorithms to form a smart home based intelligent system. In this review, we introduce the conventional rigid microelectromechanical system (MEMS) based micro/nano sensors and energy harvesters, followed by presenting the advances in the wearable counterparts for better human interactions. We then discuss the viable integration approaches for micro/nano sensors and energy harvesters to form self-sustainable IoT systems. Whereafter, we emphasize the recent development of AIoT based systems and the corresponding applications enabled by the machine learning algorithms. Smart home based healthcare technology enabled by the integrated multi-functional sensing platform and bioelectronic medicine is also presented as an important future direction, as well as wearable photonics sensing system as a complement to the wearable electronics sensing system.

1. Introduction

Recent advances in semiconductor technologies have enabled cost-effective approaches for wireless network connectivity between various sensors and processors, which lead to visible progress in the Internet of Things (IoT). IoT, which consists of a large number of devices connected to the internet, is considered a promising technology for the consumer electronics market. In particular, the smart home that provides an intelligent living environment has been touted as a market segment with a high potential to deploy IoT. The smart home's eventual realization requires integrating countless sensors with diversified functionalities distributed around the house to form a home network capable of monitoring the house environment and being managed via the internet.

In general, sensors that contribute to the smart home application can be divided into three categories. One is employed for the smart control of household appliances (e.g., voice control), another is used for environmental

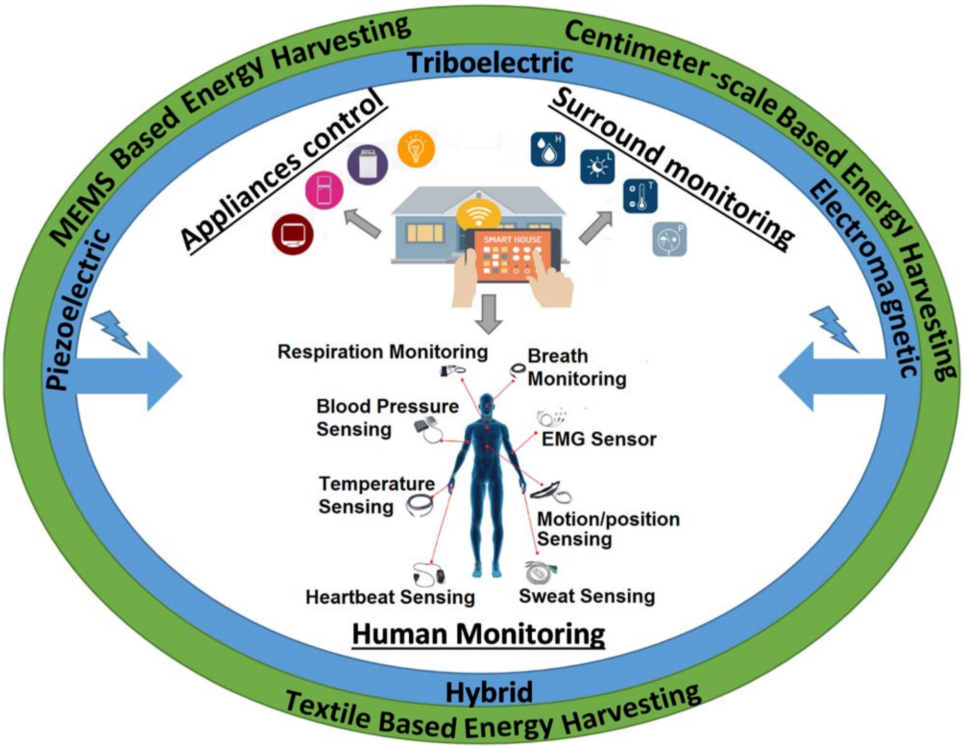

Figure 1. Illustration of smart home systems utilizing micro/nano sensors and energy harvesters.

monitoring in houses (e.g., temperature, humidity, and gas leakage detection), and the rest is adopted for human activity tracking (e.g., healthcare monitoring) as shown in figure 1. Micro/nano sensors are miniature devices that can convert changes in non-electrical signals such as temperature, pressure, humidity, motion, acoustic to changes in electrical signals. They have the advantages of small size and mass, high sensitivity, low power consumption, and low cost [1]. Therefore, micro/nano sensors have received tremendous research attention and have shown significant development in the past two decades [2, 3]. In particular, the small size of micro/nano sensors enables them to contribute to wireless sensor networks and IoT development by consuming only a tiny space. And the use of batteries can fulfill the power demand of these micro/nano sensors in terms of their low power consuption. However, when the wireless sensor network possesses a massive number of distributed sensor, a considerable number of batteries will be needed to power these sensors [4]. Moreover, the batteries have a limited lifetime and need continuous monitoring, replacing, and recycling, which would be an arduous task and uneconomical.

Thanks to micro/nano sensors' low power consumption, which can be down to micro-watts [5, 6], energy harvesters can potentially charge micro/nano sensors without the need for batteries. The energy harvesting approach as a good solution to the power problem of the IoT [7, 8] has been widely investigated in recent years to replace batteries to push forward the realization of self-sustainable IoTs and systems. The required power for micro/nano sensors can be obtained by harvesting one or more of the surrounding environmental energy sources. The mechanism of the energy harvesters varies regarding the application scenarios and the available energy sources, such as mechanical energy [9, 10], solar energy [11, 12], thermal energy[13, 14], etc. Since mechanical motions such as noise, surfaces and floor vibrations, human motions, etc, are the most available energy sources in the house. Motion energy harvesting systems have been considered as the most suitable power source for home applications, which can be ranged in size from micro-scale (MEMS) [15–17] to centimeter-scale [18] (figure 1). Motion energy harvesting systems rely on three main transduction mechanisms, which are electromagnetic [19], piezoelectric [20], and electrostatic [21]. One recent advanced technology of electrostatic transduction is the triboelectric nanogenerator (TENG). When two dissimilar materials come into contact in TENG, opposite triboelectric charges are generated on the surfaces. Those charges can generate an electrical potential when a mechanical force separates the surfaces. TENGs can be implemented with different working modes, such as contact-separation mode [22], sliding mode [23, 24], single-electrode mode [25] and free-standing mode [26]. Since the physical contact between objects and the human body in the surrounding area is abundant during daily life, TENG can be an effective energy harvesting technology for smart home sensors. Nevertheless, the selection of the energy harvester shape and size, as well as the transduction mechanism depends on the application, the natural of the input motion, and the harvesting location (figure 1).

When it comes to human body energy harvesting or human body motion sensing, intrinsically flexible energy harvesters and sensors are preferable for better wearable comfortability. Therefore, new energy harvesting devices and self-powered sensors based on textiles have been invented [27–29] in the form of piezoelectric nanogenerators (PENGs), TENGs, and hybrid of both. Textile-based devices are advantageous for smart home applications because they are lightweight, very flexible, and wearable, providing a sufficient degree of comfortability to the body during daily activities.

Moving forward, the IoT and smart home are evolving towards a more intelligent and integrated system with the on-going multidisciplinary research on sensors, energy harvesters, wireless transmission technologies, artificial intelligence (AI), etc. With the rapid development of AI technology, the fusion of AI and IoT, i.e., Artificial intellegance of things (AIoT), becomes feasible to improve human-machine interactions, enhance data analytics, refine decision-making processes, and perform intelligent tasks. Compared with IoT systems, AIoT systems can analyze the collected data and make decisions without human intervention once the system (including the signal acquisition module, data transmission module, and data analysis module) is built up. The AIoT would also shape the future personal healthcare technologies by providing comprehensive physical and chemical monitoring through the body sensor network, advanced data analysis via AI, and eventually prompt treatment through the surging neural interfaces, skin patches, microneedles, etc.

In this paper, we review the progress in micro/nano sensors and energy harvesting aiming at future AIoT-based smart home applications. Firstly, the conventional building blocks (MEMS sensors and MEMS energy harvesting) are presented, followed by discussing the new building blocks (flexible and wearable energy harvesting systems, self-powered sensors, and AI). Specifically, the new building blocks consist of self-powered sensors and energy harvesting based on PENGs and TENGs in the form of textiles are then described in detail. After that, the integration of sensors with energy systems for self-sustainable IoT systems aiming at smart home applications is demonstrated by reviewing recent self-sustainable IoT systems. Finally, future research directions in AIoT based smart home such as smart home control, healthcare technology, and wearable photonics as a complementary technology for wearable electronics are discussed.

2. Conventional building blocks of micro/nano sensors and energy harvesting systems

Micro-electromechanical systems (MEMS) usually refers to a collection of micron-level feature sized mechanical structures, sensors, actuators, and electronics [30]. The early version of MEMS devices appeared in the 1950s and developed from integrated circuit technology [31]. In the following decades, the research on MEMS devices has grown rapidly as the bulk silicon micromachining technology and surface micromachining technology gradually mature [32–34]. Researchers in succession reported many milestones in MEMS application research during this period. For instance, Nathanson *et al* developed a resonant gate transistor based on silicon technology in 1967 [35]; The Hewlett-Packard company invented a MEMS thermal inkjet printer head in 1979 [36]; Spotts *et al* fabricated a disposable blood pressure sensor based on a piezoresistive-type silicon strain gauge in 1982 [37]; Later in 1993, Younse reported a new projection display utilized a chip-based micromirror array [38]; And in the 1990s, MEMS accelerometers were commercially used in the automotive industry [39–41]. Until now, various kinds of MEMS devices have developed, like ultrasonic transducers [42–47], RF devices [48–52], biochemical sensors [53], and so on. All these MEMS devices can be mainly divided into electrostatic MEMS [54–56], piezoelectric MEMS [57–63], piezoresistive MEMS [64–66], electromagnetic MEMS [67–70], optical MEMS [71–75], and thermal MEMS [76–78] according to the driving and sensing mechanism.

2.1. MEMS based sensors

Taking the advantages of small size, high sensitivity, low power consumption, and easy to integrate [79–81], MEMS sensors are now widely used in people's daily lives, as well as in smart homes. Firstly, the use of MEMS sensors can cost-effectively detect indoor environmental conditions, such as temperature [82, 83], humidity [84–87], air pressure [88], light [89–91], PM2.5 [92], and various gases [93–95] that may affect the human health. As shown in figure 2(a), Le *et al* reported surface acoustic wave (SAW) humidity sensors based on uniform graphene oxide (GO) film [96]. The humidity sensor possesses high sensitivity, high stability and repeatability, fast response and recovery speed, enough to meet the application needs in smart homes. Besides, MEMS devices also play important roles in the convenience and safety aspects of smart homes. MEMS microphones can be used to recognize human voices, realize communication between human and smart electronic devices [97, 98], and also can act as a hearing aid for hearing impaired people [99]. For the safety aspect of smart homes, Lu *et al* developed an ultrasonic fingerprint sensor based on complementary metal-oxide-semiconductor (CMOS) compatible piezoelectric micromachined ultrasonic transducer as shown in figure 2(b) [100]. This fingerprint sensor can be integrated into smart electronic devices and doors as an unlock switch.

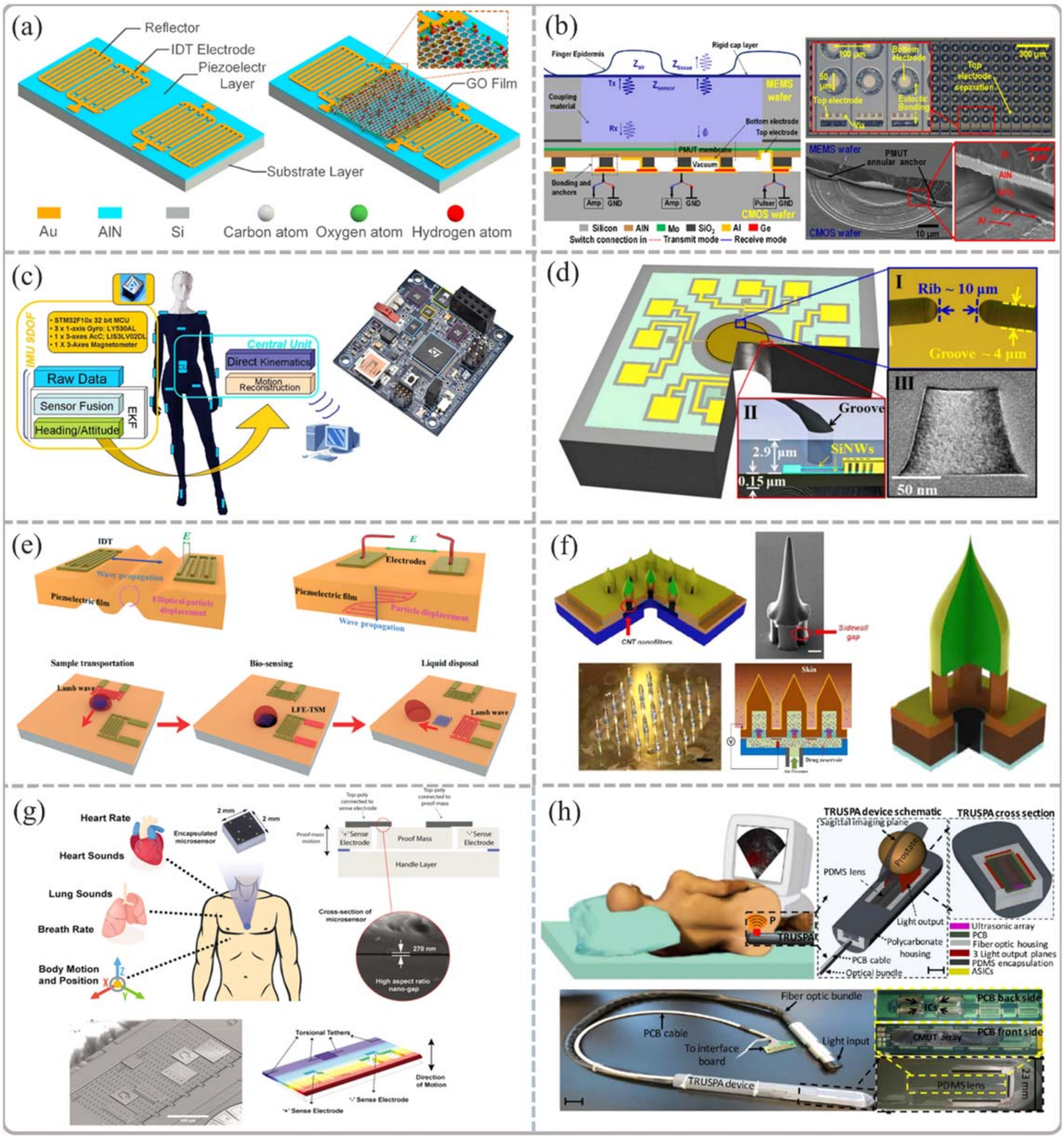

Figure 2. (a) Graphene oxide-based surface acoustic wave (SAW) humidity sensor. Reproduced from [96], CC BY 4.0; (b) Piezoelectric micromachined ultrasonic transducer (PMUT) based ultrasonic fingerprint sensor. Reprinted from [100] with the permission of AIP Publishing; (c) Wearable human body motion capture system based on MEMS inertial measurement unit (IMU). © [2011] IEEE. Reprinted, with permission, from [101]; (d) Silicon nanowires (SiNWs) embedded annular diaphragm piezoresistive pressure sensor. © [2014] IEEE. Reprinted, with permission, from [102]; (e) Flexible acoustic device integrated with microfluidic and biosensing functions. Reproduced from [103] CC BY 3.0; (f) Microneedle array for drug delivery. © [2014] IEEE. Reprinted, with permission, from [104]; (g) Accelerometer contact microphones for longitudinal monitoring of mechano-acoustic cardiopulmonary signals. Reproduced from [105] CC BY 4.0; (h) Human prostate ultrasound and photoacoustic imaging using capacitive micromachined ultrasonic transducer (CMUT) array and optical components. Reprinted with permission from AAAS [106].

