Progress in wearable electronics/photonics—Moving toward the era of artificial intelligence and internet of things

Qiongfeng Shi1,2,3,4 | Bowei Dong1,2,3,4 | Tianyiyi He1,2,3,4 | Zhongda Sun1,2,3,4 | Jianxiong Zhu1,2,3,4 | Zixuan Zhang1,2,3,4 | Chengkuo Lee1,2,3,4,5

1Department of Electrical and Computer Engineering, National University of Singapore, Singapore, Singapore, 117576, Singapore
2Center for Intelligent Sensors and MEMS, National University of Singapore, Singapore, 117608, Singapore
3Hybrid-Integrated Flexible (Stretchable) Electronic Systems Program, National University of Singapore, Singapore, 117608, Singapore
4NUS Suzhou Research Institute (NUSRI), Suzhou, 215123, China
5NUS Graduate School for Integrative Science and Engineering, National University of Singapore, Singapore, 117456, Singapore

Correspondence
Chengkuo Lee, Department of Electrical and Computer Engineering, National University of Singapore, Singapore, 117576, Singapore.
Email: elelc@nus.edu.sg

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Abstract
The past few years have witnessed the significant impacts of wearable electronics/photonics on various aspects of our daily life, for example, healthcare monitoring and treatment, ambient monitoring, soft robotics, prosthetics, flexible display, communication, human-machine interactions, and so on. According to the development in recent years, the next-generation wearable electronics and photonics are advancing rapidly toward the era of artificial intelligence (AI) and internet of things (IoT), to achieve a higher level of comfort, convenience, connection, and intelligence. Herein, this review provides an opportune overview of the recent progress in wearable electronics, photonics, and systems, in terms of emerging materials, transducing mechanisms, structural configurations, applications, and their further integration with other technologies. First, development of general wearable electronics and photonics is summarized for the applications of physical sensing, chemical sensing, human-machine interaction, display, communication, and so on. Then self-sustainable wearable electronics/photonics and systems are discussed based on system integration with energy harvesting and storage technologies. Next, technology fusion of wearable systems and AI is reviewed, showing the emergence and rapid development of intelligent/smart systems. In the last section of this review, perspectives about the future development trends of the next-generation wearable electronics/photonics are provided, that is, toward multifunctional, self-sustainable, and intelligent wearable systems in the AI/IoT era.

KEYWORDS
artificial intelligence, energy harvesting, human-machine interface, internet of things, wearable electronics, wearable photonics

Qiongfeng Shi and Bowei Dong contributed equally to this study.

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1 | INTRODUCTION

Wearable electronics, with integrated mechanical flexibility and electronic functionality, have experienced blooming development and advancement in the past few years.1-10 Compared to the traditional rigid electronics, wearable electronics exhibit unique characteristics in the aspects of flexible and/or stretchable, conformally patchable to skin, and potentially implantable. To advance from rigid electronics to wearable electronics, three popular approaches have been broadly investigated and applied, that is, reducing the thickness of rigid layers,11 transferring rigid blocks on soft substrates with stretchable interconnects,12 or using intrinsically flexible materials.13 In this regard, wearable electronics are able to achieve the same functionalities more conveniently and thereby improve the interaction experience between humans and devices. Except for the general wearable electronics, wearable photonics involving optical communication path can be a good complement and bring extra advantages in the whole wearable systems, such as ultra-fast data transmission and high reliability with electromagnetic interference (EMI)-free.14,15 Since appearance, wearable electronics and photonics have shown great impacts on our lifestyle, benefiting broad applications including electronic-skin (E-skin),16 healthcare (e.g., physical and psychological) monitoring and treatment (e.g., drug delivery),17,18 environmental monitoring and intervention,19 flexible displays,20 soft robotics,21 prosthetics,22 ultra-fast data communication,23 human-machine interactions,24 and so on.

In the new era of internet of things (IoT) and fifth-generation (5G) wireless networks,25,26 tremendous widely distributed electronic devices including wearable electronics/photonics are expected to be interconnected wirelessly with ultra-fast data exchange rate, providing real-time communication about what we want to know (information about the human body and ambient environment) and what we want to do (interaction and intervention). Under a similar scope, the concept of body area sensor network (bodyNET) is also proposed by hybridizing numerous wearable electronics around the human body, aiming at the applications in personalized healthcare and multifunctional robotics.27 For certain operation scenarios such as implantable devices and crucial security/safety monitoring, wearable electronics/photonics that are able to function independently and sustainably are highly demanded. As the current energy sources, that is, batteries, normally come with bulky occupation, heavy weight, rigid form, and limited lifespan, a more sustainable solution is urgently desired in the era of IoT and 5G. Benefited from the rapid development of energy harvesting and storage, wearable electronics, and systems equipped with these advanced technologies are receiving increasing attention and considered as a promising solution with potential self-sustainability.28-30 Generally speaking, piezoelectric, triboelectric, thermoelectric, and photovoltaic based energy harvesters and self-powered (i.e., self-generated) sensors/actuators have excellent compatibility with wearable electronics and are thus widely adopted.31-36 The investigation of sustainable power sources and self-powered electronics/photonics in wearable systems has attracted global research interests and effort to achieve higher output performance and transducing efficiency.37-40

Recently, the technology fusion of the emerging artificial intelligence (AI) with functional electronics, has nurtured a new area of intelligent systems that can detect, analyze, and make decisions with machine learning assisted algorithms.41,42 In addition, benefited from the 5G network, the acquisition rate of sensing data is able to satisfy the requirements of big data analysis and higher forms of AI.43,44 Besides, AIoT (AI + IoT) based on the collective integration of AI and IoT has also emerged and been considered as the state-of-the-art technology to enable intelligent ecosystems in broad IoT applications.45-48 When combining wearable electronics/photonics with AI technology, the resultant wearable systems are able to perform a more complicated and comprehensive analysis on the acquired data sets (training sets) beyond the capability of conventional approaches.49,50 Then this trained model can be used to predict the classification of the new incoming data, acting as the conditioning to trigger an intended event. The accuracy of prediction can be improved through choosing suitable algorithms,51 tuning the parameter of algorithms,52 and fusing different types of data from diversified sensors.53,54 Fundamentally, the intelligent systems can change the way of sensing and interaction, with a wide range of applications in advanced identity recognition, personalized healthcare monitoring and treatment, smart home/office/building, smart IoT, encrypted interactions in virtual reality (VR) and augmented reality (AR) environment, and so on.49-55

According to the recent progress of wearable electronics/photonics and systems, the presented work here provides an opportune overview of this field in the aspects of emerging materials, transducing mechanisms, structural configurations, practical applications, and advanced technology fusion. First, development of general wearable electronics/photonics is summarized for the applications in physical/chemical sensing, human-machine interaction, display, communication, and so on. Second, self-sustainable wearable electronics/photonics and systems with integrated energy harvesting and storage technologies are presented. Third, technology fusion of wearable
systems and AI is reviewed, showing the emergence and rapid development of intelligent/smart systems. In the end, perspectives about the development trends of the next-generation wearable electronics/photonics are provided, that is, innovating toward multifunctional, self-sustainable, and intelligent wearable systems in the AI/IoT era.56-61

2 | GENERAL WEARABLE ELECTRONICS AND WEARABLE PHOTONICS

Wearable electronics/photonics are rapidly emerging in diversified research areas for their promising future in broad applications, for example, robotics,62-64 medical devices,65,66 environmental monitoring,67 human-machine interfaces (HMs),51,68 healthcare,69 and so on. This section summarizes the various aspects of general wearable electronics and photonics in terms of materials, transducing mechanisms, and applications.

2.1 | Materials, transducing mechanisms, and physical sensing

The development of flexible and soft materials is essential for wearable electronics because of their unique chemical, electrical, and mechanical properties. Traditional materials for wearable electronics are mostly metals and semiconductors with relatively poor mechanical flexibility and stretchability.70-73 Recently, organic or polymeric materials are gaining more attention from the community due to their superior mechanical flexibility.13,74,75 An intrinsically stretchable electrochromic display made of composites of poly(3,4-ethylenedioxythiophene): p-toluene sulfonic acid (PEDOT:PTS) and polyurethane (PU) is reported, which can be uniformly attached to human skin as shown in Figure 1A.76 Another big branch of the electronic materials for wearable and skin electronics is the nanomaterials such as carbon nanotubes (CNTs),77,78 graphene,79,80 nanowires,81,82 and so on. A strain sensor and supercapacitor is developed with wrinkled CNTs as the conductive layer and patterned polydimethylsiloxane (PDMS) as the soft substrate, by a simple and low-cost fabrication process (Figure 1B).83 The corresponding scanning electron microscope (SEM) images of the wrinkled CNT sheets on the PDMS film are shown in Figure 1B as well. Through the integration of the highly conductive CNT sheets and the elastic PDMS layer, a composite film with good conductivity and elasticity is demonstrated. In addition to those commonly used materials, hydrogels represent a unique class of materials that possess distinctive electrochemical properties such as their ability to conduct both ions and electrons.84-86 Recently, a self-healing, adhesive, and highly stretchable ion gel is reported, with an excellent stretchability (2000% strain), conductivity and adhesion, as shown in Figure 1C.87 Its remarkable self-healing property upon cutting-induced crack has also been successfully demonstrated, showing a great potential of ion gel materials in various biomedical applications in the near future.

