Nano Energy 129 (2024) 110045



Contents lists available at ScienceDirect

Nano Energy

journal homepage: www.elsevier.com/locate/nanoen



Review



Innovations in self-powered sensors utilizing light, thermal, and mechanical renewable energy

Jihyeon Ahn [a,1], Seokjoo Cho [a,1], Lei Wu [c], Xuan Li [a], Donho Lee [a], Ji-Hwan Ha [a,b], Hyeonseok Han [a], Kichul Lee [a], Byeongmin Kang [a], Yeongjae Kwon [a], Soon Hyoung Hwang [b], Sohee Jeon [b], Bingjun Yu [c], Junseong Ahn [d,*], Jun-Ho Jeong [b,*], Inkyu Park [a,*]

[a] Department of Mechanical Engineering, Korea Advanced Institute of Science and Technology (KAIST), Daejeon 34141, the Republic of Korea
[b] Department of Nano Manufacturing Technology, Korea Institute of Machinery and Materials (KIMM), Daejeon 34103, the Republic of Korea
[c] Tribology Research Institute, State Key Laboratory of Traction Power, Southwest Jiaotong University, Chengdu 610031, China
[d] Department of Electro-Mechanical Systems Engineering, Korea University, Sejong 30019 the Republic of Korea

ARTICLE INFO

Keywords:
Self-powered sensor
Electricity generation
Renewable primary energy source
Physical sensor
Chemical sensor

ABSTRACT

In the era of the Internet of Things, which requires a vast number of distributed sensors for diverse applications, there exists a surging need for physical and chemical sensors that are self-powered. The adoption of self-powered sensors has the potential to significantly reduce the overall power consumption in electronics, enabling the development of more combined and intelligent sensing systems. Among the various self-powered sensors, those based on electricity generation are garnering considerable attention because of their compatibility with commercial electronic components. Recently, extensive research has been conducted on self-powered sensors based on electricity generation, leading to the development of several conceptual and practical sensors. This review article examines the recent advancements in self-powered sensors based on the types of wasted or renewable primary energy (RPE) sources, including light, thermal, and mechanical energy sources. Specifically, based on the working mechanisms of generating electricity from wasted or RPE sources, the appropriate types of sensors are discussed, with their respective characteristics evaluated. Additionally, several promising strategies are presented to overcome bottlenecks. Finally, potential applications are summarized and an outlook for commercialization is provided. These perspectives are expected to further advance the field of self-powered sensors and inspire further research.

1. Introduction

As human society continues to advance toward greater sophistication and intelligence, the usage of electronic devices is rapidly escalating. Specifically, to realize the advanced era of the Internet of Things (IoT) and metaverse, there exists a surging demand for numerous physical and chemical sensors.[1–16] Consequently, it is crucial to manage the power consumption of sensors to ensure stable and sustainable operation. In addition, researchers are actively exploring ways to reduce the overall power consumption considering growing concerns regarding the environmental pollution owing to energy usage. To resolve these problems, self-powered sensors are particularly essential for networks that monitor the environment, primarily because the sensors can operate independently in remote and inaccessible areas without the need for frequent maintenance or battery replacement. Continuous chemical and biosensing applications benefit from self-powered sensors as they provide long-term, uninterrupted monitoring capabilities, which is crucial for detecting pollutants or pathogens in real time. Furthermore, smart infrastructure solutions rely on self-powered sensors for continuous structural health monitoring, ensuring the integrity and safety of critical infrastructure while minimizing energy costs and maintenance efforts.[17–23] Therefore, self-powered sensors are considered one of the most promising options to advance wireless sensing applications. Representatively, a common approach to implement self-powered sensors involves integrating a green energy harvester into a conventional sensor to drive the sensor with the harvested energy.[24,25] However, while the method is useful when space is not a constraint, it is not generally suitable because it increases the overall complexity of the electronic

* Corresponding authors.
E-mail addresses: junseong@korea.ac.kr (J. Ahn), jhjeong@kimm.re.kr (J.-H. Jeong), inkyu@kaist.ac.kr (I. Park).
[1] These authors contributed equally.