With constant attention to healthcare technology and the rise of the aging population in many countries, MEMS devices have become the indispensable technology in healthcare applications including the monitoring of daily activities of the elderly, e.g., fall detection at home. MEMS inertial sensors mainly include accelerometers [107–112] and gyroscopes [113] and are the typical MEMS devices used in healthcare. The MEMS inertial sensors are usually integrated with the detection circuit as an inertial measurement unit (IMU), as presented in figure 2(c) [101], which can be further integrated into electronic devices such as mobile phones and watches, or directly be worn on the human body for physical activity measurements [114], fall detection [115], heart rate and breath monitoring [116] and sleep apnea detection [117]. As in the case of MEMS inertial sensors in human motion monitoring, MEMS pressure sensors also provide an effective way for human blood pressure monitoring [118–120], and the performance of MEMS pressure sensors continues to improve with the deepening of their applications. Zhang *et al* embedded silicon nanowires (SiNWs) into the annular grooves of a circular diaphragm to achieve a piezoresistive pressure sensor with remarkable improvement in pressure sensitivity [102], as elucidated in figure 2(d). The high-profile point-of-care-testing (POCT) technology offers a quick approach to diagnose diseases and monitor the health status of the patients at home [121–123], and microfluidic devices are an indispensable part of the POCT technology [124–126]. Recently, a single flexible acoustic device integrated with microfluidic and biosensing functions was reported by Tao *et al* [103]. Hybrid wave modes can be generated by the device, as indicated in figure 2(e), where lamb wave mode is used for fluidic actuation, and biosensing mainly depends on thickness-shear wave mode. Based on the results of POCT, the corresponding drug delivery can be carried out through microneedles to achieve personalized therapies to patients [127–131]. Figure 2(f) shows a microneedle array integrated with carbon nanotube nano filters used for transdermal drug delivery developed by Wang *et al* [104]. Under the action of air pressure or electric field, the drug molecules can be selectively delivered into the subcutaneous tissues through the microneedle array. A non-invasive medical diagnosis can also be performed at home with MEMS devices, such as using MEMS acoustic devices to detect muscle disorders [132], blood flow rate [133], and other physical signs [134]. Gupta *et al* integrated an accelerometer and a contact microphone into one wearable device, as illustrated in figure 2(g). This device can precisely detect mechano-acoustic physiological signals from the human heart and lungs, thereby realizing real-time monitoring of the human's cardiopulmonary health [105]. Meanwhile, combining MEMS devices with other transducers can endow MEMS devices with more powerful functions in healthcare. As shown in figure 2(h), Kothapalli *et al* combined wide bandwidth, high signal-to-noise ratio capacitive micromachined ultrasonic transducer (CMUT) arrays with optical components to realize an integrated ultrasound and photoacoustic device, which can be used for transrectal imaging of human prostate [106].

2.2. MEMS based energy harvesters

The rapid development of smart homes has dramatically increased the need for the types and quantity of sensors [135–137], and a large number of applications of sensors have brought about energy consumption issues. Although MEMS sensor nodes with low power consumption can be powered by small button batteries [138], regular replacement of the batteries of these sensor nodes will also bring considerable economic costs. The use of MEMS-based energy harvesters is considered to be a feasible way to solve the above problem, because they can collect the energy from ambient vibrations (human body motion or hand sharking) to charge the batteries [139, 140], thereby extending the lifetime of the sensor nodes. Typical MEMS energy harvesters include electrostatic energy harvesters [141], electromagnetic energy harvesters [142–145], and piezoelectric energy harvesters [146–148]. Electrostatic energy harvesters convert the external vibrations into the devices' varying capacitance through different configurations (e.g., in-plane overlap structure, in-plane gap-closing structure, and out-of-plane gap-closing structure) of the capacitor electrode plates [149]. Figure 3(a) presents a 2D in-plane MEMS electrostatic energy harvester [150], which utilizes capacitor electrode plates with a rotational in-plane overlap structure to harvest kinetic energy from ambient planar vibrations. For electromagnetic energy harvesters, the ambient vibrations are generally converted into the relative motion between conductive coils and permanent magnets in the devices and then translated into electrical power through the electromagnetic induction effect [151–154]. As shown in figure 3(b), Liu *et al* assembled a stationary magnet with moveable metal coils patterned on micromachined spring-mass structures to achieve a wafer-scale in-plane electromagnetic energy harvester [155]. They broadened the operation range of the device by incorporating four small suspension mass-spring structures. Compared with the other two types of energy harvesters, piezoelectric energy harvesters have the advantages of simple configuration and high electromechanical coupling effect [156, 157]. Piezoelectric energy harvesters use the direct piezoelectric effect of piezoelectric materials to convert energy from ambient vibrations into electrical energy. Their typical structure is illustrated in figure 3(c) [158–161], mainly composed of a piezoelectric microcantilever with a proof mass fixed at its free end. Since the above three energy harvesters (i.e. electrostatic, electromagnetic, and piezoelectric) have different advantages [162], integrating different mechanisms into one energy harvester will bring potential benefits, e.g., higher output energy. Yang *et al* reported a hybrid piezoelectric and electromagnetic energy harvester, which consists of a piezoelectric cantilever with a permanent magnet fixed at its free end, and a substrate integrated with metal coils, as displayed in figure 3(d) [163]. In addition to vibration energy, ambient thermal energy (e.g., the heat from the human body) can also be collected and converted into electrical energy by using MEMS thermoelectric power generators [164–166]. Figure 3(e) shows a thermoelectric power generator designed by Xie *et al* [167], in which the thermopiles (core components) are embedded between the top and bottom cavities of the device. The thermopiles' hot and cold junctions are used to sense the temperature difference between the human body skin and ambient air, and realize energy conversion through the Seeback effect. Besides, acoustic energy harvesters are also wildly used for non-contact energy delivery [168–170]. They can collect energy from the vibrations of external acoustic/ultrasonic waves, and are suitable for occasions where motion energy and thermal energy are unstable or difficult to collect, such as forming a self-powered system with implanted biomedical devices. Figure 3(f) illustrates the principle of non-contact acoustic energy transfers. The ultrasonic energy harvester based on a PZT PMUT array is integrated with a pacemaker and placed around the heart [171]. When an external

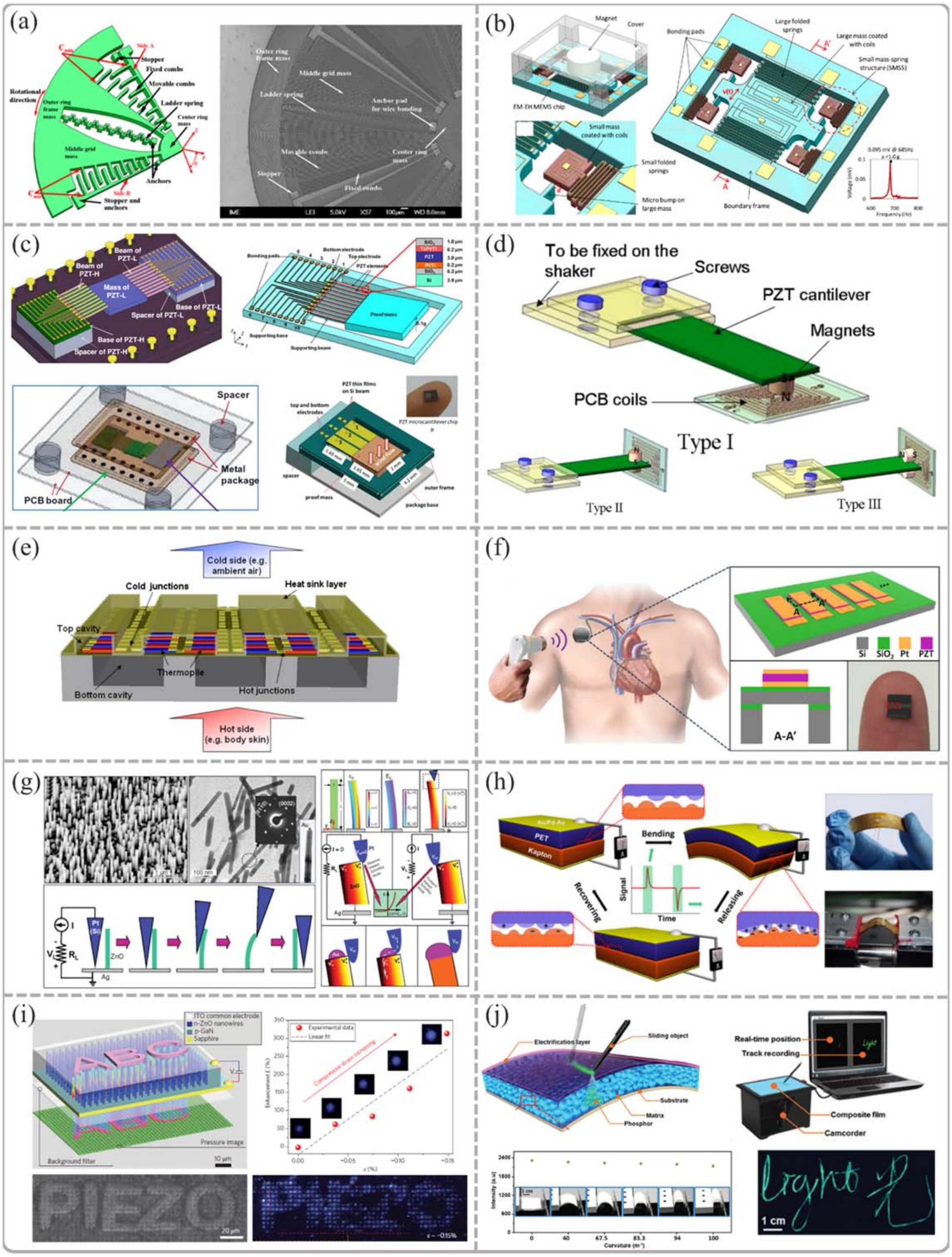

Figure 3. (a) In-plane MEMS electrostatic energy harvester using capacitor electrode plates with a rotational in-plane overlap structure. Reproduced from [150] © IOP Publishing Ltd. All rights reserved; (b) Wafer-scale MEMS electromagnetic energy harvester with broadband operation range [155]; (c) Various kind of MEMS piezoelectric energy harvester. Reprinted from [158–161] Copyright (2011), with permission from Elsevier; (d) MEMS hybrid piezoelectric and electromagnetic energy harvester. Reprinted with permission from [163] Copyright SPIE, Micro/Nanolithography, MEMS, MOEMS 9 023002; (e) MEMS thermoelectric power generators with top and bottom cavity configuration. Reprinted from [167] with the permission of AIP Publishing; (f) MEMS piezoelectric ultrasonic energy harvester for non-contact energy delivery to implantable biomedical devices. Reproduced from [171] CC BY 4.0; (g) Zinc oxide nanowire arrays based piezoelectric nanogenerators. Reprinted with permission from AAAS [172]; (h) Typical structure of a triboelectric generator. Reprinted from [173] Copyright (2012), with permission from Elsevier; (i) Pressure distribution imaging using the piezo-phototronic effect. Reprinted by permission from Springer Nature Customer Service Centre GmbH: Springer, Nat. Photonics 7 752-8 (2013) [174]. (j) Dynamic triboelectrification-induced electroluminescence. John Wiley & Sons. © 2016 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim [175].

ultrasound head approaches the human body and emits ultrasound waves, the ultrasonic energy harvester will convert the vibration energy of ultrasonic energy into electrical power to charge the pacemaker's battery and extend its lifetime.

Apart from various MEMS energy harvesters, the microsensor nodes in a smart home can also be powered by many other forms of energy harvesters. Nanogenerators based on zinc oxide nanowire arrays that can collect ambient low-frequency vibration energy is one of them [176]. The first zinc oxide nanowire arrays based piezoelectric nanogenerator was reported by Wang *et al* [172], and its structure and working principle are shown in figure 3(g). The zinc oxide nanowires with coupling properties (piezoelectric and semiconducting) and the Schottky barrier formed when they contact metal tip are the key to the nanogenerator's energy conversion. In recent years, triboelectric generators as a new type of energy harvester have received extensive research attention. As schematically shown in figure 3(h), the triboelectric generator is formed by assembling two polymer sheets with different triboelectric characteristics [173]. When the two triboelectric layers contact, equal charges with opposite signs will be generated at two sides due to triboelectrification, and the charges can be collected by the metal electrodes deposited on the top and bottom surfaces of the structure upon the separation of the two triboelectric layers due to electrostatic induction.