Physical sensing is one of the most fundamental functions required for wearable electronics to monitor different kinds of physiological signals. Traditional transducing mechanisms adopted widely include resistive sensing and capacitive sensing. As shown in Figure 1D, the schematic of a capacitive pressure sensor with micro-patterned elastic hydrogel for improving sensitivity is sketched.88 As the applied pressure varies, the resulting deformation of the microstructures induces a change in the capacitance of the device, through which the applied pressure can be accurately monitored. Similarly, the working principle of a piezoresistive pressure sensor based on a millefeuille-like architecture of reduced graphene oxide (rGO) is provided in Figure 1E.89 By applying a small pressure to the multilayer structure, the charge transport governed by electron tunneling between the layered rGO sheets leads to a tremendous reduction in the resistance of the sensor. Besides the aforementioned two popular methods, thin-film transistors can also be implemented as sensing elements for direct force monitoring. It is considered as a new pressure sensing technique that enables the use of miniature sensing elements with high sensitivity and large-area scalability in production. A zinc oxide thin-film transistor functioning as both a transistor and a force sensor with the same device structure is presented in Figure 1F.90 Furthermore, a sensor array with the force-sensing transistors is fabricated without additional addressing elements.

For the widespread applications of wearable physical sensors, monitoring the vital signs of humans is of great importance, such as blood pressure,91 pulse (heart rate),92 and breathing rate (respiratory rate).93 As demonstrated in Figure 1G, flexible pressure sensors are attached to the wrist and the breast for recording the epidermal pulse and respiration rate/heartbeats, respectively, providing abundant information about the health status of the subject.94 Similarly, capturing body motions with the wearable strain sensors on various body parts is also feasible, as depicted in Figure 1H.95 This pressure-insensitive strain sensors are fabricated using an all-solution process, and have high sensing selectivity of applied strain over pressure. By assembling them on fingers and knees, the bending motions of respective parts can be continuously monitored. In addition, epidermal electronics with the capability of
measuring thermal properties of human skins have attracted broad attention due to the provided insights of physical changes closely related to blood perfusion, hydration, and various other pathologies. A wireless and battery-free sensor that softly interfaces with skin is reported to enable precise monitoring of the skin temperature and thermal transport properties (Figure 1). Moreover, the sensor is also able to monitor vascular perfusion variations related to trauma and wound healing, suggesting a potential wide utility in clinical monitoring.

### 2.2 Chemical/gas sensing

Chemical/gas sensors are tremendously needed to identify the matter parameters in various environments,
especially in the potential IoT applications to collect useful information for human beings. To meet with the fast development of 5G, the future chemical/gas sensors are aiming at small size, high sensitivity, low concentration sensing, and compatibility in all kinds of extreme environments and complicated systems. Besides, along with the technology development trends of wearable electronics for the comfort and convenience of human beings, the conventional rigid silicon based chemical/gas sensors are gradually replaced by flexible wearable sensors. Due to the advantage of flexibility in materials, the concept of wearable chemical/gas sensor presents its vivid application to assist human beings in healthcare, disease diagnosis, and/or environmental monitoring. Among all of the gas sensing approaches, for example, chemiresistor, optical frequency, acoustic and plasma, and so on, the chemiresistive method using metal nanoparticles as the sensing component exhibits great advantages in flexible sensors because of the small size of functional nanoparticles and the excellent gas response at room temperature. To detect ammonia (NH$_3$) at room temperature, Figure 2A presents an ultrasensitive flexible silver-nanoparticle sensor using the mechanism of oxygen chemisorbs with NH$_3$. It is demonstrated that the metal nanoparticles contribute a positive effect to NH$_3$ detection, leading to a detection limit of as low as 500 parts-per-trillion. Besides metal nanoparticles, two-dimensional (2D) material (e.g., graphene) is another important functional component in gas sensing due to its large surface area and high flexibility. As shown in Figure 2B, a flexible gas sensor for the detection of ethanol at room temperature can be achieved with conductive CNTs on flexible glossy paper substrates. The electrical response has a good linear relationship with the ethanol concentration.

**FIGURE 2** Typical sensing principles and development of wearable chemical/gas sensors. A, NH$_3$ sensing using material of guar gum/silver film and its sensing response. Reproduced with permission from Reference 99, Copyright 2013, Nature Publishing Group. B, Flexible ethanol sensor using carbon nanotube on a paper substrate. Reproduced with permission from Reference 100, Copyright 2010, Elsevier. C, The deposition of ZIF-8 nanocrystals using a drop coating method and its H$_2$ gas sensing response. Reproduced with permission from Reference 102, Copyright 2018, Elsevier. D, Schematic diagrams of the multifunctional textile based on triboelectrification for CO$_2$ gas sensing. Reproduced with permission from Reference 104, Copyright 2019, Elsevier. E, Biomimicry laser-induced graphene electronic nose sensor and its H$_2$ gas sensing response. Reproduced with permission from Reference 106, Copyright 2019, American Chemical Society. F, Flexible glove-based biosensor for organophosphorus chemical sensing and its mechanical flexible response with stretching cycles. Reproduced with permission from Reference 108, Copyright 2017, American Chemical Society. ZIF, zeolitic imidazolate frameworks.
To detect gas with an ultra-low concentration, many researchers have studied the use of metal-organic frameworks (MOFs) in gas sensing. The most commonly used MOF is zeolitic imidazolate frameworks (ZIF-8 and ZIF-67). The main reason for choosing this MOF material is that the large porous size (about 1.6 nm for ZIF-8 and ZIF-67) and trap cage (easily absorbed gas molecules) from polymer molecules can result in a higher surface area which benefits gas sensing at low concentration. The detection of low-concentration gases (10 ppm) such as toluene, ethanol, carbon monoxide (CO), hydrogen (H2), and nitrogen dioxide (NO2) is achieved through measuring the resistance change in ZIF-8, as depicted in Figure 2C.102,103

To address the power consumption and system integration issues in the chemical/gas sensors, the combination of self-powered ability and flexibility in the sensor has attracted increasing research interests recently. For example, to accurately evaluate the wellbeing conditions of a person, a smart and multifunctional textile based on a simple dip-coating method is illustrated in Figure 2D.104,105 It is shown that a maximum output power density of 2 Wm−2 can be realized with a polymer-coated textile, which also possesses good CO2 sensing response. With these technologies, this smart textile could be further incorporated into real clothes as both energy harvesters and functional self-powered sensors for healthcare monitoring. In addition, wearable electronic noses with electrical analysis circuit systems have recently captured the interests of researchers. Wearable electronic noses exhibit great potentials as physiological indicators in real-time monitoring of health status and/or body motions. A biomimetic gas sensing nose is proposed based on a laser-induced graphene, as presented in Figure 2E.106,107 The biomimicry electrical nose shows a linear relationship in sensing response to H2 in real-time monitoring. It is also concluded that the biomimetic turbinate-like microstructured electronic nose demonstrates a much better sensing performance in selectivity (H2, NH3, CO, and NO2) and low-concentration response. On top of typical gas sensing approaches, a flexible glove-based electrochemical biosensor with highly stretchable printed electrodes is reported for chemical sensing in applications of defense and food security (organophosphorus chemical threats), as depicted in Figure 2F.108 The glove-based biosensor system is illustrated to have excellent robustness for on-glove sampling/sensing operation, through detailed investigation of dynamic mechanical deformation such as bending and stretching. Therefore, this glove-based biosensor system offers considerable opportunities for the detection of nerve-agents and pesticides in defense and food-safety relative applications.