https://doi.org/10.1016/j.nanoen.2024.110045
Received 1 May 2024; Received in revised form 3 July 2024; Accepted 23 July 2024
Available online 25 July 2024
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device. Another approach is colorimetric sensing, which uses the color changes of the sensor to indicate the sensor output value without an electrical power source.[26,27] The method can reduce power consumption to zero; however, it encounters challenges in achieving precise quantification and compatibility with existing electronic systems. Therefore, in recent years, research has been actively conducted to implement self-powered sensors utilizing an electricity generation mechanism from wasted or RPE sources, such as light, thermal, and mechanical energy sources, directly to the sensor.[28–30] Generally, conventional sensors require external power to convert the physical change of the sensor by input stimuli into an electrical output signal that can be measured. (e.g., a continuous voltage or current should be applied to measure the physical change of an electrical resistance-based sensor. The generated voltage or current should then be measured to determine the resistance value in reverse.[31]). However, self-powered sensors generate electric signals directly as the output of the sensor in response to an external physical parameter change, making them directly compatible with other electronic components, and thus consume less power while having high systematic efficiency. For example, Seo et al. reported a gas sensor using a photovoltaic (PV) cell that converts photons into electrons.[32] The authors introduced a self-powered gas sensing system by mechanically designing a film whose light transmittance changes based on the concentration of the target gas and integrating it onto a photovoltaic cell. In another study, Luo et al. developed a self-powered pressure sensor based on a triboelectric nanogenerator (TENG) that converts wasted mechanical energy into electrical energy.[33] The authors claimed that the TENG can be effectively applied as a self-powered pressure sensor because the amount of triboelectricity generated depends on the magnitude of the mechanical pressure input. Overall, recent advancements in self-powered physical and chemical sensors based on electricity generation have made significant strides in developing new sensing mechanisms and improving sensing performance through rational structural and material design. However, previous literature reviews have primarily focused on individual mechanisms, such as TENG-based self-powered sensors [34] or PV-based self-powered sensors.[35,36] Additionally, there are reviews on various types of self-powered sensor systems and reports on recent structures of these sensors.[37,38] Therefore, there is a pressing need for a comprehensive and detailed review that encompasses the latest developments in this field, specifically in terms of their energy conversion mechanisms from renewable energy sources. The focus of this review is essential because harnessing renewable energy for direct sensor operation is the primary objective of self-powered sensors.

This review aims to fill this gap by providing an extensive overview of recent advancements in self-powered physical and chemical sensors that utilize light, thermal, and mechanical renewable energy sources, as illustrated in Fig. 1. By emphasizing the integration of these energy conversion mechanisms, we highlight unique points that differentiate this review from previous ones, ensuring its relevance and contribution to the field. To this end, we first classify these sensors into three

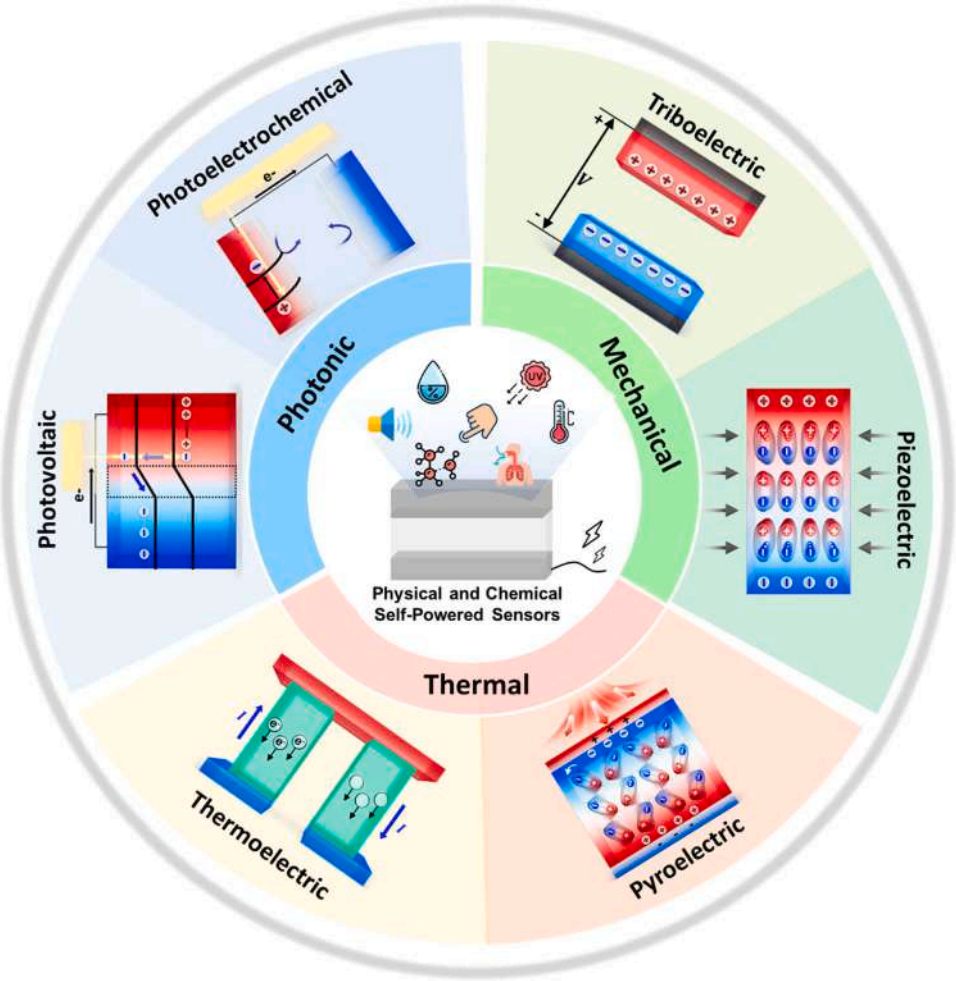


Fig. 1. Self-Powered Physical and Chemical Sensors based on Electricity Generation. Schematic of self-powered sensors classified based on external energy sources and working mechanisms, including those based on a light energy source (PEC reaction and PV effect), mechanical energy source (triboelectric effect and piezoelectric effect), and thermal energy source (pyroelectric effect and thermoelectric effect).