Interestingly, both the piezoelectric effect and triboelectric effect can be utilized for self-powered lighting and visualization. As shown in figure 3(i), a pressure sensor array (with a pixel density of 6350 dpi) integrated with a light-emitting diode (LED) array was demonstrated by Z.L. Wang's group in 2013 [174]. The electroluminescence of each pixel composed of a single n-ZnO nanowire/p-GaN LED is determined by the local strain due to the piezo-phototronic effect. Specifically, the voltage generated in the n-ZnO nanowires by the piezoelectric effect in response to external pressure drives the GaN LED. When the mold patterned with the word 'piezo' touches the sensor array, the blue light luminescence very well reflects the strain profile. A triboelectric self-powered electroluminescence device counterpart was reported in 2016 (figure 3(j)) [175]. The high voltage generated by the triboelectric effect induces the luminescence of the underlying phosphor. Due to the broad material selection of triboelectric devices, the presented self-powered electroluminescence device possesses good flexibility. The luminescence intensity shows negligible degradation when the curvature increases from 0 m-1 to 100 m-1. The application for writing visualization is demonstrated by the real-time recording of writing the character 'Light 光' through a computer interface.

2.3. Centimeter-scale based energy harvesters

In addition to MEMS-based energy harvesters, plenty of centimeter-scale energy harvesters (Cm-EHs) are presented [177–180]. Cm-EHs can be more suitable than MEMS based ones for some cases. Generally, cm-EHs have a simple fabrication method. They can be assembled and fabricated using conventional methods [177] compare to MEMS-scale ones which need more sophisticated expensive equipment, and more complicated fabrication steps. Higher output power could be expected from cm-EHs [181]. Thus, they are more appropriate for the applications of higher power demand with relatively large allowable size [182]. More complicated mechanical systems/mechanisms for better performance [183, 184], or matching lower frequencies [185–187] can be easily fabricated in cm-scale.

Many sources of harvestable motion or energy are available in the house. Among them are the surface vibrations, which can be due to the motion of nearby people or nearby vehicles moving outside the house, human motion inside the house, Light and noise energies, wind energy, etc. All those types of energy can be simply harvested using cm-EHs. Figure 4 shows samples of cm-EH that can deal with those types of energy. Figure 4(a) and (b) present two prototypes for harvesting surface vibrations. Basically, surface vibrations can be harvested using simple resonators. The resonator should be tuned to the input frequency to reach the optimum performance. However, the input vibrations are usually random and unsteady. A single-frequency resonator can cover a very narrow band of vibration frequencies. If the input frequency lies slightly away from this band, the power drop drastically. Gupta *et al* [188] (figure 4(a)) introduce a broadband energy harvester based on a non-linear polymer spring and Electromagnetic/Triboelectric hybrid mechanism. The broadband frequency is achieved by utilizing a polymer spring that exhibits multimodal energy harvesting and mechanical stoppers that introduce a non-linear stiffening effect [139]. Unlike many previously presented broadband EHs, this prototype can reach broadband energy harvesting at a wide range of input accelerations (in the range of 0.1 g to 2 g). Besides, Dhakar *et al* [189] describe a broadband energy harvester based on the triboelectric mechanism using a cantilever to generate triboelectric charges between contact surfaces (figure 4(b)). This mechanism introduces nonlinearity in the cantilever, which promotes the broadband behavior of the triboelectric energy harvester. A peak output power of 0.91 μW is achieved at an acceleration of 1 g. The amplitude limiter design allows the bandwidth to increase, so that it can reach 22.05 Hz at 1.4 g.

For human motion energy harvesting, there are also many reported prototype designs based on piezoelectric, electromagnetic, and triboelectric transductions, or a hybrid of both. One of the recent prototypes

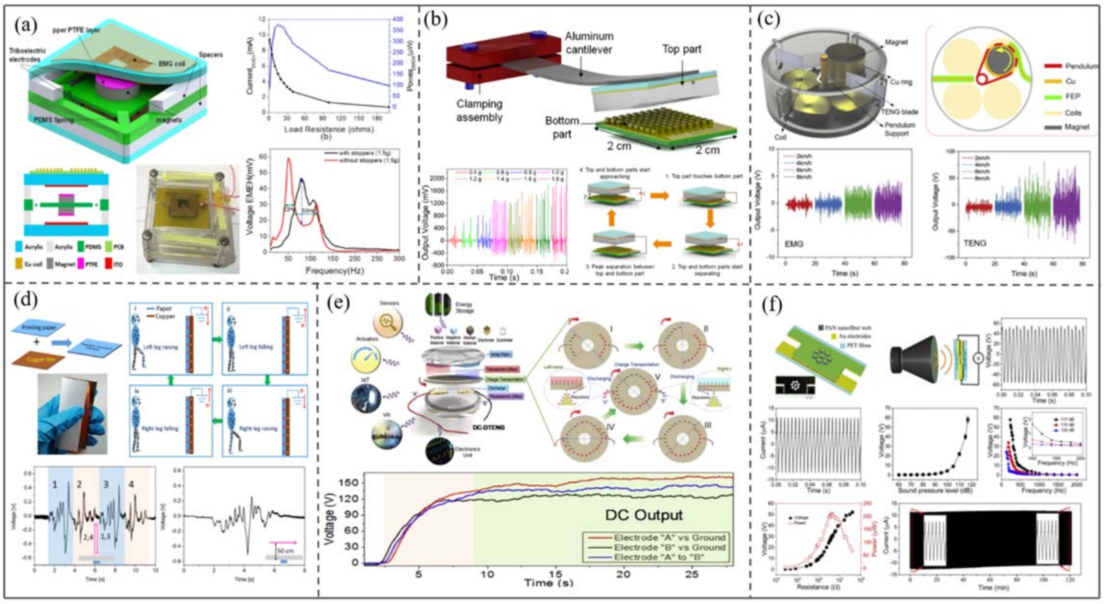

Figure 4. Centimeter-scale motion energy harvesters (a) broadband energy harvester based on a non-linear polymer spring and Electromagnetic/Triboelectric hybrid mechanism. Reproduced from [188] CC BY 4.0; (b) broadband energy harvester based on triboelectric mechanism and implemented by oscillating cantilever. © [2015] IEEE. Reprinted, with permission, from [189]; (c) Rotational pendulum triboelectric—electromagnetic hybrid generator. Reprinted from [190] Copyright (2019), with permission from Elsevier; (d) Noncontact mode TENG for human motion energy harvesting and monitoring. Reprinted from [191] Copyright (2020), with permission from Elsevier; (e) DC triboelectric nanogenerator by charge transportation for next-generation IoT and real-time virtual reality applications. Reprinted from [192] Copyright (2020), with permission from Elsevier; (f) Sound noise energy harvester based on electrospun polyacrylonitrile (PAN) nanofibrous membranes. Reprinted from [193] Copyright (2020), with permission from Elsevier.

is that presented by Hou *et al* [190]. They proposed a rotational pendulum triboelectric-electromagnetic hybrid generator that can harvest mechanical vibrations of frequency less than 5 Hz (figure 4(c)). The prototype consists of four stacked disk-shaped rotor magnets that can oscillate under the gravity or inertia force with a wideband frequency range. Electromagnetic generator (EMG) is achieved by placing 4 stator coils in the way of the pendulum oscillation, while the triboelectric generator (TENG) is realized through the contact-separation between a copper ring attached to the rotor and fluorinated ethylene propylene (FEP) flexible strips attached to the frame. In fact, TENGs are considered as promising energy harvesting technologies. They are very suitable for low frequency irregular mechanical motions with a broad range of frequencies. Besides, they are flexible, low cost, lightweight, easy to fabricate, and reliable with high output voltage. However, the main drawback of TENGs is the low output current. On the other hand, EMGs generally can give a high output current due to low internal impedance. Thus, coupling both generators can be a good approach for high harvesting performance from unsteady—low frequency motion. Many hybrid TENG—EMG systems are presented in the literature [194–197]. However, the prototype presented by Hou *et al* [190] based on rotation motion shows a good performance with human motion and ocean waves. It shows a maximum power density of 3.25 W m^{-2} and 79.9 W m^{-2} at a frequency of 2 Hz and 14 cm amplitude by the TENG and EMG, respectively. Another way of harvesting human motion in the house is by the movement of the whole or part of the body towards and away from the walls. TENG can be utilized to harvest the body movement by considering the body as one of the triboelectric layers and attaching the other layer to the wall. A recent study of this mechanism is presented by Xi *et al* [191] (figure 4(d)), which can be used as an energy harvester or self-powered human motion monitoring. They demonstrated a single electrode TENG working in a non-contact mode. The human body acts as one of the TENG layers, and the other layer is composed of a printing paper together with a metallic electrode film. The proposed TENG prototype can charge a capacitor of 4.7 μF to 2 V when a human subject is stepping at the same place with a distance of around 30 cm against four A4 sized of the proposed TENGs in series connection for 20 min.

TENG and other motion energy harvesting techniques usually produce an AC output voltage/current [198]. However, a DC output current is very necessary for IoT applications and other electronic devices. To obtain a stable DC output from TENG, a rectifier bridge in conjunction with a power management circuit is employed. This usually affects the system portability by increasing the total size of the system, as well as increases the power losses and consequently decrease the overall system efficiency. Some unique ways are proposed to produce a DC output directly from TENG. For instance, Zhu *et al* [192] (figure 4(e)) developed a novel triboelectric mechanism using dual intersection TENGs and charge transportation for DC output to directly power the next-generation self-sustained IoT and its real-time control in VR. This mechanism is Inspired by ancient waterwheel transport water and P-N junction theory. They employed tribo-polarity reversal porous material as charges transportation carrier sliding among the ultra-negative and ultra-positive dielectric materials, and the charges were continuous unidirectional transported and repelled discharge onto electrodes for DC output without a rectifier bridge. An output DC voltage is obtained of up to 5 times higher than the air breakdown in conventional TENG, and a charging rate of up to 2 times higher than that of a TENG of the same materials.

Noise is considered as unwanted loud sound that causing discomfort or unpleasant feelings whether inside and outside the house. It can be due to the nearby railways, highways, airports, machine workshops, etc. Since this kind of sound is quite high and carries so much energy, it can be harvested and converted into a useful energy source. Several technologies have been demonstrated to harvest sound energy. Among them are the piezoelectricity [199, 200] and triboelectricity [201, 202], which received more attention because of their relatively high conversion efficiency and larger output power density. Triboelectric devices mainly show high output voltage. However, to ensure a responsive contact and separation, the inter-distance between the triboelectrification layers has to be controlled precisely. Piezoelectric devices are easy to prepare and do not need to control the inter-distance between electrodes precisely. Shao *et al* [193] (figure 4(f)) utilized electrospun polyacrylonitrile (PAN) nanofibrous membranes for the first time to convert low-mid frequency noise into electricity with high output power. A thing PAN fibrous membrane is sandwiched between two metal-coated plastic film electrodes. Under 117 dB sound (frequency 100–500 Hz), a 3×4 cm^2 PAN membrane can generate a peak electrical of 58 V and 12 μA, with a maximum power of 210.3 μW (surface power density of 17.53 μW cm^{-2}). This output is much higher than that generated by PVDF nanofiber counterpart, and is sufficient to power some electronic or portable devices after rectification.

3. New building blocks of self-powered sensors and energy harvesting systems

3.1. Textile based self-powered chemical sensing

As we know, the toxic gas monitoring plays an important role in industry security. Existing approaches (e.g., resistors) suffer from the requirement of external power supply, which may limit the human mobility. Hence, the self-powered piezoelectric gas sensor may mitigate the limitation. A group from Northeastern University developed a self-powered smelling electronic skin (e-skin) by employing a piezoelectric gas sensor array (figure 5(a)) [203]. The multifunctional e-skin was composed of bare ZnO nanowires for humidity sensing, Pd/ZnO nanowires for ethanol sensing, CuO/ZnO nanowires for hydrogen sulfide sensing, TiO_2/ZnO nanowires for methane sensing, which promoted the practical application in the smart home occasion. Simply driven by daily human motions, the e-skin can operate independently without an external power supply, in which the piezoelectric signal was significantly influenced by the surrounding atmosphere. Apart from environmental monitoring, there is a requirement for the deep understanding of chemical events of the human body to capture comprehensive information of health status. As provided in figure 5(b), Han et al reported a self-powered multifunctional sweat sensing e-skin based on the piezoelectric-enzymatic coupling effect [204]. The four piezo-biosensing units enabled glucose, uric acid, lactate, and urea detection from sweat, respectively. The corresponding oxidase functionalized ZnO nanowire would generate signals when biomarkers combined with immobilized oxidases by applying mechanical deformation. The electronic skin achieved noninvasive and self-sustainable perspiration analysis, facilitating its use in personalized healthcare monitoring. Meanwhile, the PENG also shows great potential in smart home-related applications through the capability of environmental monitoring. Correspondingly, Zhu et al developed a TENG for melamine (Mel) detection (figure 5(c)), in which the Aluminum (Al) surface was coated with a layer of Mel to enhance the output. Via etching the film of Mel, the nanostructure was created and contacted with another layer of Al. Owing to Mel's strong electron negativity, the exposure of the sensor to Mel would greatly enhance the output of the triboelectric sensor. A linear range (1 ppb-500 ppb) was obtained with a low detection of limit (0.5 ppb) [205].