### 2.3 | Human-machine interfacing

With the increasing intimacy of humans and machines especially in the era of IoT, HMIs are of great importance to provide critical connections in between. Fingers, as one of the most dexterous parts of human body, are quite suitable to be utilized as the interactive interfaces between humans and machines.109,110 Tremendous information and commands can be defined by the combined operation of the 10 fingers, where the resultant interactive mode is simple and intuitive to perfectly match the logic of our brain. Many efforts have been carried out so far on the development of finger sensors and glove-based HMIs for sensory information collection, for example, finger bending degrees,111-114 contact forces,115-117 friction during sliding,118,119 and so on. Consequently, real-time monitoring of hand motions can be achieved, showing the great prospect of building a dynamic interaction system between human and the virtual world. The traditional way to build a wearable data glove is to use commercialized accelerometers and gyroscopes as sensing units. A data glove composed of three 3-axis accelerators, one controller and one Bluetooth module is proposed in Figure 3A, which can realize the three-dimensional (3D) hand motion tracking as well as hand gesture recognition.120 For real-time visualization, a 3D digital hand model is built to demonstrate the gesture recognition results. Another more systematic glove with motion sensors integrated on the wrist and fingers is shown in Figure 3B.121 The constructed VR system integrated on the wrist and fingers in the rehabilitation area can investigate the criterion validity of upper extremity (UE) performance of stroke patients according to the collected data from the glove, showing the possibility to be applied in the rehabilitation area.

Although these traditional micro-electro-mechanical systems (MEMS) based sensors can achieve high-precision measurement of continuous finger motions in 3D space, sensor-wise they are rigid and complicated to be fabricated, thus limiting their applications in light and flexible wearable situations. Flexibility, stretchability and light-weight of wearable electronics, as the key factors determining the comfort level of users and the portability of devices, have drawn tremendous attention across the world for developing finger/glove sensors with such characteristics.122-125 The common flexible strain sensors are normally based on resistive sensing123,126-137 or capacitive sensing,138,139 whose output signals can dynamically respond to the variation of applied force or strain under continuous motions. A finger-bending strain sensor is presented using stretchable gallium-based conductors, as indicated in Figure 3C.140 Accordingly, a digital hand in the VR environment is built to reflect the actual hand kinematics based on resistance change of the sensor in a...
real-time manner. This gallium-based strain sensor has advantages of high flexibility and stretchability, as well as precise, repeatable and durable electromechanical performance with a simple structure. Besides, a wearable glove based on all-soft-matter stretchable capacitive sensors with tunable sensitivity enabled by liquid metal (LM) microstructure is also reported (Figure 3D). Different grasped objects can be recognized according to the output variation during the grasping motions. This work shows the great potential of programmable LM composites in developing flexible HMI with tunable functionalities. Apart from the strain sensors which can monitor the dynamic motions of fingers, tactile sensors that can detect contact forces between hands and other objects are also indispensable in glove-based HMIs. A microfluidic tactile sensor is proposed based on embedded Galinstan microchannels with a high sensitivity of 0.0835 kPa−1 and a fast response time of 90 ms (Figure 3E). The
flexible sensors can be integrated onto a PDMS glove to provide comprehensive tactile feedback of a human hand when touching or holding objects. Compared with traditional rigid sensors, these flexible/stretchable strain and tactile sensors mentioned above exhibit great advantages in improving the interaction experience and comfort level of users without losing the detection accuracy and sensitivity for finger/hand motion monitoring.

2.4 Wearable optoelectronic displays

The optoelectronic display (or display) is an indispensable component in electronic systems as displays project information in the form of texts, images, and videos for intuitive visualization to aid human cognition. The current display market is valued at more than $100 billion and is expected to expand to more than $200 billion in 2025. Traditional displays utilize mainly solid-state light-emitting diode (LED) and liquid crystal display (LCD) technologies, and are massively used in consumer electronics including televisions, laptops, mobile phones, and tablets. With the demand of, but not limited to, the personalized healthcare monitoring system and more realistic wearable VR/AR system for entertainment, wearable electronics has rapidly advanced over the past 10 years. In accordance, as required by the conformal human skin, the edge of the display technology is also pushed so that the mechanical flexibility and stretchability are introduced to the display. Fundamentally, three methods similar to those adopted in wearable electronics can be used to achieve mechanical flexibility and stretchability in displays, namely reducing the display film thickness, replacing the rigid electronic interconnects by stretchable interconnects while leaving the tiny active devices rigid, or using stretchable materials in the whole system. Figure 4A shows the critical tensile strain for the delamination of a structure comprised of a PDMS film on a polyester substrate. The structure can withstand a much higher tensile strain before delamination when the PDMS thickness is reduced to less than 300 μm. Based on film thickness reduction, an array of LEDs and photodetectors as well as silicon solar cell power sources on PDMS can be successfully adhered on human skin to realize conformal flexibility. In the same work, besides solar cells, LEDs and photodetectors, the wearable system is also equipped with electrophysiological, temperature sensors, strain sensors, transistors, radio frequency (RF) inductors, capacitors, oscillators, rectifying diodes, as well as wireless coils. The second method involves replacing rigid electrical connections by flexible connections but leaving the tiny active components rigid in order to maintain their high performance. As presented in Figure 4B, an elastomeric microlens array and a stretchable array of photodiodes are bonded together. In the photodiodes array, the active photodiodes are rigid while the interconnect matrix is realized using filamentary serpentine wires which are responsible for withstanding the strain during stretching. After bonding, the integrated camera is deformed into a hemisphere shape to mimic the compound eye of anthropods. A photodiode is right beneath each microlens with specifically designed parameters. Such a design enables the combination of elastomeric compound optical elements with deformable arrays of thin rigid silicon photodetectors into integrated sheets with flexibility and stretchability. Using this method, micro-LED and photodetector arrays are realized with excellent stretchability to integrate with various classes of substrate. With proper encapsulation, waterproof ability is also demonstrated. The third method uses stretchable materials in the whole system. Early in 2009, a rubber-like active-matrix organic LED (OLED) display with 16 × 16 pixels was developed by integrating OLED for lighting, organic transistor as the driver, and printed elastic conductors as interconnects. Because the system is built up solely by stretchable components, it has very strong mechanical robustness so that it remains functional even when folded or crumpled up.

Besides OLED, another category of the active display is polymeric light-emitting devices (PLED). Compared with OLED which is based on small molecules, PLED is based on polymers and has the advantage of flexibility and large-area display. Liang et al demonstrated a stretchable elastomeric PLED in 2013. It is semitransparent with good surface electrical conductivity and smoothness. On top of the simple all-solution-based fabrication process, the PLED is foldable, can tolerate a maximum linear strain of 120%, and can survive after 1000 cycles of stretching at 30% strain repeatedly. Despite the good performance and broad applicability of LED-based display systems, the ultimate strains are limited to less than 120%, posting a challenge for their application in soft robotics and on human joints. Alternatively, the ultimate strain of elastomers can be as high as 400% to 700%. Therefore, elastomer-based electroluminescent materials are used to complement OLED and PLED when high strain is required. Larson et al reported a highly stretchable electroluminescent (EL) skin for optical signaling and tactile sensing. The active electroluminescent layer is a ZnS phosphor-doped dielectric elastomer layer (Ecoflex). The two electrodes are PAM-LiCl hydrogels and the whole device is encapsulated by two Ecoflex layers. Even under a high strain close to 400%, the device still presents high luminescence (Figure 4C). By selectively doping the EL phosphor layer, the emission of light...
at different wavelengths can be realized. A panel consisted of three pixels with different emission colors that can be controlled independently is successfully demonstrated. For applications such as skin treatment, light detection ranging, and high intensity displays that require high temporal and spatial coherence of light, lasers are irreplaceable light source. Recently in 2018, a flexible and ultra-lightweight polymer membrane laser was developed based on a solution-based process. The 200-nm thick membrane laser can work independently in air or on other substrates such as human nail cover (Figure 4D).

In addition to the device level development, wearable displays are also integrated into wearable electronic systems to provide the visualization function on a system level. In traditional E-skin, especially E-skins with a focus on pressure sensors, the electronic readout scheme is normally used but not intuitive. C. Wang et al presented a user-interactive E-skin that not only provides the applied pressure information but also offers an immediate visual response through the built-in wearable display system. The entire system consists of 16 × 16 pixels with a total size of 3 × 3.5 cm². Each pixel features the integration of CNT network based thin-film transistor (TFT), OLED and a pressure-sensitive rubber (PSR). The PSR is in electrical contact with the OLED cathode so that the emission intensity of the underlying OLED is a function of the PSRs conductivity that changes with applied pressure. The emission color of each pixel is predetermined by using different emissive layer materials.