In addition to the PENG that offers self-sustainable response to external chemical stimulus, benefitting from the low cost, light weight, broad material choices, simple mechanism, the TENG has also attracted increasing attention from the academic community since 2012 [173]. Generally, the TENG either serves as the power source or the self-powered sensor. As shown in figure 5(d), a self-powered electrochemical system was developed by Chen *et al*. The electrochemical lactate sensor was consisted of the PdAu nanoparticle modified carbon fibers (anode), and Pt decorated carbon fibers (cathode) in which the L-lactate oxidase was immobilized on the surface of anode [206]. The TENG enabled by the microstructured PDMS and Gelatin pairs was used to supply power to the as-fabricated electrochemical sweat sensor. Besides, the self-powered TENG sensor is another major branch in the TENG-related domain. As depicted in figure 5(e), Khandelwal *et al* introduced an attractive material-metal organic framework (MOF) to enhance the triboelectric sensor performance [207]. Observing from the 3D

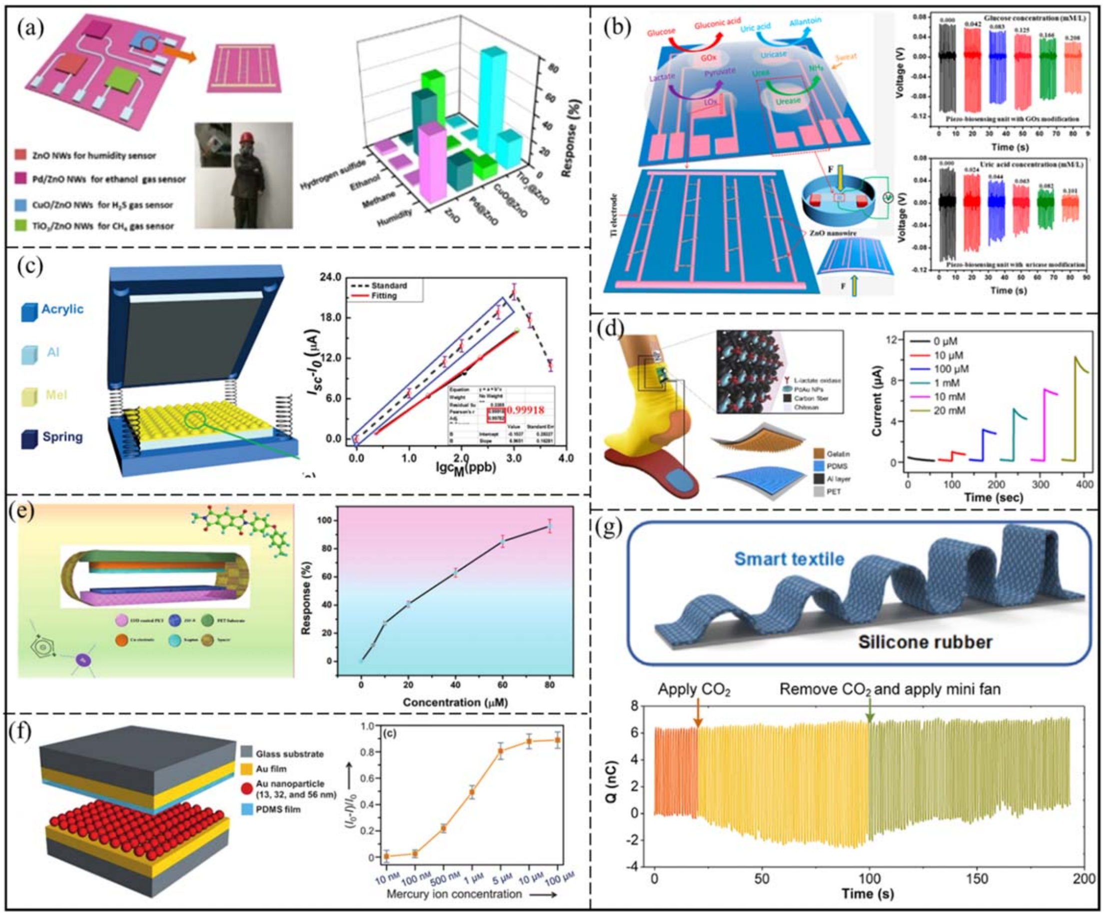

Figure 5. Representative works of PENG and TENG for healthcare monitoring and chemical sensing. (a) the self-powered smelling e-skin based on the piezo-gas-sensor array. Reprinted from [203] Copyright (2018), with permission from Elsevier; (b) the multifunctional sweat sensing e-skin based on piezoelectric-enzymatic coupling effects. Reprinted with permission from [204] Appl. Mater. Interfaces 9 29526-37, Copyright (2017) American Chemical Society; (c) Mel enhanced TENG for Mel detection [205] John Wiley & Sons. © 2016 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim; (d) the electrochemical lactate system powered by TENG. Reprinted from [206] Copyright (2017), with permission from Elsevier; (e) the MOF-based TENG for tetracycline detection [207] John Wiley & Sons. © 2019 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim; (f) the self-powered triboelectric nanosensor for Hg^{2+} ion Detection [208] John Wiley & Sons. Copyright © 2013 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim; (g) the triboelectric textile for CO_2 sensing. Reprinted from [209] Copyright (2019), with permission from Elsevier.

architecture of MOF-TENG, the MOF family ZIF-8 vertically contacted with Kapton. Interestingly, the ZIF-8 was highly selective to tetracycline, in which the benzene ring of tetracycline interacted with the imidazole ring of ZIF-8 via π–π interactions. Upon contact-separation, increased tetracycline concentration would alter the charge transferred. On the other hand, there are some works that use triboelectric self-powered sensors to sense the hazard substance, which should facilitate its use in the surrounding monitoring and create great potential in the smart home scene. For example, Wang and his co-workers demonstrated a self-powered triboelectric nanosensor for mercury ion detection (figure 5(f)) [208]. They assembled Au nanoparticles onto the metal surface to improve the performance of TENG and then further modified these metallic particles via 3-mercaptopropionic acid (3-MPA) molecules decoration that was highly sensitive and selective to Hg^{2+} ions. The as-fabricated self-powered ion sensor showed a linear range from 100 nM to 5 μm with a detection limit of 30 nM. Finally, surrounding atmosphere monitoring is of vital importance for smart home-related applications. CO_2, as a critical indicator of air quality, is always an interesting target in the gas sensing field. As shown in figure 5(g), Lee's group initiated a textile triboelectric sensor for CO_2 monitoring [209]. The poly(3,4-ethylenedioxythiophene) polystyrenesulfonate (PEDOT:PSS) coated textile showed good performance not only on the daily human activity tracking but also on PEI-based CO_2 sensing by contacting with PTFE. The unique soft characteristic of textiles provided a great possibility to integrate sensors on the cloth, achieving improved wearability and portability.

3.2. Textile based self-powered physical sensing

For healthcare applications, PENG and TENG sensors are helpful in body motion detecting, voice repeating, and even pulse or heartbeat monitoring, etc [210–215]. For instance, Fan *et al* developed a high-pressure sensitive

Figure 6. Various advanced TENG and PENG for the wide range sensing applications of healthcare, HMI and smart home. (a) Schematic diagram of a machine-knitted textile sensor (up), and photographs of arterial pulse waves (down). Reprinted with permission from AAAS [216]; (b) Self-powered system for autonomous tumor inhibition and cancer therapy. Reprinted with permission from [217] Copyright (2020) American Chemical Society; (c) Device structure of a piezoelectric 3D textile with pre-strained monofilament (up), and photographs of the device detecting signals of voice, pulse and respiration (down). Reprinted from [218] Copyright (2020), with permission from Elsevier; (d) Synthesis process of PEDOT:PSS cotton sock using piezoelectric and triboelectric mechanism for energy harvesting and healthcare monitoring. Reprinted with permission from [219] Copyright (2019) American Chemical Society; (e) Demonstration of super-elastic liquid metal fibers and textiles based on triboelectric mechanism with self-powered breathing monitoring and gesture sensing capabilities. Reproduced from [220] CC BY 4.0; (f) Schematic drawing of gloved-based interface for applications in real/cyber space. Reprinted from [221] Copyright (2019), with permission from Elsevier. (g) A ZnO nanowires-based bedding for imperceptible sleep monitoring for sleep healthcare and early disease diagnosis. Reprinted from [222] Copyright (2020), with permission from Elsevier; (h) A 3D schematic of a piezoelectric hollow microstructured pressure blanket for noncontact heartbeat and respiration monitoring applications. Reprinted with permission from [223] Copyright (2018) American Chemical Society; (i) Schematic diagram showing the bedsheet with triboelectric arched nanogenerator arrays for real-time and self-powered sleep behavior monitoring [224] John Wiley & Sons. © 2017 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim ; (j) Schematic of a highly shaped adaptable resilient 3D braided textile (left), and self-powered identity recognition carpet for safeguarding entrance and early warning of intrusion. Reproduced from [225] CC BY 4.0; (k) Schematic diagram of a transparent triboelectric nanogenerator for energy harvesting and home windows raindrop sensing for smart home applications. Reprinted from [226] Copyright (2020), with permission from Elsevier.

(7.84 mV·Pa−1) and comfortable textile TENG sensor array, which exhibits wide working frequency bandwidth (up to 20 Hz), fast response time (20 ms), and advantages of stable (over 100,000 cycles) and washable ((>40 washes). The machine-knitted textile is suitable for monitoring the epidermal and respiratory physiological signals. In addition, a health monitoring system is developed for some chronic diseases, including cardiovascular disease and sleep apnea syndrome, etc (figure 6(a)) [216]. Apart from monitoring and detecting disease, many works are focused on therapy as shown in figure 6(b) [217]. The device shows a self-powered photodynamic therapy system (s-PDT) with a bimorph piezoelectric nanogenerator. By harvesting from body motion, the PDT is powered to stimulate the pulse light mode for inhibiting the growth of tumor cells. The s-PDT device is implanted in mice for experiment and which realizes effective tumor tissue suppression and killing, i.e., an 87.46% tumor inhibition rate is achieved after 12 days of continuous miniature LED stimulation. In this way, the self-powered system may be used for cancer treatment in future clinical applications. Recently, Ahn *et al* reported a wearable piezoelectric sensor for multi-local strain detecting, as illustrated in figure 6(c), which consists of 3D textile monofilament with pre-strain and PVDF film in between [218]. The pre-strained textile structure can amplify the piezoelectric output voltage of sensing strain results up to 5 times. The good pressure sensitivity of the device performs multiple applications on human motion and healthcare, which means it not only can detect joint (neck, elbow, and knee) movement, fingertip pressure, and gait based on the tensile and compression signals, but also can fulfill voice repeating, respiration and blood pressure based on the vibration signals. PENG and TENG devices rely on hybrid mechanisms of piezoelectric and triboelectric own diversified advantages, including high output performance, multi-application for powering and sensing, etc figure 6(d) demonstrates a cotton sock by combining PEDOT: PSS-coated triboelectric nanogenerator and PZT chips for foot-based energy harvesting and monitoring [219]. It can successfully detect physiological signals of humidity, temperature, and weight variations. Besides, the sock can recognize walking patterns and track motion conditions for smart home applications. These wearable generators are remarkable candidates for power sources and sensors. Instead of partly attaching to the human body, the functional textiles and fiber fabrics have the potential to be clothing for human daily life. Dong *et al* demonstrated a fabrication process of stretchable triboelectric fibers with high electrical output and sustain strain, as shown in figure 6(e) [220]. By using the thermal drawing process and integration of micro-textured surface and liquid metal electrodes, the triboelectric fibers are not only capable of energy harvesting, but also competent to monitor breath and sense joint gestures.

To extend the application scope of wearable textiles, efforts have been made into the Human Machine Interface (HMIs), which basically realizes the communication between humans and electronics [227–230]. In 2019, He *et al* reported a self-powered triboelectric glove consists of a PEDOT: PSS coated strip and a layer of silicon rubber film (figure 6(f)) [221]. The glove-based system is suitable for a wide range of applications, including different controls in 2D/3D (wireless car, drone, robotic hand, etc), games, and cursor in cyberspace. Except for applications in real space, wearable generators using an HMI can broaden to virtual space, including virtual/augmented reality applications to enhance natural environments and offer perceptually enrich experiences and real-time interactions [231, 232]. Besides, combing with machine/deep learning technology, the electronics can achieve recognition applications including object, shape, gesture, motion recognition [233, 234].

Wearable devices based on smart home applications for the lives of people are greatly investigated in the past few years [235–237]. Especially for disease prevention and healthcare monitoring, textile-based sensors have brought a bright future to complementary medical system technology. Up to now, the sensors are demonstrated by diversified applications range from pillow, blanket, bed to floor and window. Recently, a triboelectric sensor pillow for sleep monitoring is reported for remote healthcare and early disease diagnosis, as shown in figure 6(g) [222]. Inside the pillow, high sensitivity feather-like structure sensors can distinguish various activities, such as breathing, moving, turning over, and so on. It provides remote detecting for human bodies on sleep healthcare, and therefore complete surveillance for patients or elderly people in case of sudden death during sleeping. In addition to pillow structure for sleep monitoring, a blanket and bed can also achieve the goal. Chen *et al* demonstrate a non-contact battery-free pressure sensor with the advantages of working under a high-pressure region and sensitivity (figure 6(h)) [223]. The piezoelectric-based sensor presents a reliable heartbeat and respiration detection to transmit to a remote cell phone. Similarly, a triboelectric sensor with an arched structure and conductive fiber using for bedsheets to fulfill the sleep detecting task, as shown in figure 6(i) [224]. Due to the superiorities of high sensitivity, fast response time, and stability, the pressure sensor array can monitor the condition, evaluate the quality, and warn dangers during sleeping. Figure 6(j) shows a 3D textile TENG based on a five-directional braided structure [225]. It presents a special frame structure thanks to its outer braided and inner axial yarns twine, which achieves high flexibility, output, and washable advantages. The textile demonstrates good potential in smart home applications as shoe-embedded human motion monitoring and remote emergency rescue system. As well as being an identification of carpets/floor to recognize passcodes for safe entrance and guard against theft system. Furthermore, Zhou *et al* present a transparent and flexible TENG which can support finger-touching and pen-based screen (figure 6(k)) [226]. In this way, it can not only perform as smart pens connecting to electrical devices, but also work as home windows to collect signals when raindrops fall down and then send out to smartphones to inform people of closing window in time. With the wireless transmission process, the device acts as a real-time weather monitoring smart window system for energy harvesting and sensing applications. Accordingly, PENG and TENG sensors are desired for multiple applications as crucial security/safety monitoring devices or interesting human-machine interacting electronics for people. In the long run, this kind of sensors would play a more essential role in complementary applications in human life contribution.

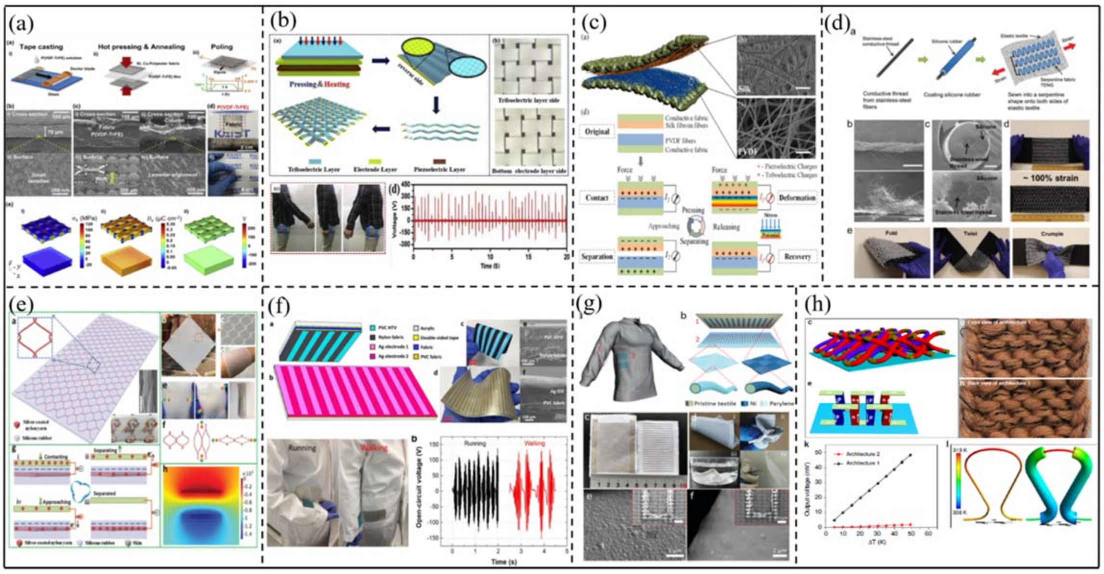

Figure 7. Textile-based human motion energy harvesters (a) fabric-based wearable piezoelectric energy harvester. Reprinted from [248] Copyright (2020), with permission from Elsevier; (b) Single-Thread-Based Wearable and Highly Stretchable TENG [213] John Wiley & Sons. © 2016 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim ; (c) washable textile-structured single-electrode TENG based on a nanofibrous polytetrafluoroethylene (PTFE). Reproduced from [249] with permission of The Royal Society of Chemistry; (d) Textile-based TENG with alternating positive and negative freestanding grating structure. Reprinted from [29] Copyright (2019), with permission from Elsevier, (e) All fiber-based hybrid piezoelectric- triboelectric nanogenerator for wearable gesture monitoring. Reprinted from [250] Copyright (2018), with permission from Elsevier; (f) flexible and stretchable fabric Piezoelectric-triboelectric hybrid nanogenerator. Reprinted from [251] Copyright (2019), with permission from Elsevier; (g) hybrid textile-based energy harvester by integrating fabric grating structure TENG with fiber-shaped dye-sensitized solar cells [252] John Wiley & Sons. © 2016 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim; (h) Stretchable fabric thermoelectric generator based on woven thermoelectric fibers Reproduced from [239] CC BY 4.0.

3.3. Textile based energy harvesting

Self-powered sensors can work effectively independently without any external power supply if the output signal is sufficiently high to operate the sensing system. However, if the output signal is low, an additional power unit will be needed. In order to realize a self-sustainable sensing system in that case, an energy harvester that can convert one or more of the other environmental signals to electricity should be integrated with the sensor.

Embedding energy harvesters in textile or textile based energy harvesters (T-EHs) attract great attention in the field of human motion energy harvesting. T-EHs can be embedded in textiles in the form of fibers, yarn, and fabrics using cost-effective and well established textile fabrication processes [28, 238–247]. Figure 5 shows different presented T-EHs based on different mechanisms. Kim *et al* [248] (figure 7(a)) presented a strongly integrated fabric-based wearable piezoelectric energy harvester (fabric-WPEH) using a ferroelectric polymer, P(VDF-TrFE), and conducting fabrics, nickel and copper coated polyesters. The simulation and experimental results show that the presented prototype has a piezoelectric d_{33} coefficient as high as 32 pC N^{-1}. It can generate an output voltage of up to 5.3 V and current of 69 nA from human pressing and bending motions, and an output power density of 16.83 nW cm^{-2} at an applied impact pressure of 55.5 kPa. Triboelectric nanogenerator is also a good candidate for textile-based energy harvesting, and is able to efficiently scavenge energy from human motion in this form, since it depends on relative motion, compressive force, or stretching to active materials. All does not require a high force, which is compatible with human motion, and does not make a disturbance to the human body. For example, Lai *et al* [213] (figure 7(b)) presented a single—thread—based TENG. It is fabricated from multi-twisted stainless steel thread, which acts as an electrode and coated with silicone rubber, which acts as a negative triboelectric material. The fabricated prototype is sewing in serpentine shape on an elastic textile. Thus, a large area and highly stretchable energy harvesting textile are obtained. The proposed prototype can generate an electric output that reached up to 200 V and 200 μA. The ability to harvest different kinds of human motion, such as joint movements, walking, taping, etc, is also demonstrated. Ning *et al* [249] (figure 7(c)) presented a washable textile single-electrode TENG (TS-TENG) based on polytetra fluoroethylene (PTFE) polymer with high hydrophobicity. A strained TS-TENG can be easily cleaned by washing in water. It can be sewed on cloths, and effectively converted human motion such as arm swing into electricity by simple friction with clothing material. A TS-TENG prototype is tested with simple arm swinging while walking and running. The obtained output voltage and current are 1050 V and 22 μA, respectively. With this electric output, it shows the ability to power a night running light and a digital watch without any energy storage component. Along with its flexibility, breathability, washability, TS-TENG may be considered as a significant development in the self-powering of wearable electronics. And Paosangthong *et al* [29] (figure 7(d)) demonstrated a new design textile-based Triboelectric nanogenerator with alternate grated strips of positive and negative triboelectric materials operating in freestanding mode. This design is different than previously presented grating—structure TENGs, where the air gap is replaced by another triboelectric material with opposite polarity to the existing material. Hence, an increase in the system performance is obtained due to the increase in the contact surface area. The presented prototype, as shown in figure 7(d), consists of an upper substrate with gratings of nylon fabric and polyvinyl chloride heat transfer vinyl (PVC HTV) and a lower substrate with screen-printed silver (Ag) IDEs on a PVC coated fabric. An improvement in the output performance by this design is observed. A prototype of 10 gratings of nylon fabric and PVC heat transfer vinyl delivers an RMS voltage, RMS current, and maximum RMS power density of 136 V, 2.68 μA, 38.8 mW m^{-2}, respectively.

The concept of a hybrid nanogenerator and combining the effect of two energy harvesting mechanisms are utilized in the fabrication of T-EHs to improve the energy conversion efficiency. A hybrid triboelectric-piezoelectric (TPNG) is a good example of hybrid system, which is capable of generating both triboelectricity and piezoelectricity at the same time. Guo *et al* [250] (figure 7(e)) demonstrated an all-fiber wearable hybrid TPNG. It consists of silk fibroin nanofibers and poly (vinylidene fluoride) (PVDF) nano-fibers, which were electrospun on conductive fabrics, respectively. Both the silk nanofibers and PVDF nano-fibers on the conductive fabrics were attached together to form a cloth-shape device, which has great mechanical flexibility as well as desirable wearing comfort. The presented prototype shows high output power levels with output voltage, short-circuit current, and power density of 500 V, 12 μA, and 0.31 mW cm^{-2}, respectively. The prototype is also tested with human body motion detection as a sensor. It is embedded with the wearer's clothes to distinguish the types of gesture by the difference of generated electric signals. He *et al* [251] (figure 7(f)) reported another example of textile-based hybrid triboelectric—piezoelectric generator. The demonstrated prototype is based on an intrinsic flexible and stretchable functional composite material, which involves two triboelectrification processed and one piezoelectric electrification process. The two triboelectrification processes mainly exist in contact-separate between warps and wefts, and between triboelectric layers of the prototype and external materials, respectively. By these three linked energy harvesting processes, the human movement can be efficiently harvested. An optimized prototype can produce an electrical output of maximum open circuit voltage and short circuit current of 600 V and 17 μA, respectively, and maximum power density of 1.11 W m^{-2} at a load resistance of 20MΩ. Besides, Pu *et al* [252] (figure 7(g)) reported a hybrid textile-based generator by integrating a fabric TENG with fiber-shaped dye-sensitized solar cells (FDSSCs). This hybrid generator can be suitable for indoor and outdoor applications. Actually, FDSSCs show many advantages for self-powering of wearable electronics. They are flexible, lightweight, with have high output power and low fabrication cost. They have high 3D light-harvesting capability, and can also be threaded into fabric and give the same performance as flat solar cells [11]. As shown in figure 7(g), the TENG is fabricated from two fabrics parts; the sleeve and underneath the arm (moving fabric and stator fabric, respectively). They act as two pairs of sliding-mode TENGs. They harvest the swing energy of the arm during walking and running. The stator fabric underarm has two metal electrodes with interdigitated configuration, while the moving fabric consists of series of parallel grating segments, of which the number, size, and spacing are identical to that one electrode under the arm. The output power of the TENGs is optimized by reducing the segment size, achieving a peak power density of 3.2 W m^{-2} at a sliding speed of 0.75 m s^{-1}. For FDSSC, it is designed in the way that it can be sewed into the cloth as schemed by the lower part of figure 5(g). It is composed of a Ti wire coated by a mesoporous TiO_2 layer, which is wrapped by a twisted Pt wire serving as the counter electrode. FDSSC shows an average power conversion efficiency of 6% with an average short circuit current density of 10.6 mA cm^{-2} and an average open circuit voltage of 0.6 V. The FDSSC pack and rectified TENG fabric is connected in parallel, and the output current is about the sum of both. A self-charging system is presented by charging a lithium-ion battery with the hybrid—textile generator.

Human body heat is another source of energy that can be harvested and used for the self-powering of wearable electronics. It can be harvested using thermoelectric generators (TEGs). However, most of the existing TEGs are too rigid and bulky to be integrated with portable devices and keep some degree of comfort to the human body. The remarkable effort has been devoted to developing flexible TEGs [240–243]. Textile–based generators can provide a significant degree of stretchability and comfort to the human body. However, when it comes to textile-based TEGs [253, 254], it is hard to maintain a high degree of stretchability without sacrificing the thermoelectric performance. One of the effective trails to meet the wearable TEG criteria [255–257] in the textile form is that proposed by Sun *et al* [239] (figure 7(h)). They demonstrated a thermoelectric module produced from thermoelectric fabric made out of thermoelectric fibers. Doped carbon nanotubes alternately wrapped with acrylic fibers are woven into π-type thermoelectric modules. Thus, the obtained interlocked thermoelectric modules can provide an adequate degree of elasticity, and consequently the stretchable 3D thermoelectric generators can give sufficient alignment with the heat flow direction. The demonstrated prototype shows a peak output power density of 70 mW m^{-2} for a temperature difference of 44 K, and an excellent stretchability (of about 80% strain) without output degradation.

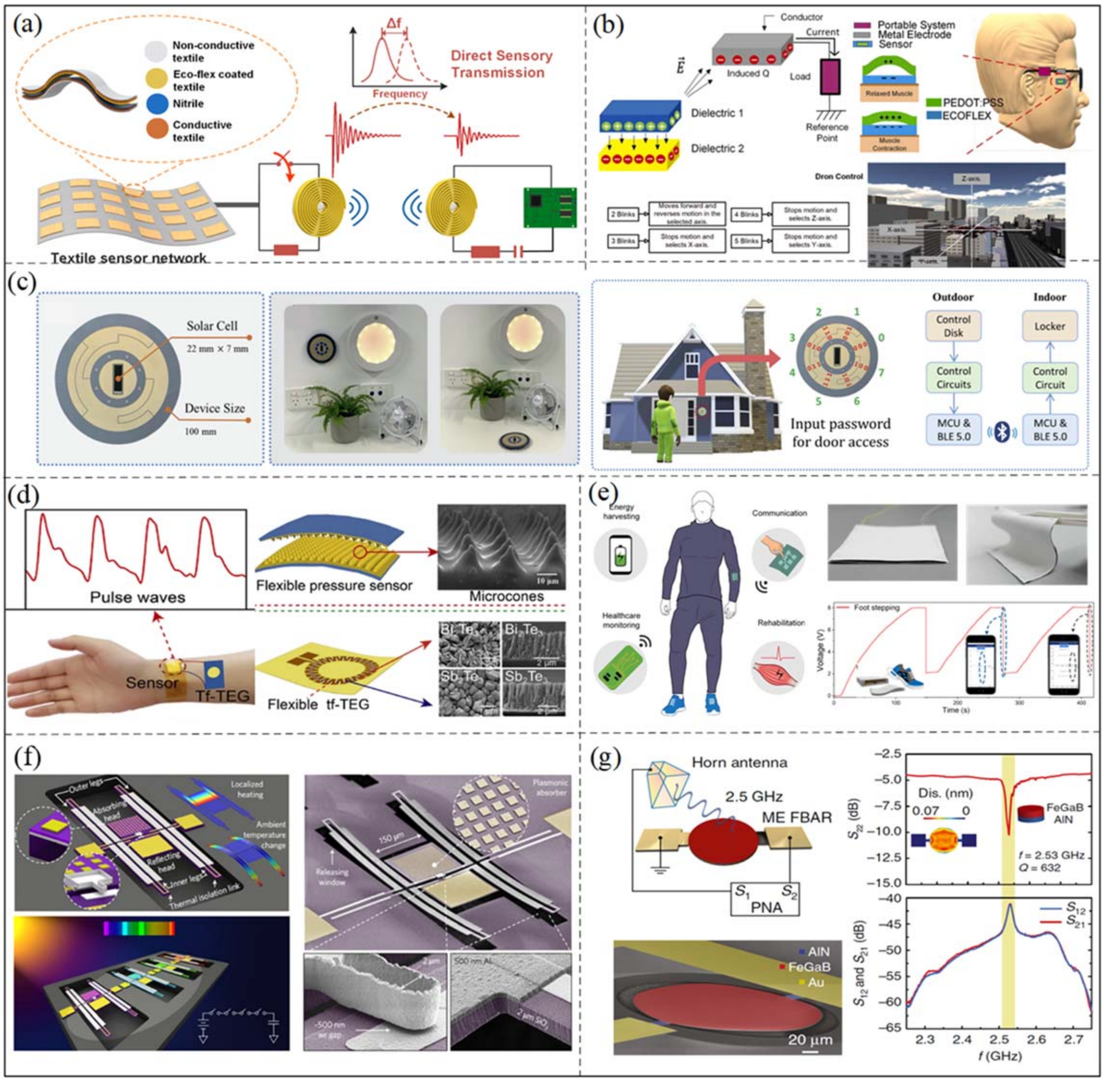

Figure 8. Self-sustainable IoT: (a) A battery-free wireless sensor network based on textile-based TENGs Reprinted from [262] Copyright (2020), with permission from Elsevier; (b) A self-powered wearable eye motion sensing system employing the near-field electrostatic induction. Reprinted from [211] Copyright (2020), with permission from Elsevier; (c) A self-powered control interfaces with hybrid triboelectric and photovoltaics energy harvesters Reprinted from [263] Copyright (2020), with permission from Elsevier; (d) A self-powered wearable pressure sensing system with a flexible thermoelectric generator and a pressure sensor Reprinted from [229] Copyright (2020), with permission from Elsevier; (e) A self-sustainable wearable healthcare monitoring system with textile-based TENGs. Reproduced from [264] CC BY 4.0; Near zero-powered IoT: (f) A zero-power infrared digitizer based on infrared event-driven photoswitch [265] Reprinted by permission from Springer Nature Customer Service Centre GmbH: Nature Nanotech 12, 969–973 (2017). (g) An ultra-compact antenna based on magnetoelectric nanoplate resonator. Reprinted from [266] CC BY 4.0.