**FIGURE 4** Wearable optoelectronic displays. A, Flexible LED enabled by reducing the film thickness and using meander structure. Reproduced with permission from Reference 11, Copyright 2011, AAAS. B, Stretchable photodetector array enabled by connecting the rigid active devices using stretchable interconnects. Reproduced with permission from Reference 12, Copyright 2013, Nature Publishing Group. C, Stretchable transparent elastomeric polymer LED. Reproduced with permission from Reference 153, Copyright 2016, AAAS. D, Flexible polymer membrane laser. Reproduced with permission from Reference 154, Copyright 2009, Nature Publishing Group. E, Ultraflexible organic photonic skin with sensor and analog/digital display. Reproduced with permission from Reference 156, Copyright 2016, AAAS. LED, light-emitting diode.
When PDMS slabs with letters C, A, and L shapes are used to apply specific spatial pressure on to the system, the OLED provides direct optical response that maps the spatial pressure information for intuitive human visualization, without the need of complicated data acquisition circuits and electronic boards. In order to minimize the discomfort experienced by human skin, an ultrathin, ultraflexible, and high-performance integrated PLED/organic photodetector (OPD) system is developed with both displaying and sensing functions. As presented in Figure 4E, the thin film optoelectronic system laminated on human skin is only 3-μm thick including both the substrate and the encapsulation layer, which is one order of magnitude thinner than the epidermal layer. In the integrated system, light emitted from the PLED penetrates human skin and interacts with human blood, after which it is reflected back and detected by the OPD. Consequently, the system unobtrusively measures the oxygen concentration of blood when it is worn on a finger. Meanwhile, another PLED helps the visualization of sensing data on the body directly.

2.5 Wearable photonics

The practical personalized wearable healthcare system requires not only a single or a few sensors and displays. Instead, a sophisticated sensor network is demanded. As demonstrated by Bao’s group in 2019, a body area sensor network, that is, bodyNET, hybridizes numerous chip-free and battery-free wearable sensors distributed over the human body. The sensing signals are transmitted wirelessly through passive radiofrequency identification technology (RFID) to the flexible silicon readout circuit attached to a textile. As the number of sensors deployed in the bodyNET increases to realize more system-level functions, the sensors will interfere with each other due to electromagnetic perturbation. Meanwhile, the communication bandwidth needs to be broadened in order to instantaneously transmit all the sensing signals and receive feedback from the cloud in the IoT scheme. Wearable photonics is a promising candidate to complement wearable electronics in complicated systems. On the one hand, by using the optical sensing path, the wearable photonic sensors are invulnerable to EMI. On the other hand, the photonic interconnects can easily achieve GHz data transmission rate that enables real-time monitoring and feedback. Furthermore, the mid-infrared (MIR) photonic sensors are miniaturized devices with selective, label-free, and damage-free sensing capability. Since the molecular vibrational fingerprints of many biological and environmental substances in their gaseous or liquid forms are in the MIR region, MIR photonic platform is promising for applications varying from environmental monitoring, healthcare monitoring, and industrial inspection. To date, many MIR photonic building blocks have been developed that form the foundation for the future realization of MIR wearable photonics. Meanwhile, the photonic neural network is also evolving as a complementary technology for the current transistor-based electronic neural network. It is envisaged that the photonic neural network integrating with the photonic sensors monolithically can perform AI functions such as learning and recognition on-chip. In such a way, the data can be processed on-chip and only the final critical small amount of data is sent to the cloud server to ease the requirement of high computing power in the AIoT era.

Regarding wearable photonics, polymer-based flexible photonics are studied and developed due to ease of fabrication, good flexibility, and stretchability. Since most organic bonds are absorbing beyond the near-infrared which is defined as the electromagnetic spectrum covering from the approximate end of the response of the human eye to that of silicon, polymer-based flexible photonics are mainly used in the near-infrared and visible range. An early polymer-waveguide-based flexible tactile sensor array for direct pressure response was developed in 2014 (Figure 5A). Two layers of photocurable fluorinated liquid prepolymers are prepared on a Si wafer to act as the waveguide core layer and cladding layer, respectively. The difference in refractive index is created by altering the fluorine contents in the pre-polymer. Light with wavelength between 550 nm and 1000 nm can transmit in the waveguide with more than 90% transmittance. When the touch layer is pressed to contact the waveguide core, the total internal reflection condition changes and leads to the variation in the output light intensity. The final photonic sensor array detects contact force at 27 points independently even when the flexible device is wrapped around human arms. Meanwhile, the system provides a fast response (less than 10 ms), high reproducibility (Pearson correlation coefficient of 0.99 and hysteresis of 6.7%), and high bendability (10.8% sensitivity degradation at 1.5 mm bending radius). On top of sensing in vitro, sensing in vivo is also realized by implanting the wearable photonics device into animal objects. Figure 5B shows a light-guiding hydrogel for cell-based sensing and optogenetic synthesis in vivo. The hydrogel provides a low loss optical path for light transmission via total internal reflection (loss of <1 dBcm⁻¹) and possesses excellent stretchability such that it can be twisted by 540° and rolled. By using blue light for optical excitation, light-controlled optogenetic therapy that targets diabetes in live mice is achieved. Besides exciting the cells, the hydrogel optical communication channel also
serves as a link for real-time cell-based toxicity sensing. For implantable wearable photonics applications, bio-absorbable system is desired. Compared with conventional non-biocompatible optical fibers which should be removed from the patient soon after clinical use, the bio-absorbable waveguides can be used for long-term optical treatment and do not require removal since they can be gradually resorbed by the tissue without causing any toxicity. As presented in Figure 5C, the transparent and flexible biopolymer film prepared by the melt-pressing technique can withstand severe twist. Furthermore, simple laser cutting can be adopted to fabricate thin waveguides with well-controlled meshes. The fabricated bioabsorbable polymer waveguides can guide visible light all the way from blue to red 2-cm deep into tissues. By using dyed porcine skin that can be photoactivated by green light, it is clearly indicated that an efficient light delivery is realized due to the presence of photobleaching down the entire depth of the tissue interface after 30 minutes of illumination. Waveguide-assisted photochemical tissue
bonding is achieved. The tensile strength of the bond assisted by waveguide optical treatment shows a fivefold enhancement compared to those without waveguide. Beyond the development of flexible waveguides, integrated light sources are required to realize a fully integrated photonic system toward miniaturization. A semiconductor nanowire laser was successfully integrated with polymeric waveguide devices on a flexible substrate in 2017 (Figure 5D). Coupling schemes including endfire coupling into a waveguide facet and from nanowire laser printed directly onto the waveguide top surface are demonstrated. The optimal coupling loss of −17 dB dominated by mode mismatch is reported together with a waveguide peak power of 11.8 μW. Other than sensing, another critical application of wearable photonics is high-speed data transmission. Figure 5E shows a recent advance of flexible photonics for high-speed data transmission applications. By using multimode polymer waveguides that work at 850 nm, a flat frequency response up to 30 GHz can be achieved even when the flexible waveguide substrate is wrapped around a mandrel of a 4-mm radius. Negligible degradation in the eye-diagram at 40 Gb/s is observed when comparing the flat waveguide devices and devices with a 4-mm bending radius.