4. Toward self-sustainable IoT and near zero-powered event-driven IoT

With the rapid development of wireless sensor networks and body sensor networks for smart home and healthcare applications, the matched power system for such randomly and massively distributed sensing nodes is in need [4, 258, 259]. Self-powered sensors and portable power supplies have emerged as promising candidates to solve the upcoming energy crisis [208, 210, 221, 260, 261]. To push forward the revolution of wearable electronics especially under the smart home and healthcare framework, there are plenty of studies published to provide various approaches for the future realization of self-sustainable IoT. Wen *et al* proposed a battery-free wireless sensor network based on a novel direct sensory transmission mechanism as indicated in figure 8(a) [262]. A textile-based TENG pressure sensor is fabricated, which is connected to a coil through a mechanical switch. Upon closing the switch, the charges are released immediately, forming an oscillating signal in the closed-loop RLC circuit, which can be inductively coupled to an external coil wirelessly. In this way, the short-range wireless transmission of the triboelectric output can be achieved. Besides, unlike previous works where the signal amplitude is used as the sensing parameter, the sensory information is contained in the frequency spectrum of the transmission signal, which can largely reduce the environmental interferences, such as humidity. Figure 8(b) presents another method for the battery-less wireless signal transmission, i.e., near-field electrostatic induction [211]. The working mechanism of the non-attachable electrode-dielectric triboelectric sensor is elucidated in figure 8(b), where the electrostatic charges are generated on the dielectric surface and coupled by the nearby electrode for the alternating current generation. Since it is based on the near-field electrostatic induction effect, the effective transmission distance is quite short. By applying this sensing technique, an Orbicularis Oculi muscle motion sensor is developed based on the glass platform to monitor voluntary and involuntary eye blinks, where the sensor is attached to one side of the eye and the charge collection electrode and portable signal transmission system fixed on the glasses. The whole system can function as a wearable HMI for various control applications and even for driving fatigue monitoring. To realize a longer transmission distance for smart home applications, an energy source with a larger power is in need. Qiu *et al* reported a self-powered control interface combining a photovoltaic cell and a sliding operation TENG, as shown in figure 8(c) [263]. This device can harvest solar energy as well as mechanical energy to be stored for signal readout and wireless transmission. The control disk interface can generate 3-bit binary-reflected Gray-code by sliding on the control disk interface, which is employed for smart home control (e.g., remote appliance control) and password authentication access control. This integration architecture that combines energy harvesters and sensors/wireless transmission modules has become a promising approach for the realization of self-sustainable IoT nodes for various applications. Figure 8(d) presents a self-powered wearable pressure sensing system by integrating a conductive elastomer-based pressure sensor with a flexible thin film thermoelectric generator (TEG) that converts body heat into electricity [229]. The flexible TEG provides a reliable and renewable power supply for the pressure sensing system. This self-powered pressure sensing system achieved a high sensitivity of 17.1%/kPa, which can be used for real-time monitoring of diversified physiological signals, e.g., wrist pulse. Besides body heat, the biomechanical energy involving ubiquitous body motions is also an abundant and renewable energy source that can be utilized for future self-sustainable IoT. As shown in figure 8(e), He *et al* proposed a narrow-gap triboelectric textile that can harvest energy from various body motions, which is soft, thin, and can be seamlessly integrated with regular garments [264]. To improve the output and the charging speed, a mechanical switch is introduced to produce instantaneous discharging. By integrating the triboelectric textile, mechanical switch with a Bluetooth lower power module, a self-sustainable temperature and humidity sensing system is developed, as shown in figure 8(e). Within 80 times of stepping, the charged voltage is sufficient enough for the powering of the Bluetooth module, which will transmit the current temperature and humidity level to the paired smartphone. It can be anticipated that multifunctional self-sustainable sensing systems could be feasible when integrating low-power modules with more functionalities.

In addition to self-sustainable sensing nodes, the use of event-driven extremely low-power sensing nodes offers another effective way to solve the energy crisis and greatly extend the lifetime of the wireless sensing nodes [267, 268]. The event-based sensing nodes achieve extremely low power consumption by staying in a dormant state for most of the time and only be activated when an event-related signal is detected. For event-related signals, they could be the measured objects' value changes, such as acceleration, light intensity, and temperature, etc [269–271]. Qian, Z *et al* designed and fabricated a plasmonically enhanced micro photoswitch as shown in figure 8(f), which will undergo off-to-on state transition only when specific spectral band infrared radiates on its surface [265]. The photoswitch can be acted as a near zero-power infrared digitizer integrating sensing, signal processing, and comparison with this property in place. Except for the event-driven signals of the measured object's value changes, the sensing nodes can also be activated by artificially sending RF wakeup signals. To implement this functionality, ultralow-power wakeup receiver front ends are required to integrate with sensing nodes to receive RF wake-up signals [272, 273]. As one of the core components in the wakeup receiver front ends, the performance of RF antennas is of vital importance. To solve the miniaturization problem of the RF antennas, Nan, T *et al* developed a nano-sized ultra-compact antenna based on a magnetoelectric nanoplate resonator [266], as depicted in figure 8(g). The antenna is fabricated on ferromagnetic/piezoelectric heterostructure and utilizes both magnetoelectric and piezoelectric effects to receive and transmit electromagnetic waves.

5. Future research directions in AIoT based smart home

5.1. Current demonstration of AIoT in the smart home application including gaming, HMI, and healthcare

Recently, machine learning technologies as sub-filed studies of AI power many aspects of modern society, which is increasingly presenting in various consumer products such as cameras and smartphones [274–277]. Therefore, the cutting-edge technology of machine learning with rapid development enables the micro/nano sensors to form a whole intelligent system related to the process of data acquisition, processing/analysis, and transmission [278–280]. By combing the appropriate learning algorithms with specific sensing systems, more comprehensive information can be extracted to better control the MEMS system [281, 282]. Significant progress

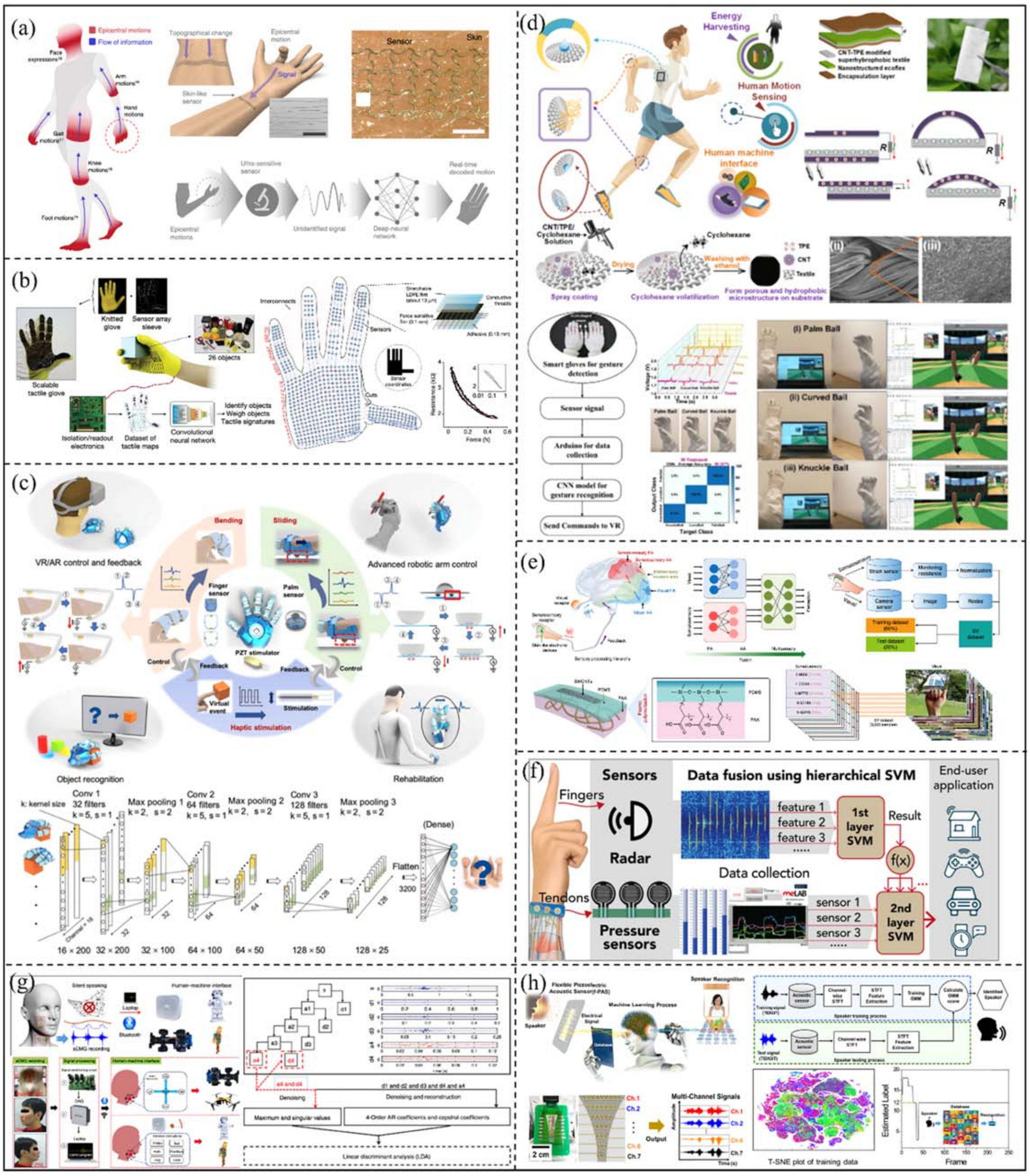

Figure 9. The future of micro/nano Systems based on AIoT. (a) Electronic skin integrated with a deep neural network that captures dynamic motions. Reproduced from [293] CC BY 4.0; (B) Scalable tactile glove with CNN analytics [289] Reprinted by permission from Springer Nature Customer Service Centre GmbH: Nature 569, 698–702 (2019); (c) Haptic-feedback smart glove with triboelectric and piezoelectric sensors. Reprinted with permission from AAAS [233]; (d) A facile carbon nanotubes/thermoplastic elastomer (CNTs/TPE) coating gloves. Reproduced from [294] CC BY 4.0; (e) Bioinspired data fusion architecture by integrating visual data with somatosensory data from skin-like stretchable strain sensors Reprinted by permission from Springer Nature Customer Service Centre GmbH: Nat Electron 3, 563–570 (2020)[295]. (f) HSVM algorithm for radar and pressure sensor. Reproduced from [296] CC BY 4.0; (g) Imperceptible, flexible epidermal sEMG tattoo-like patch for patients with loss of voice. Reproduced from [286] CC BY 4.0; (h) Flexible piezoelectric acoustic sensor based on the GMM algorithm. Reprinted from [297] Copyright (2018), with permission from Elsevier.

has been witnessed in tactile sensors for HMIs, related embodiments including smart keyboards [283–285], voice recognition systems [286–288], robotics control [289–291], and smart home control systems [212, 292].

Wearable glove-based HMIs possess the unique advantages in high precision and multiple degrees of freedom (DOFs) control, which would be an important complementary solution to vision and voice recognition in micro/nano systems. For instance, a new measuring system for a novel electronic skin integrated with deep neural network analytics captures dynamic motions from a distance without creating a sensor network (figure 9(a)) [293]. A long short-term memory (LSTM) network was designed to utilize temporal sensor patterns to correctly determine the hand motion. Thus the device can detect minute deformations from the unique laser-induced crack structures. A single skin sensor decodes the complex motion of five fingers in real-time, and the rapid situation learning (RSL) ensures stable operation regardless of its position on the wrist. For device expansion on other body parts, a concrete ergonomic analysis will be needed to select an optimum location to measure epicentral motions.

Moreover, figure 9(b) shows a scalable tactile glove (STAG) [289]. By analogizing the fundamental perception primitives between the visual and tactile domains, the STAG is assembled with a 584 piezoresistive sensor array distributed on the palm for interacting with 26 different objects. After identifying the tactile map of the 32×32 arrays in the sensor coordinates, the STAG uses a ResNet-18-based architecture [298] and reaches the maximal classification accuracy in seven random input frames. The above methods reveal that a much larger volume of information is accessible for studying interaction processes at a deeper level with the improvement of micro/nano sensors and the assistance of AI techniques, thereby aiding the future design and development of the next-generation wearable electronics and systems. In addition, a haptic-feedback smart glove with triboelectric and piezoelectric sensors using a convolution neural network (CNN) expands the capabilities of realizing advanced HMI, as shown in figure 9(c) [233]. To evaluate the mapping of the static pressure during the grabbing activities of different objects, the proposed glove is focusing on the investigation of the dynamic changes along with the complete cycle of grabbing waveforms from triboelectric sensors. In this regard, under a trained CNN model with three convolution layers, the realization of object recognition can achieve an accuracy of 96%. Moreover, Wen *et al* designed a facile carbon nanotubes/thermoplastic elastomer (CNTs/TPE) coating approach is investigated in detail to achieve superhydrophobicity of the triboelectric textile for performance improvement, as shown in figure 9(d) [294]. By leveraging machine learning analytics, a minimalist design with each finger only distributed one triboelectric sensor can perform recognition of complex and similar gestures. Meanwhile, benefited by the superhydrophobic characteristic of the materials, the negative effect of sweat is minimized, leading to an improved recognition accuracy (96.7%) compared to that without superhydrophobicity (92.1%).

Recently, another important technology for smart glove systems is combining diversified sensors to form an intelligent system and improve recognition accuracy. As shown in figure 9(e), a bioinspired data fusion architecture was developed to perform human gesture recognition by integrating visual data with somatosensory data from skin-like stretchable strain sensors [295]. The strain sensors were made from single-walled carbon nanotubes and the learning architecture used a convolutional neural network for visual processing and then implemented a sparse neural network for sensor data fusion and recognition at the feature level. This approach of data fusion achieves a high recognition accuracy of 100% and maintains recognition accuracy in non-ideal conditions of the image sensor, e.g., noisy and under-or over-exposed. The demonstration of robot navigation via hand gestures shows the stability of this data fusion approach with an error of 1.7% under normal illumination and 3.3% in the dark. Another novel approach of data fusing from multiple sensors using a hierarchical support vector machine (HSVM) algorithm is presented in figure 9(f) [296]. The validation of this method is experimentally carried out using an intelligent learning system that combines a radar for detecting the movements of the hands and fingers with a flexible pressure sensor array for measuring pressure distribution around the wrist. The HSVM architecture is developed to effectively fuse different data types in terms of sampling rate, data format, and gesture information from the pressure sensors and radar. The results of the collected datasets from 15 different participants show that the radar on its own provides a mean classification accuracy of 76.7%, whereas the pressure sensors provide an accuracy of 69.0%. At the same time, the proposed HSVM algorithm by integrating the output of pressure sensors with radar improves the classification accuracy to 92.5%.

Speaker recognition has received the spotlight as an important research direction of micro/nano systems, such as personalized voice-controlled assistants, smart home appliances, biometric authentication based on AI and IoT framework. Owing to the recent advances in soft materials and fabrication, the emerging field of micro/nano systems offers a technological solution to realize voice recognition systems. As shown in figure 9(g), the design of an imperceptible, flexible epidermal sEMG tattoo-like patch is used as a new HMI for patients with loss of voice [286]. When a tester speaks silently, the patch shows reliable performance in recording the sEMG signals from three muscle channels with high accuracy by using the wavelet decomposition and pattern reorganization. With the aid of the linear discriminant analysis (LDA) algorithm, the average accuracy of action instructions can reach up to 89.04%, and the average accuracy of emotion instructions is 92.33%. Besides, another speaker recognition system is reported using a flexible piezoelectric acoustic sensor (f-PAS) based on the Gaussian Mixture Model (GMM) algorithm as indicated in figure 9(h) [297], which get an excellent speaker recognition accuracy of 97.5%. The intrinsic voice information is obtained from the highly sensitive multi-channel membrane, which is beneficial for identifying speakers. Finally, the 75% reduction of the error rate compared to the commercialized MEMS sensors indicates that the f-PAS platform can be further applied to voice-based biometric authentication and highly accurate speech recognition.

5.2. New trend of healthcare—Bioelectronic medicines (or electroceuticals)

Since the creation of transistors, there have been different kinds of devices developed to build up a communication channel between humans and the digital world [299]. With the rapid progress on wearable electronics, diversified flexible physical sensors such as tactile sensors or strain sensors have been developed, which communicate with the digital system effectively by reflecting user intent from the user movement [300, 301]. Moving forward, a direct communication channel bypassing these devices becomes the ultimate goal of such communication, which creates a bridge between the user intent (i.e., neural signals) and the digital world [302–304]. This kind of devices that directly interact with biological tissue is termed a neural interface, which not only can record neural signals to detect the human intent but also could deliver electrical stimulation to the biological tissues for modulating biological functions [305]. In this regard, the neural interfaces have successfully built up a bidirectional communication channel between a subject's nervous system and a synthetic device.

The physical interaction between the neural interface and biological tissue could be sophisticated, which is an essential consideration when choosing the active materials of the neural interfaces. Biocompatibility and biostability are also important considerations for the implanted interfaces. Koo *et al* reported a peripheral nerve stimulation platform with bioabsorbable active materials, including magnesium and silicon oxide, which has opened up a new possibility to future transient electronics [306]. This implantable wireless stimulator consists of a radio frequency power harvester and an electrical interface to the peripheral nerve. The harvester combines a bilayer and dual-coil loop antenna (Mg) with a PLGA dielectric interlayer, a radio frequency diode, and a parallel-plate capacitor, as shown in figure 10(a). The whole system is constructed with materials that can be resorbed in a controlled manner. Figure 10 (a) shows photos of the devices at various timing after immersion in PBS at 37 °C. It can be observed that the constituent materials dissolved within 3 weeks, and all the residues completely disappeared on day 25. Soft microelectronic devices with similar mechanical properties as biological tissues will provide an intimate and stable electrical coupling with neural tissues for efficient recording and stimulation. Besides, it is also suggested by recent studies that reduced mechanical mismatch between the tissue and electronics would significantly reduce adverse immune response for chronic implantation [307]. To address this issue, Liu *et al* developed a soft and elastic hydrogel-based microelectronic interface for localized neuromodulation [308]. This soft neural interface consists of a micropatterned electrically conductive hydrogel (MECH) sandwiched by two PFPE-DMA encapsulation layers that are tuned to match Young's modulus of nerve tissue, as shown in figure 10(b). This MECH shows a highly reduced interfacial impedance with biological tissue and a ~30 times higher current injection density than that of platinum electrodes, which is demonstrated for localized electrical stimulation of the sciatic nerve in live mice. Recently, to accommodate rapid tissue growth and avoid repeated interventions and complications, a morphing electronic device (MorphE) is developed with novel growth-adaptive properties, as presented in figure 10(c) [309]. This MorphE consists of a viscoplastic polymer electrode and a self-healable insulating viscoplastic polymer. This device showed zero stress at a low strain rate of 0.05% s^{-1}, indicating no mechanical constrain applied to the sciatic nerve at a normal growth rate. The MorphE causes minimal damage to the rat nerve during the 2-month monitoring and chronic stimulation process, which grows 2.4-fold in diameter along with the fast growth of the rat. Combining with the self-healing property, the MorphE paves the way to growth-adaptive pediatric electronic medicine in the near future.

Moving forward, neural interfaces not only become more capable in terms of electrical and mechanical properties but also are evolving towards implantable systems to enable long-term monitoring or stimulation for various applications, such as translational therapeutic solutions [317]. The power source is an essential part of the implantable system, and conventional batteries are widely adopted solutions for powering implantable systems [318–320]. However, the battery suffers from a limited lifetime, a potential hazard to health, and subsequent replacement requirements. New solutions, including wireless powering and energy harvesting, then have emerged to replace the battery in recent years [321, 322]. Among them, self-powered energy harvesting is receiving tremendous research attention from multidisciplinary fields [264, 323, 324]. Lee *et al* developed a self-powered neuromodulation system by integrating a triboelectric nanogenerator with a flexible neural clip interface, as shown in figure 10(d) [310]. The bladder contraction for micturition can be successfully induced with the neuromodulation system by apply mechanical force to the TENG to deliver current to the flexible clip interface on a pelvic nerve in a rat. Unlike nerve that μA level current is high enough to penetrate the nerve tissue, muscle typically requires higher current for stimulation. Similarly, figure 10(e) presents a self-powered muscle stimulation system combining a triboelectric nanogenerator and a flexible multiple-channel intramuscular electrode [311]. A stacked-layer TENG is developed to boost up the current output, and a multiple-channel intramuscular electrode is designed, allowing mapping of sparsely distributed motoneurons in the muscle tissue to further improve the stimulation efficiency. For a self-sustainable and fully implantable medical device, implantable energy harvesters that directly convert inner-body biomechanical energy into electricity is of crucial importance. Figure 10(f) demonstrates an implanted symbiotic cardiac pacemaker based on an implanted TENG [312]. The implantable TENG harvests energy from the heartbeat, which is then delivered to the pacemaker for the regulation of cardiac physiological activity. It is demonstrated that the symbiotic pacemaker

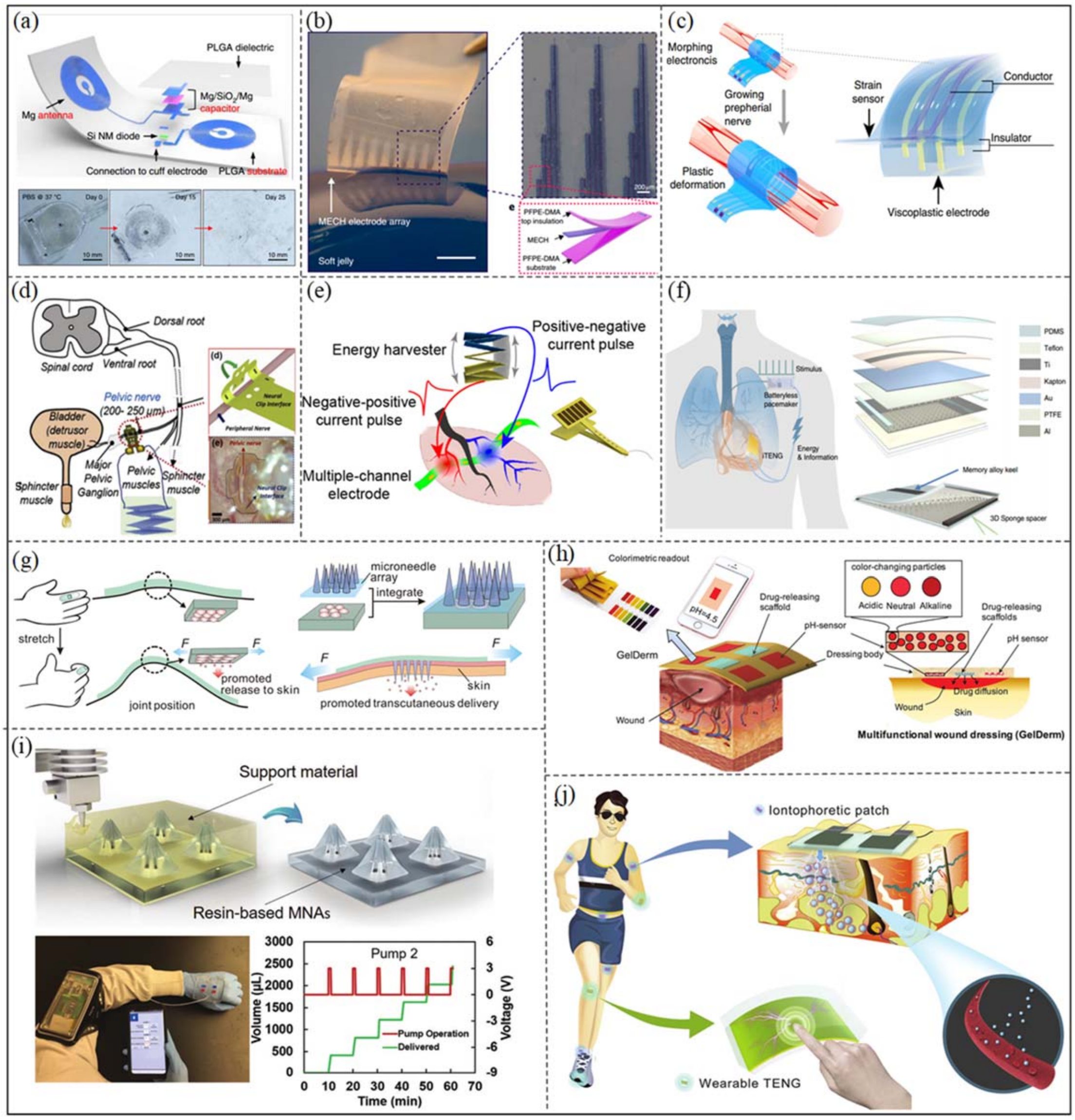

Figure 10. Healthcare new trend. (a) A bioresorbable and wireless electrical stimulator for neuroregeneration. Reprinted by permission from Springer Nature Customer Service Centre GmbH: Nat Med 24, 1830–1836 (2018) [306]; (b) A soft and elastic hydrogel-based neural electrode for localized neuromodulation. Reprinted by permission from Springer Nature Customer Service Centre GmbH: Nat Biomed Eng 3, 58–68 (2019) [308]; (c) A multilayered morphing neural interface for neuromodulation in growing tissues. Reprinted by permission from Springer Nature Customer Service Centre GmbH: Nat Biotechnol 38, 1031–1036 (2020) [309]. (d) Mechano-neuromodulation of autonomic pelvic nerve realized by integrating a TENG with a flexible neural clip interface. Reprinted from [310] Copyright (2019), with permission from Elsevier; (e) Self-powered direct muscle stimulation achieved with a stacked TENG and a flexible multichannel electrode. Reprinted with permission from [311] Copyright (2019) American Chemical Society; (f) A self-powered implanted symbiotic pacemaker based on an implantable TENG. Reproduced from [312] CC BY 4.0; (g) Stretch-trigger drug delivery based on integrated microdepots and microneedles. Reprinted with permission from [313] Copyright (2015) American Chemical Society; (h) The multifunctional sensing- therapeutic system composed of the pH sensors and drug delivery scaffolds. John Wiley & Sons. © 2017 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim [314]; (i) the wireless drug delivery patch based on miniaturized needles. John Wiley & Sons. © 2020 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim [315]; (j) The TENG-driven iontophoretic transdermal drug delivery system. John Wiley & Sons. © 2019 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim [316].

can correct sinus arrhythmia and avoid the deteriorating condition. With the profound investigation and improvement of the neural interface, it can be foreseen that it would reshape healthcare monitoring and treatment significantly by integrating with emerging self-powered technologies, data transmission, and artificial intelligence.

As a new trend with the background of aging of the population, domiciliary medical care is emerging to improve the quality of life, especially for the elderly and patients with chronic disease [325]. Implantable electronics make a great contribution to the development of home care, which helps to understand the health status via physiological monitoring but cannot apply for a medicine according to indications. Thus, researchers devote extensive efforts to develop easy-to-use medical devices to fulfill the personalized requirement of patients. Conventional oral administration is limited by the low bioavailability and metabolism in the digestive system. On the other hand, due to the pain associated with needles, common subcutaneous intravenous injection suffers from low patient compliance [326]. The emerging drug delivery technology is highly desirable for medical care at home by offering easy access and controlled administration, which keeps the patient from frequently going to the hospital for expertise equipment and allows them to participate in their own health management. Furthermore, the on-demand drug delivery provides great significance with the feedback therapeutic system building [327]. Among various drug delivery platforms, microneedles have been explored as a promising candidate that has high patient compliance and avoids some of these drawbacks, such as patient acceptability and injection safety [328].