Most polymer-based waveguides work in the near-infrared range below 1 μm wavelength but do not apply to longer wavelengths because of material absorption. However, the 1310 and 1550 nm wavelength in the short-wave infrared are of great importance since they are massively used in telecommunication and data center. The choice of these two wavelengths is attributed to the lowest dispersion and lowest loss of Si, respectively. The silicon-on-insulator (SOI) material platform is used in foundries for mature, stable and mass production of silicon photonics (SiP) devices working at 1310 and 1550 nm. Up to 2019, many commercially available SiP transceivers can be found in the market where 100G and 40G SiP transceivers are dominating. Nonetheless, the SOI material platform is rigid with a thick Si substrate so that it is not suitable for flexible photonics. It is desired to equip the SOI platform with flexibility and stretchability so that the standard Complementary Metal Oxide Semiconductor (CMOS) fabrication infrastructures and processes can be utilized. In 2012, M. Li’s group reported a flexible and tunable SiP circuit on a flexible substrate (Figure 5F). The devices were firstly fabricated on an SOI platform using the standard CMOS fabrication process. Then the buried oxide (BOX) layer was partially released with only tiny tips supporting the waveguide device membrane. Finally, a PDMS substrate was adhered to the waveguide membrane top surface to pick it up due to the stronger Van Der Waals force. The device maintains high quality after the membrane transfer process. A quality factor (Q factor) as high as $1.5 \times 10^5$ was achieved in a micro-ring resonator. Then the device was further adopted as a strain sensor. In the same year, M. Qi’s group also reported a bottom-up direct fabrication of silicon photonics devices on a flexible platform and used the device for strain sensing. Other waveguide devices and nitride-based materials were investigated as well for wearable photonics, offering a more versatile device and material library. In B. Li’s work, silicon nitride was used as the waveguide material in an optoelectronic probe whose flexibility is originated from the 23.5-μm overall device thickness. Among various material platforms, the chalcogenide material is also a promising photonic waveguide material for applications beyond 1 μm. Chalcogenide waveguides can be fabricated on flexible SU-8 substrate by the deposition and lift-off process. Assisted by planarization after the patterning of each photonic layer, the next photonic layer can be deposited and patterned on top of the previous layer to realize 3D integration. In L. Li’s work, a flexible photonic circuit consisting of three waveguide layers was demonstrated. Most previously reported flexible integrated photonics use multimode waveguide which will experience undesired mode conversion, and require stringent mode control. Although single-mode waveguides are anticipated for many applications, a common bottleneck in flexible photonics is the realization of single-mode waveguide due to its ultra-narrow width that makes the waveguide mechanically weak. The first single-mode stretchable photonic waveguide was reported in 2018 by J. Hu’s group. In this work, the design strategy involves local substrate stiffening to minimize shape deformation of critical photonic components. As shown in Figure 5G, the narrow-core single-mode chalcogenide functional waveguide devices are embedded in large-core SU-8 waveguides. The transition between the two waveguide layers is achieved by adiabatic tapers. The SU-8 transmission line adopts a meander shape to absorb the mechanical strain. After 3000 stretching cycles at 41% nominal tensile strain, the device still presents high performance.

Based on the flexible chalcogenide photonics technology, L. Li also developed a flexible chalcogenide waveguide-integrated InP photodetector in 2018 (Figure 5H). The flexible substrate is still SU-8. The flexible waveguide-integrated photodetector can operate with a high performance of 0.3 A W$^{-1}$ responsivity, 0.02 pW Hz$^{1/2}$ noise equivalent power (NEP), and a 3-dB bandwidth of 1.4 GHz even after 1000 bending cycles at 0.8 mm bending radius. The flexible waveguide-integrated photodetector, together with the previously mentioned flexible semiconductor nanowire lasers, is envisaged to realize the ultra-thin and ultra-lightweight fully integrated flexible
photonics circuits for applications including artificial skins and soft wearable robotics.

3 | SELF-SUSTAINABLE WEARABLE ELECTRONICS INTEGRATED WITH ENERGY HARVESTING TECHNOLOGIES

With the prosperous development of wearable electronics and photonics in almost every aspect of applications, electronics, and systems that can operate independently and sustainably are of great significance in the new era. In this section, advanced energy scavenging and transducing technologies used in wearable systems are introduced, with the common forms of integrated energy harvesters and/or self-powered functional components.

3.1 | Energy harvesting and storage

Developing toward the next-generation wearable electronics, energy becomes one of the most challenging bottlenecks that needs to be addressed urgently. Under the scope of IoT and 5G with wide-spread and interconnecting devices, electronics with less power consumption or even with self-sustainability (ie, self-powered capability) are highly desired. In order to achieve such an objective, potential approaches have received broad research interests and investigation across the world. Normally these approaches can be divided into two main categories, that is, the integration of energy harvesters and storage units in systems as prolonged power supply, or the direct utilization of self-powered electronics as functional components to reduce the overall power consumption of the whole system.

Other approaches such as the event-driven sensing mechanism have also been considered to realize near-zero power sensors and systems, but they are normally based on event-triggered switches with MEMS structures and this review here is mainly focused on the abovementioned two approaches.

Energy harvesting technologies have received rapid development in the past decade, including the widely adopted piezoelectric, electromagnetic, electrostatic, triboelectric, thermoelectric, pyroelectric, photovoltaic transducing mechanisms, and so on. In the field of flexible wearable electronics, thermoelectric, piezoelectric, photovoltaic materials, and their hybrid mechanisms are commonly adopted due to the good compatibility. Briefly speaking, thermoelectric energy harvesters are relied on the well-known piezoelectric effect, converting the applied mechanical energy into electricity through adopted piezoelectric materials. Functional piezoelectric materials can range from nanoparticles, nanowires, nanosheets, thin/thick films, to bulk materials. Since 2012, triboelectric nanogenerators (TENGs) based on the conjunction of contact electrification and electrostatic induction have attracted global research interests and been developed into diversified mechanical energy harvesters and self-powered electronics (such as sensors, actuators, interfaces, etc.). In addition, photovoltaics is the technology to convert light energy into direct current electricity through the photovoltaic effect on solar cells.

Figure 6 summarizes some of the recently developed wearable energy harvesters according to different mechanisms and their further integration with energy storage units as a complete power supply. For thermoelectric devices in personal wearable electronics, it is difficult to maintain a large temperature gradient across them, especially with the trend of miniaturization. Thus, in Figure 6A, an architectural solution is proposed by designing active thermoelectric materials in compliant and open 3D forms, which can multiply the heat flow through the device as well as enable efficient thermal impedance matching. For an 8 × 8 array of coils at a temperature gradient of 19 K, the generated open-circuit voltage and power are 51.3 mV and ~2 nW, respectively. In addition, the generated voltage maintains constant over time, indicating that the steady state of thermal profile can be achieved with the 3D soft structure. Other than thermal energy, kinetic energy is another type of ubiquitous energy source in human daily activities. As depicted in Figure 6B, a flexible piezoelectric energy harvester (f-PEHs) together with an energy extraction enhancement circuit (EEEC) to improve energy harvesting efficiency from irregular human motions, is presented as a potential power source for wearable electronics. With the help of the optimized EEEC (low static power consumption of 1.15 nW), maximized output voltage (165 V) and energy can be extracted from an f-PEH, showing an enhancement of 495% compared to a conventional full bridge rectifier based power management circuit.

TENGs of different operation modes (ie, contact separation, lateral sliding, single electrode, and freestanding mode) can be configured with no limitation in terms of materials, exhibiting particular suitability for wearable applications. Other than the conventional polymer based TENGs, fiber/textile based TENGs due to their unique features of fatigue resistance to various complicated deformations, good air permeability, warmth...
retention, and high comfort, are of great significance to realize the seamless combination of wearable TENGs and diverse human motions.37,231-233 Figure 6C demonstrates a conformable and washable textile-based TENG for scavenging kinetic energy from human motion induced skin contacts.234 The functional textile is coated with black phosphorus and hydrophobic cellulose oleoyl ester nanoparticles, serving as an effective electron-trapping layer with long-term robustness and good triboelectric negativity. Upon hand touching at ~5 N and ~4 Hz, output voltage and current of ~250-880 V and ~0.48-1.1 μA cm⁻² can be generated to supply the operation of multiple LEDs and a digital watch. This developed all-textile TENG can also be incorporated onto clothes/skin to capture subtle skin frictions (with an output of 60 V), highly suitable for daily wearable operations. Apart from textile-based TENGs, another common type of wearable TENGs is the tattoo-like TENGs with thin thickness, light weight, and good stretchability that can be conformally attached onto skins. Figure 6D presents a stretchable and transparent TENG based electronic skin using soft elastomers and hydrogels. A tough interfacial bonding can be achieved through interfacial modification of the hydrophobic elastomer layer and hydrogel.
hydrophilic hydrogel layer, ensuring excellent characteristics in both mechanical robustness and electrical performance. Moreover, the dehydration process of the hydrogel-elastomer hybrid is found out to be significantly inhibited, showing good long-term stability. Besides, the fabricated single-electrode device has an ultrathin thickness of 380 μm and high deformability, which can be conformally attached onto human skins to produce outputs of 70 V and 0.46 μA under skin contacts.

Due to the irregular and scenario-dependent characteristics of ambient energy sources, energy harvesters with a single transducing mechanism are difficult to provide sufficient time-averaged power. To address this issue, a hybrid thermo-triboelectric generator is proposed in Figure 6E, targeting to harvest human relative energy with higher efficiency.236 The hybrid generator is composed of an array of bismuth telluride (Bi₂Te₃) tiles (in form of p-type and n-type) for thermoelectric energy harvesting and PDMS filled in between for triboelectric energy harvesting by touches. After optimizing the operation frequency and tile spacing, the hybrid generator demonstrates an average output power of 3.27 μW·cm⁻³ under human touches at a frequency of 2.5 Hz. To produce constant and stable power supply to functional electronics, energy storage units are indispensable to be integrated with energy harvesting units. As depicted in Figure 6F, an elastic and sustainable power source in the form of a bracelet is reported for simultaneous energy harvesting and storage.237 The energy harvesting part consists of hybridized fiber-shaped dye-sensitized solar cells (DSSCs) and single-electrode TENGs for scavenging energy from both ambient sunshine and human motions. On the other hand, the energy storage part is an array of supercapacitors that can store the direct current energy from solar cells and the alternating current energy from TENGs after the rectification circuit. For normal operations during the day, the supercapacitors can be charged smoothly from 0 to ~1.8 V in 43 seconds, showing the capability as a sustainable power source toward self-powered wearable electronics.