At the early stage, mechanical force stimulus, such as compression and stretch, provides an easy and simple way to trigger the drug release [329], in which the strain variation can be expediently achieved by daily motions of humans. Di *et al* reported a finger joint stretch-triggered microneedle array as shown in figure 10(g) [313]. The microgel-depot that contained drug-loaded nanocapsules was fabricated on the stretchable elastomer. By integrated with microneedle channels, the drug-release patch was obtained and tensile stress would promote the drug release from microdepots along the microneedle. After 40 stretch cycles, the doxorubicin hydrochloride (DOX) release amount reached 110 μg ml^{-1} for *in vitro* study. Regarding *in vivo* results from diabetic mice, the stretch cycles can readily control the delivered insulin and hence control the blood glucose (BG) level, while the passive group (natural release) was only effective at the beginning and gradually cannot maintain the normal BG level. However, pure drug delivery obviously cannot meet the need for feedbacks that indicate when to start and end the drug delivery. To mitigate the drawback, Akbari's group developed a multifunctional sensing-therapeutic system for smart wound management (figure 10(h)) [314]. It could be seen that there were four pH sensors and two drug-releasing scaffolds on the wound dressing, in which the colorimetric response of the pH sensor indicated the bacterial infection of the wound site and reminded drug delivery actions. Besides, the interface smartphone was used for digital image capture to quantify the pH value. Moving forward, the smart-home application puts a requirement on the portability of the medical device, so as to achieve less restriction on human activity for the realization of portability, the capability of wireless transmission is greatly significant to achieve such vision. Accordingly, Derakhshandeh *et al* proposed a wirelessly controlled smart bandage with 3D-printed microneedle arrays. As shown in figure 10(i), the 3D printer fabricated the miniaturized needle in a biocompatible resin, followed by dissolving the support material in NaOH solution [315]. To reduce the cost of bandage, a reusable module and a disposable microneedle patch were separately designed, in which the reusable module housed the drug reservoirs, micropump, Bluetooth, and power source components. The applied voltage could control the micropump and regulate the flow rate through the app on the smartphone. As expected, each pump operation increased the delivered drug volume. Apart from the capability of wireless communication, independent and sustainable operation is also of vital importance for a portable system, especially in the condition of long-term wear. Nowadays, the most popular mobile energy supplier is the traditional battery that is subject to limited lifetime and periodic replacement. Developed energy harvesting technology offers a facile and cost-effective approach to achieve a self-sustainable system, which overcomes the limitation of batteries and steps forward to a more integrated system. As provided in figure 10(j), Wu *et al* investigated a biomechanical motion driven drug delivery system [316]. A wearable insole (TENG) that consists of PTFE and Al triboelectric pairs and Kapton as the spacer was fabricated on the PET substrate. Integrated with the hydrogel-based drug patch, the energy converted from mechanical motions of humans actively promoted the iontophoretic transdermal drug delivery. It was worth noting that the precise relationship between the delivered dose and generated energy needed further clarification.

5.3. Next generation of wearable electronics—toward the wearable photonics systems

In the era of AIoT, numerous sensors and processers are interlinked with each other to allow the flow of abundant information. Photonics is envisioned to be a complementary technology to electronics because it provides information communication channels with ultra-high data transmission speed [330] and sensing channels invulnerable to electromagnetic interferences [331]. Flexible photonics have been studied and found in various applications in data communications, robotics, optogenetics, and tactile sensing.

Flexible waveguides have been developed as optical interconnects for data transmission [330]. Currently, most flexible waveguides for data links are based on polymer materials and working in the multimode. As shown in figure 11(a), flexible waveguides can be fabricated on a large flexible substrate (145 mm $\times$ 129 mm) [332]. The cross-section of the polymer waveguides is relatively large ($H > 50$ μm) compared to waveguides fabricated on the silicon-on-insulator (SOI) platform [333] ($H = 0.22$ μm) because of the small refractive index difference between the waveguide core and cladding. At a bend radius of 4 mm, the flexible waveguide can transmit data at a rate of 40 Gb s^{-1}, demonstrating the state-of-the-art technology. Flexible waveguides have also been adopted in robotics applications because they offer advantages, including easy to fabricate, chemically inert,

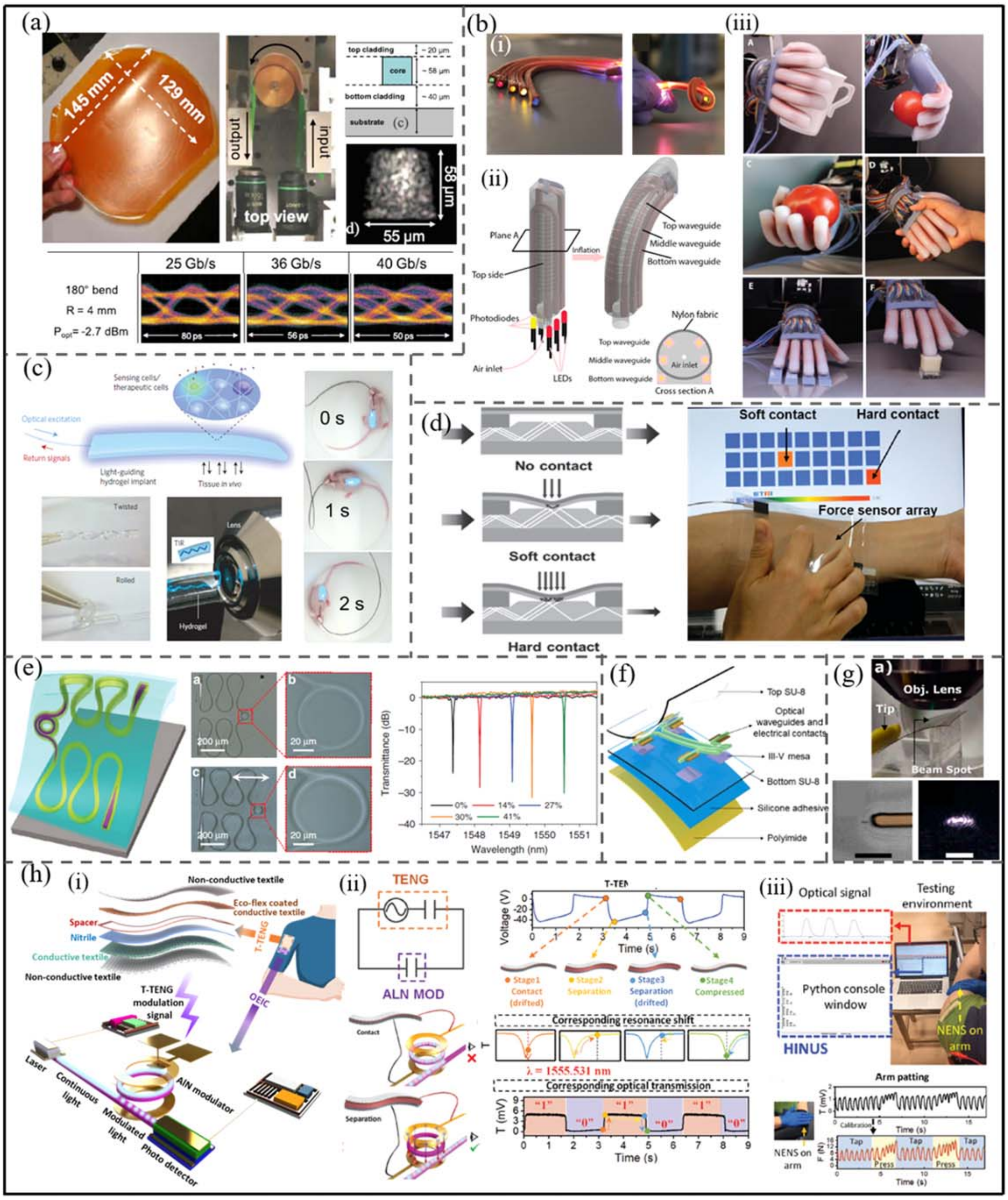

Figure 11. (a) Flexible optical interconnects. © [2018] IEEE. Reprinted, with permission, from [332]; (b) Optical fiber-based robotic hand. Reprinted with permission from AAAS [334]; (c) Implantable light-guiding hydrogel. Reprinted by permission from Springer Nature Customer Service Centre GmbH: Nature Photon 7, 987–994 (2013) [335]; (d) Polymer waveguide based flexible tactile sensor array. John Wiley & Sons. © 2014 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim [337]; (e) Flexible single mode waveguide. Reproduced from [339] CC BY 4.0; (f) Flexible waveguide photodetector. Reproduced from [340] CC BY 4.0; (g) Flexible nanorod laser. Reprinted with permission from [341] Copyright (2017) American Chemical Society; (h) Wearable triboelectric-aluminum nitride photonics nano-energy-nano-system. Reproduced from [260] CC BY 4.0.

environmental stability, high speed, as compared to flexible electrical sensors. Figure 11(b) presents an optoelectronically innervated soft prosthetic hand based on flexible optical waveguides [334]. The waveguides can be bent, twisted (figure 11(b.i)), and embedded in soft robotic fingers. Upon inflation, the waveguides bend, causing the transmission change in each waveguide. By embedding a total of six waveguides in one soft robotic finger (figure 11(b.ii)), the robotic finger motion can be precisely monitored. By equipping the full robotic hand with the flexible waveguides, object holding, grasping, hand-shading, roughness-sensing, and softness-sensing are demonstrated (figure 11(b.iii)). Flexible waveguides have found applications in optogenetics [335, 336]. Light-guiding hydrogels based waveguides have been developed with a low loss of <1 dB cm^{-1} and good stretchability (>540° twist angle) as shown in figure 11(c) [335]. Optogenetic therapy targeting diabetes in mice has been demonstrated using blue light excitation. Flexible photonics were also used in tactile sensing [337, 338].

As shown in figure 11(d), a polymer waveguide based flexible tactile sensor array was demonstrated based on the total internal reflection mechanism [337]. Upon touching, the top free-standing layer approaches the middle waveguide core and disturbs the total internal reflection. The transmitted light indicates the decree of touching. The demonstrated sensor array consists of 27 pixels working independently, showing a fast response, high bendability, and high reproducibility.

Although polymer waveguides have the advantages of broad material availability, easy-fabrication, and good intrinsic flexibility, many polymer materials are only transparent in the visible light, and realizing single-mode polymer waveguides is also a challenge [342, 343]. Thus, research effort has also been devoted to developing single-mode flexible waveguides working in the 1310 nm and 1550 nm near-infrared wavelength region [344, 345]. In 2018, Hu's group demonstrated the first single-mode flexible waveguide using chalcogenide (figure 11(e)) [339]. The rigid chalcogenide waveguides are embedded in large core SU-8 waveguides used to absorb the mechanical strain. The reported device still presents high performance after 3000 stretching cycles at 41% nominal tensile strain. In the same year, a flexible chalcogenide waveguide-integrated indium phosphide (InP) photodetector was reported by the same group (figure 11(f)) [340]. After 1000 bending cycles at a 0.8 mm bending radius, the waveguide-integrated photodetector can still operate with 0.3 A W^{-1} responsivity, 0.02 pW·$Hz^{1/2}$ noise equivalent power, and 1.4 GHz speed. Flexible lasers have also been investigated], as shown in figure 11(g), a nanowire laser directly integrated into flexible waveguides was demonstrated in 2017 [341]. Both the end-fire coupling scheme and the evanescent coupling scheme were demonstrated successfully with an optimal coupling loss of 17 dB and peak power of 11.8 μW measured from the waveguide output. Besides waveguides, photodetectors, and lasers, the other critical component of integrated photonics is modulators. Recently in 2020, Lee's group reported the wearable triboelectric-aluminum nitride (AlN) photonics nano-energy-nano-system (NENS) [231, 260]. The triboelectric nanogenerator (TENG) serves as a self-generated power source for nanophotonics modulation, while the AlN nanophotonics provides a robust and real-time sensing channel for TENG sensors in the other way round (figure 11(h.i)). Electronically, the TENG is a high impedance power source with a high capacitance (figure 11(h.ii)). The AlN modulator is a pure capacitor. The high voltage output ($>$100 V) from the TENG can be supplied to the AlN modulator with negligible degradation to alter its optical transmission via the Pockels effect. Under the optimized working condition, self-sustainable photonic modulation is achieved with clear '1's and '0's. Meanwhile, the optical transmission also serves as a readout for the tactile sensing information of TENG sensors. Optical Morse code transmission and human arm patting monitoring are demonstrated with continuous sensing information in real-time (figure 11(h.iii)).

6. Conclusion

With the development of IoT systems, self-sustainable and battery-free sensing systems become essential to realize long term functionality. Energy harvesting technologies have emerged as an alternative and promising choice of wireless sensors' power source, leading to self-sustainable electronics/systems. MEMS-based devices show a significant contribution to the development of self-sustainable sensing systems, due to their low power consumption. They can be integrated with MEMS or centimeter-scale energy harvesters to form self-sustainable sensing systems. However, when it comes to smart home and human body applications, more flexible and planar devices are needed to provide more comfort to the human body during daily activities. Thus, a new generation of self-powered sensors and energy harvesters using textile materials based on PENGs and TENGs mechanisms has been presented. These devices are lightweight, wearable, and highly flexible. Besides, textile is the most associated material with the human body and is very available inside the house. All make textile-based devices very suitable for smart home applications. On this basis, significant research activities have been done for further development of AIoT based smart home, for example, the development of HMI, voice recognition, etc, for smart home control. Moreover, the next generation of healthcare systems where the multi-functional physical and chemical sensing is provided along with the prompt treatment approach through the advanced neural interfaces, microneedles, skin patches, etc. Beyond wearable electronics, wearable photonics is a promising platform for the next generation of wearable technology because it can provide high data transmission speed and EMI-free sensing paths.

The development of wearable, self-sustainable, and intelligent sensing systems accelerates the realization of a smart home. However, some technical gaps still lay in building a real smart home. First of all, the healthcare monitoring system's function needs to be diversified and not limited to a single physical or chemical sensing. Ideally, medical treatment components such as microneedles should be integrated at the same time. Thus, with the help of machine learning algorithms, the monitoring data can be analyzed to timely guide corresponding medical treatment (drug injection via microneedles) for patients with chronic diseases (like high blood pressure and diabetes). Secondly, all sensing systems in a smart home, including house environmental monitoring and human healthcare monitoring systems, should be consolidated to realize information interaction to enhance the smart home's role. For example, by comparing the monitoring information of human body temperature and sweat sensors with the ambient temperature and humidity sensors, it can be inferred whether environmental factors or diseases cause the abnormal body temperature and sweating. Last but not least, low-cost and integrated high-speed networks for big data transmission should be built in the sensing systems to achieve interlink between numerous sensors and processers, and to meet the 5 G era's development needs. The use of photonic devices provides possible solutions to solve the above issue. Nevertheless, significant improvement still needs to be done to deal with the current photonic devices' high energy consumption, high fabrication cost, and difficulty integration with other components in the sensing system to promote their practical progress.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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