3.2 | Self-powered HMIs

With more and more distributed sensor nodes and functional units, interactions between human and machines are becoming inevitable and increasingly intimate in daily life, such as in the scenarios of healthcare,238-240 disabled aids,241,242 robotics,243-245 entertainment,246,247 gaming,248 VR/AR,219,249,250 and so on. As mentioned in the previous section, using self-powered functional components in the whole system can effectively reduce the overall power consumption. Therefore, self-powered HMIs with the capability to produce self-generated signals under external mechanical stimulations have been widely developed in the past few years.104,251-254

According to the types of human-machine interactions, common HMIs can be defined based on voice, breath, body motions, hand motions (tapping and sliding), hand/finger gesture, and so on. Figure 7 shows various types of self-powered HMIs targeting for different human-machine interactions including voice, breath, body, and hand motions. Meanwhile, Figure 8 focuses on hand/finger gesture based self-powered HMIs as one of the most rapidly developed fields in HMIs.

The auditory system can serve as one of the most straightforward and efficient communication interfaces between human beings and robots. A triboelectric auditory sensor (TAS) is developed for electronic auditory system in the application of intelligent robotics (Figure 7A).255 Through proper optimization of the device structure and materials, the TAS exhibits a broadband response ranging from 100 to 5000 Hz with an ultrahigh sensitivity of 110 mV dB⁻¹. Detailed characterizations show that the TAS has a high-quality music recording feature and an accurate voice recognition ability. Moreover, the resonant frequency of the TAS can be adjusted through modification of the geometric boundary, with potential application for natural sound wave amplification. Based on this property, a hearing aid is then developed with a simplified processing circuit and reduced power consumption, showing great advantages in the human robot interactions. While most of the current HMIs are based on voices and physical contact motions, breath can also be an alternative interaction approach for HMIs, especially for disabled persons. Figure 7B shows the implementation of a breath-driven single-electrode TENG as a self-powered HMI for the communication with various electrical devices.256 The breath-driven TENG is mainly composed of a flapping polyethylene terephthalate (PET) thin film and a bottom copper (Cu) electrode, which is able to generate responsive electrical signals with an incoming airflow from human breathing. Through the integration with signal processing and wireless transmission circuits, a real-time breath-driven HMI system is constructed using deliberate breathing to control electrical appliances, which can be a more convenient interacting way for disabled people.

Physical motions of human body are most commonly adopted in HMIs, and they can also contain distinct information to enable personal identity recognition. As indicated in Figure 7C, a triboelectric band is adopted for human identity recognition by the detected electrical signals from muscle movements that are associated with gait patterns.58 The self-powered triboelectric band consists of a stretchable rubber layer as the friction interface
with skin and physiological saline filled inside as the electrode. Electrical signals are generated in response to muscle movement induced change in the contact area between the rubber surface and skin. With proper calibration, the band not only can detect human walking step/speed/distance, but also can recognize each individual based on the unique signal patterns for employee clock in and computer login applications. Another type of keystroke-dynamics-based HMI system is also developed for personal authentication in cybersecurity through machine learning assisted typing behavior recognition (Figure 7D). The complete system is composed of a TENG based keystroke device for converting typing motions into electrical outputs, and a software classification platform based on support vector machine (SVM) algorithm. Through feature extraction from user's typing of “8-0-7-3-4-5”, that is, five typing latencies, six hold time, and six signal magnitudes, satisfactory accuracy of 98.7% can be achieved for the identification of five different users. These developed intelligent HMIs can enable next-level and smarter interactions such as user identification and personal information protection.

**FIGURE 7**  HMIs based on devices with self-generated signals. A, Triboelectric auditory sensor for electronic auditory system and external hearing aid. Reproduced with permission from Reference 255, Copyright 2018, AAAS. B, Breath-driven TENG for communication with various electric devices. Reproduced with permission from Reference 256, Copyright 2019, Elsevier. C, Triboelectric band for human identity recognition. Reproduced with permission from Reference 58, Copyright 2018, Elsevier. D, Keystroke-dynamics-based HMI system for personal authentication in cybersecurity. Reproduced with permission from Reference 257, Copyright 2018, Elsevier. E, Self-powered, flexible, triboelectric sensor patch for robotics control. Reproduced with permission from Reference 258, Copyright 2018, American Chemical Society. F, Single-electrode triboelectric interface with bio-inspired spider-net structure. Reproduced with permission from Reference 259, Copyright 2019, Wiley-VCH. HMI, human-machine interface; TENG, triboelectric nanogenerator.
One research direction of conventional HMI is to develop minimalist HMIIs, thus to simplify the signal acquisition/processing circuitry and reduce the overall power consumption. Figure 7E shows a self-powered, flexible, triboelectric sensor (SFTS) patch with four sensing electrodes for robotics control. The four sensing electrodes are located at the edges of the 2D SFTS patch to monitor contact positions of fingertip through the generated voltage ratios. In order to facilitate sliding trajectory sensing, a grid structure is attached on top of the patch sensing surface to induce alternative contacts and separations during the continuous finger sliding. In this way, both tapping and sliding motions of fingertip on the SFTS patch can be detected with only four sensing electrodes. Combining the 2D SFTS patch with another one-dimensional (1D) SFTS strip for z-axis control, complete spatial information can be applied to manipulate the 3D motions of a robotic arm. Real-time demonstrations of velocity control, 3D motion control, trajectory control such as character writing are successfully realized. Toward ultimate minimalist HMIIs, the number of sensing electrodes can be further reduced to one. As depicted in Figure 7F, a single-electrode triboelectric interface is developed based on the bio-inspired spider-net structure. All the electrode patterns are connected into one spider-net layout, with unique information coding (e.g., binary 0 and 1 coding) introduced on the grating electrodes along the eight radial directions. Thus, finger
sliding in different directions can be recognized and used for multi-directional and/or multifunctional control. Benefited from the advanced information coding configuration, the developed triboelectric interface exhibits high scalability and excellent reliability that is independent of sliding speed, sliding force, and humidity. This minimalist interface with only one sensing electrode can greatly simplify the electrode layout design, signal readout circuitry, and data processing, showing great potentials in various human-machine interactions.

In terms of hand/finger gesture based self-powered HMIs, sensors based on the piezoelectric \(^{111,116,260,261}\) and triboelectric \(^{262-264}\) transducing mechanisms have been extensively developed for soft wearable glove-based electronics. Moreover, because of the wide choices of flexible and stretchable triboelectric materials, for example, metal, oxide, wood, fabric, rubber, and polymer, \(^{265}\) many triboelectric-based finger sensors have been developed recently, proving its great potential as self-powered wearable HMIs. Figure 8A shows a ladder structure TENG consisting of multiple single-electrode units on the elastic rubber substrate. \(^{266}\) The stretching and contracting motions of the rubber substrate can induce the contact and separation of the opposite-charged triboelectric materials, generating corresponding electrical outputs. This stretchable TENG sensor is then integrated with a data circuitry, and data processing, showing great potentials in various human-machine interactions.

This sensor is further mounted on the human fingers to realize real-time gesture monitoring for sign language conversion, robotic hand control, VR game control, and drone control. Besides, a highly stretchable yarn-based TENG with coaxial core-sheath and built-in spiral winding structures is proposed and shown in Figure 8C. \(^{267}\) Thanks to its special structural design, this TENG sensor has a higher sensitivity and faster response time compared with previous triboelectric tactile sensors based on contact-separation mode, and thus can be further designed as a self-powered gesture-recognizing glove.

However, these TENG strain sensors mentioned above can only detect instantaneous motions using output peaks generated in the simple contact and/or separation process. In order to realize continuous sensing functionality of self-powered TENG sensors, a novel joint motion triboelectric quantization sensor (jmTQS) with arranged interdigital (IDT) electrodes working on grating-sliding mode is developed as in Figure 8D, which can directly quantify the flexion-extension degree/speed of a finger joint according to the output pulses and peak numbers. \(^{244}\) Besides, this pulse-counting detection approach also shows a better stability compared with the output-amplitude detection approach used by other TENG sensors, thus demonstrating the possibility of continuous sensing using TENG based finger sensors. Another grating electrode structural TENG pressure sensor is depicted in Figure 8E, based on the triboelectrification between interfacing liquid and soft polymer within a fluidic channel. \(^{268}\) This pressure sensor can detect the dynamic pressure change when liquid is driven to flow in the fluidic channel and thus can be used to continuously monitor finger bending degree and bending frequency. Apart from the grating-sliding mode, the triboelectric-photonic phenomenon is also another potential sensing mechanism for continuous motion monitoring. A stretchable triboelectric-photonic smart skin is presented to enable multidimensional tactile and gesture sensing for robotic hand (Figure 8F). \(^{40}\) The detection is based on the sensory information from both the generated open-circuit voltage (triboelectric) and photocurrent (photonic), showing more possibilities for the future development of wearable TENG based HMIs.

Besides using strain/pressure sensors to directly monitor finger bending motions and contact force between hands and external stimuli, developing fingertip-like tactile sensors with multi-functionalities is a hot research direction in the field of glove-based HMIs. These tactile sensors are expected to mimic the sensory mechanoreceptors in the skin that can detect and recognize the surface roughness. A fingertip-like E-skin composed of double spiral CNT-PDMS electrodes is proposed for triboelectric sliding sensing and piezoresistive pressure detection (Figure 8G). \(^{269}\) This E-skin is demonstrated to be able to complete multiple complicated tasks, for example, differentiating roughness of surfaces and holding-releasing execution, through combining and analyzing these two kinds of sensory (triboelectric and piezoresistive) information. A similar self-powered finger skin is also developed as illustrated in Figure 8H. \(^{270}\) The triboelectric layer here mimics the fast adaptive (FA) mechanoreceptors in human skin, which is more sensitive to vibrations during sliding and produces electrical output to support the sensing system. While the graphene sensor array mimics the slow adaptive (SA) mechanoreceptors in the skin that can continuously monitor applied pressure. This integrated device is capable of classifying 12 fabrics with complex patterns according to the collected sensory information when finger slides across different fabric surfaces (with a classification accuracy of 99.1%). The above two demonstrated fingertip-like tactile sensors (Figure 8G,H) are both...
composed of a functional triboelectric part and a piezoresistive part. The triboelectric part is able to produce self-generated electrical signals by itself, but the piezoresistive part still needs a power supply to drive, thus the entire device can be regarded as a semi-self-powered system. Besides, the triboelectric sensor is more sensitive to high-frequency vibration and high-speed sliding, which is capable of collecting dynamic sensory information in the integrated system, while the piezoresistive part is more suitable for detecting distribution of relatively static pressure. These developed wearable TENG sensors including TENG strain sensors, pressure sensors as well as tactile sensors, can be further integrated to form a more systematic glove-based HMI that has the potential to be widely applied in future human-machine collaboration and digital twin areas.

3.3 Self-powered and battery-free wearable and implantable systems

Wearable and implantable electronics with desired functionalities, operational safety, and long-term stability are in urgent demand for the diversified applications in IoT, healthcare, entertainment, and so on. In this case, power becomes a critical issue for a sustainable electronic system. Conventional batteries fail to meet the rising requirements of the energy storage units in wearable or implantable devices, hence various energy harvesting strategies are proposed to address the limitations of the bulky batteries.\(^{215,271-279}\) Solar energy as the cleanest and most abundant renewable energy source has been widely adopted by many self-powered wearable systems. A self-powered sensor system containing a solar cell is developed on a plastic substrate to convert the incoming light into electricity as the power supply of the whole sensing system (Figure 9A).\(^{280}\) To realize the continuous operation of sensing system without the limitation of surrounding conditions such as insufficient light intensity, planar MnO\(_2\)-based supercapacitors are integrated into the system as intermediate energy storage units. By further combining with the SnO\(_2\) gas sensor, a self-powered ethanol/acetone sensor with high sensitivity has been demonstrated, showing its great potential for a wide variety of biomedical monitoring applications. Besides, mechanical energy is also ubiquitously available in ambient and has been considered as another promising power source for self-sustainable wearable and implantable electronics.\(^{281,282}\) A high-output magneto-mechano-triboelectric nanogenerator that can generate electricity from the alternating magnetic field has been reported lately, and it can successfully power up an indoor wireless positioning system as shown in Figure 9B.\(^{283}\) The generated electrical energy is connected to a storage unit through a power management circuit, which enables the continuous operation of an IoT Bluetooth beacon for wireless signal transmission. Converting human body heat into a form of usable energy provides another reliable approach for self-powered wearable systems.\(^{284,285}\) As shown in Figure 9C, a flexible thermoelectric generator (TEG) is developed with a polymer-based heat sink assembled on the top surface to further increase the output power density from 8 to 38 μW cm\(^{-2}\).\(^{286}\) An electrocardiography (ECG) sensing circuit is also fabricated on a flexible PCB substrate and powered by the wearable TEG using body heat as the power source. Different from the solar energy or mechanical energy, despite a lower energy density, body heat exists reliably with minimal interferences from the ambient environment.

For implantable electronic devices, the power sources could be limited in terms of the targeted applications and usage scenarios. By separating the physical location of the power source and the implanted functional elements, a self-powered implantable rehabilitation system could be feasible by making use of the large output from the wearable energy harvesters.\(^{264,287-289}\) A self-powered system with a stack-layered TENG and a multiple-channel epimysial electrode is demonstrated for direct muscle stimulation (Figure 9D).\(^{290}\) The generated current output is directly connected to the muscle tissue through the inserted multi-channel electrodes. It is found that the generated force output is more stable than using the conventional square wave stimulation as well as enveloped high-frequency stimulation. Besides, the unique current waveforms of the TENG can effectively reduce force fluctuation caused by the synchronous motoneuron recruitment at the simulation electrodes. The results indicate a promising future of using TENG in direct muscle stimulation for self-powered rehabilitation and treatment of muscle function loss. To eliminate the wire connection from the outside of body to the inside, the inclusion or delivery of electrical power becomes a major challenge for implantable medical devices. Harvesting biomechanical energy from cardiac motion, respiratory movement, and blood flow can be a possible solution, but with the limitation of low output power density and highly restricted implantation sites.\(^{214,291,292}\) In this regard, delivering mechanical energy from the outside of the body to the implanted devices becomes the most promising technology to provide enough power for a battery-free implantable medical system. Energy delivery through ultrasound using capacitive triboelectric technology is reported lately (Figure 9E).\(^{293}\) The implantable TENG is designed to be inserted underneath the skin, which consists of a perfluoroalkoxy (PFA) membrane that is able to vibrate under the pressure of ultrasound. A rectifier,
transformer, voltage regulator, and battery are integrated with the TENG device, forming the energy converting, and storage unit. In terms of output performance, this prototype can generate an output power of milliwatts to charge up capacitors and Li-ion batteries, demonstrating its great potential in providing continuous energy to implanted medical devices. Another strategy to avoid the essential need of rechargeable batteries is the use of a radio-frequency coupling method to wirelessly operate the implanted sensing elements.\textsuperscript{294} A biodegradable and flexible arterial-pulse sensor is proposed for wireless blood flow monitoring, as illustrated in Figure 9F.\textsuperscript{295} The device consists of a capacitive sensor and a bilayer coil for radio-frequency data transmission. The change of the capacitance resulted from the vessel diameter variations as blood flowing through leads to a shift in the resonant frequency of the inductor-capacitor-resistor circuit, which can be monitored wirelessly through inductive coupling with the external reading coil without any batteries inside the body. Its biodegradable property also avoids the issue of secondary procedure for implant removal. In the near future, this kind of battery-free sensing technique could be optimal to provide biomedical functionalities for implantable electronics that largely benefit the personalized healthcare monitoring and rehabilitation.

**FIGURE 9** Self-powered and battery-free wearable and implantable systems. A, Self-powered gas monitoring system with embedded solar cells as the energy source. Reproduced with permission from Reference 280, Copyright 2018, Wiley-VCH. B, Self-powered indoor IoT positioning system integrated with energy harvesting and storage units. Reproduced with permission from Reference 283, Copyright 2019, The Royal Society of Chemistry. C, Self-powered wearable electrocardiography system powered by a wearable thermoelectric generator. Reproduced with permission from Reference 286, Copyright 2018, The Royal Society of Chemistry. D, Self-powered muscle stimulation system with a stacked-layer TENG as the power source. Reproduced with permission from Reference 290, Copyright 2019, Wiley-VCH. E, Implantable TENG for ultrasound energy harvesting through skin and liquids. Reproduced with permission from Reference 293, Copyright 2019, American Association for the Advancement of Science. F, Biodegradable pressure sensor for arterial pulse monitoring that is operated wirelessly. Reproduced with permission from Reference 295, Copyright 2019, Nature Publishing Group. IoT, internet of things; TENG, triboelectric nanogenerator
The rapid development of AI technologies has significantly promoted the enormous advances in wearable electronics to achieve intelligence in the processes of sensory data acquisition, processing/analysis, and transmission. The conventional method for signal analysis is to manually extract basic features from the sensory signals. AI technology not only can assist wearable sensors to detect more complex and diverse sensor signals, but also can automatically extract the dramatic features representing the internal relationship of data sets from sensors. By matching the proper learning models with specific sensing applications, more comprehensive information can be extracted from these diversely designed sensors, leading to a progressive revolution of wearable electronics. For instance, a sandwich-structure piezoelectret with high equivalent piezoelectricity constructs an active pulse sensing system which can detect the weak vibration patterns of the human radial artery based on machine learning analysis, as shown in Figure 10A. Through comparing the similarity between two pulse waves with a dynamic time warping (DTW) algorithm, a DTW distance is calculated to reflect the similarity. As a result, the true positive rate (TPR) values is 77.0%, which means a...
volunteer will be identified successfully in 770 out of 1000 trials. Besides, a wearable and flexible strain sensor that is capable of detecting swallowing activity is proposed for the dysphagia monitoring and the potential identification of the degradation in the swallowing function for patients with head and neck cancer (Figure 10B). A machine-learning algorithm based on the L1-distance is adopted to identify the human swallowing process, that is, to distinguish the signals of a healthy subject (86.4% accuracy) and a dysphagic patient (94.7% accuracy) when swallowing the same bolus. These results may lead to non-invasive and home-based systems for the monitor of swallowing function and the clinical usage of such wearable electronics. Moreover, another speaker recognition system is reported using a flexible piezoelectric acoustic sensor (f-PAS) based on the Gaussian Mixture Model (GMM) algorithm (Figure 10C), which can reach an excellent speaker recognition accuracy of 97.5%. The intrinsic voice information obtained from the highly sensitive multi-channel membrane 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.

For decades, different from conventional machine-learning techniques that are limited by their relatively weak ability to handle natural data sets, deep learning can extract much higher-level and more meaningful features by training an end-to-end neural network. In addition, deep learning as a new subfield of machine learning provides an efficient way to adaptively learn representative features from collected raw signals especially on unsupervised and incremental learning, which has made great achievements in image processing, speech recognition, human activity recognition, and so on. With the development of various sensing mechanisms, the design of wearable electronics is also moving toward huge amounts of data points and high-level features with significant complexity. Deep learning method has unique advantages in processing high-dimensional and nonlinear data, which can discover the intricate structure in large data sets. A self-powered neural finger skin is developed with a triboelectric layer and a graphene sensor array, mimicking the fast, and the slow adaptive mechanoreceptors in human skin, to continuously monitor the applied pressure (Figure 10D). Benefited from the advantages of deep learning technology, the proposed method of neural network pattern can help the device distinguish the delicate difference between the 12 fabrics’ surface textures with an accuracy of 99.1%. Moreover, a low-cost (about 10 USD) and scalable tactile glove (STAG) is developed, as shown in Figure 10E. By analogizing the fundamental perception primitives between the visual and tactile domains, the STAG is assembled with a minimal sensor count as that for image processing (32 × 32 pixels) of 584 piezoresistive sensor array distributed on palm for interacting with 26 different objects. After identifying the 32 × 32 tactile map in the sensor coordinates, the STAG uses a ResNet-18-based architecture 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 interactions at a deeper level with the improvement of flexible electronic elements and the assistance of deep learning techniques, thereby aiding the future design and development of the next-generation wearable electronics and systems.

5 | PERSPECTIVE

According to the recent progress of wearable electronics/photonics, the advancement of the next-generation wearable electronics and photonics will be continued toward systems with multifunctionality, self-sustainability, and higher intelligence. First of all, more functionalities are expected to be integrated into one wearable device to achieve higher productivity. In this regard, a major research direction in this field is to mimic the somatosensory system of human skin using mechanically flexible/stretchable sensor networks (also known as electronic-skin or mechanosensation electronics) that could detect and quantify multiple external stimuli, including but not limited to pressure, strain, temperature, humidity, light, and so on. Recently, a highly stretchable matrix with integrated multi-sensors on a polyimide network was successfully developed to achieve multiple sensing functionalities, such as pressure, in-plane strain, temperature, humidity, light, magnetic field, and proximity. Configuring into 3D integrated scheme, this sensing matrix is able to achieve simultaneous multi-stimulus detection, showing significant impacts in broad interacting technologies such as humanoid robotics, prosthetics, healthcare monitoring, and HMIs. In addition, wearable optoelectronic display and photonic communication/sensing modules can be further integrated to enable a complete monitoring system with easy visualization, high data transmission rate, and EMI-free wireless communication. Apart from advancing to multifunctionality, energy is always one inevitable bottleneck in modern electronic systems. To realize a long-term functionality that is difficult to achieve using conventional batteries as the power sources, the rapid innovation of energy harvesting and storage technology provides an alternative and promising solution, leading to a field of self-sustainable or self-
powered electronics/systems. With the integration of hybrid energy harvesters and storage units in wearable systems, available energy such as contact, vibration, heat, and light in the ambient surroundings can be effectively scavenged by different transducing mechanisms. The scavenged ambient energy is converted into useful electricity (through piezoelectric, triboelectric, thermoelectric, pyroelectric, photovoltaic effect, etc.), and stored in integrated storage units for the continuous operation of the wearable systems. Even with the use of hybrid energy harvesting mechanisms, the actual average power from most current energy harvesters is still unsatisfactory to support the real-time operation. The common scenario in most of the current self-sustainable systems is that energy harvesting units need to work for a relatively long period to support the operation of the whole system in a short period. In this regard, the energy harvesting performance and efficiency of various mechanisms need to be continuously improved, in order to realize a truly self-sustainable wearable system with real-time and continuous functionality. Last but not least, the prosperous development of AI and wearable electronics/photonics has facilitated the emergence of a brand-new research area, that is, intelligent/smart wearable systems, with broad applications in personalized healthcare monitoring and treatment, identity recognition, smart home/office/building, and intelligent interactions in VR/AR environment, and so on. Benefited by novel machine learning algorithms in the process of data analysis, the intelligent systems are able to automatically extract critical features with internal relationships from the complicated and diverse sensory signals. Through matching a particular functional system with a proper machine learning model, more comprehensive information can be extracted for later identity recognition and decision making, leading to highly intelligent/smart wearable systems. In summary, the development trends of the next-generation wearable electronics/photonics will be continuously advanced toward multifunctional, self-sustainable, and intelligent systems in the era of AI/IoT.

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CONFLICT OF INTEREST
The authors declare that they have no conflict of interest.

ORCID
Chengkuo Lee https://orcid.org/0000-0002-8886-3649

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Qiongfeng Shi received his BE degree from the Department of Electronic Engineering and Information Science, University of Science and Technology of China (USTC) in 2012, and received his PhD degree from the Department of Electrical and Computer Engineering, National University of Singapore (NUS) in 2018. He is currently a Research Fellow in the Department of Electrical and Computer Engineering, National University of Singapore, Singapore. His research interests include energy harvesters, sensors, nanogenerators, human-machine interfaces, wearable, and implantable electronics.

Bowei Dong received the BS degree in physics with second major in mathematics from Nanyang Technological University, Singapore, in 2015, the PhD degree from the NUS Graduate School for Integrative Sciences and Engineering at the National University of Singapore, Singapore, in 2019. He is currently a research fellow in the Department of Electrical and Computer Engineering, National University of Singapore, Singapore. His research interests include integrated silicon photonics and mid-infrared photonics.

Chengkuo Lee received his MSc Degree in Industry and System Engineering from Rutgers University in 1993, and PhD degree in Precision engineering from the University of Tokyo in 1996. In 2001, he cofounded Asia Pacific Microsystems, Inc., where he was the Vice President. From 2006 to 2009, he was a Senior Member of the Technical Staff at the Institute of Microelectronics, A-STAR, Singapore. Currently, he is the director of Center for Intelligent Sensors and MEMS at National University of Singapore. He serves as the co-editor-in-chief of IEEE Transactions on Nanotechnology. His research interests include sensors, IoT, and nanophotonics.

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