categories based on the type of waste or renewable energy source used. Subsequently, each category is further classified into subsections based on the working mechanisms for electricity generation.

The remainder of this review is organized as follows: Subsection 2.1 describes sensors based on electricity generation strategies from light energy sources, such as PV and photoelectrochemical (PEC) methods. Subsection 2.2 discusses sensors based on electricity generation strategies from thermal energy sources, such as pyroelectric and thermoelectric methods. Subsection 2.3 covers sensors based on electricity generation strategies from mechanical energy sources, such as triboelectric and piezoelectric methods. For each mechanism, we explore various studies that have utilized these methods as sensors and discuss the appropriate types of sensors, including the design methods of the structures and materials required to further optimize the sensing performance. Further, we summarize the niche applications of self-powered sensors based on their working principles and highlight the unique merits of self-powered sensors as next-generation electronic devices. Table 1 presents a brief overview and classification of self-powered physical and chemical sensors based on renewable primary energy (RPE) sources. Table 2 presents the detailed specifications and typical applications of these sensors. Subsection 2.4 introduces recently reported hybrid devices that integrate two or more self-powered sensors to exploit their synergistic effects. Section 3 discusses the summary and current limitations of self-powered sensors and provides insights into future research areas to overcome existing limitations. Finally, Section 4 provides the concluding remarks.

2. Self-powered physical and chemical sensors based on electricity generation

As the field of self-powered physical and chemical sensors continues to evolve, remarkable advancements have been made in developing new sensing mechanisms and improving sensor performance through the rational design of structures and materials. Self-powered sensors that utilize renewable energy sources such as light, thermal, and mechanical energy have shown great promise in various applications, including water pollution detection, human motion detection, and acoustic detection.

These applications demand specific performance requirements from self-powered sensors, including but not limited to the following:

For applications in water pollution detection, such as microcystin-LR (MC-LR), the following criteria must be satisfied [39]:

$R^2 > 0.996$,

The detection range exceeding 0.5–30000 ng/mL,

Limit of detection (LOD) < 0.2 ng/mL.

The specifications for a wearable strain sensor that is used in workout monitoring should be as follows [40]:

Stretchability > 50 %

Gauge Factor (GF) > 1

Response time < 200 ms

A sensor for detecting coughing must be designed to satisfy the following specifications [41,42]:

The ratio of the signal during coughing compared to the signal during breathing >1.06: 1

Response time < 100 ms

Stability > 8000 cycles

To accurately sense acoustic properties, a pressure sensor must possess the following characteristics [43,44]:

Sensitivity $> 0.018 kPa^{-1}$

Stability > 5000 cycles

Understanding and meeting these requirements is crucial to ensure the successful implementation of self-powered sensors in real-world scenarios. In the following sections, we provide an extensive overview of recent advancements in self-powered sensors based on different renewable energy sources. We first classify these sensors into three categories based on the type of waste or renewable energy source used. Subsequently, each category is further classified into subsections based on the working mechanisms for electricity generation. For each type of sensor, we briefly discuss their performance characteristics, including sensitivity, dynamic range, and response time, and how they satisfy the requirements of their respective applications.

2.1. Self-powered sensors based on electricity generation from light energy sources

Light energy sources such as sunlight or artificial lighting provide an abundant power supply for various applications, particularly in powering devices for health and environmental monitoring. For instance,

Table 1
Summary of Self-Powered Physical and Chemical Sensors based on Electricity Generation.

Energy sources	Electricity generation mechanism	Applicable types of sensors	Characteristics	Representative applications	References
Light energy	Photoelectrochemical reaction	Pollution, bio-, and gas sensors	High selectivity and sensitivity. Solar light intensity sensitivity and long-term instability.	Monitoring cancer cell concentration, and wearable sensors	[49–71]
	Photovoltaic (PV) effect	Pressure, strain, gas, and humidity sensors	High degree of dependability. Sensitive to the external environment and inconsistent data.	Human motion monitoring, wind detection, and structural health monitoring	[72–80,219,220]
Thermal energy	Thermoelectric effect	Temperature, pressure, strain, and gas sensors	Suitable for steady-state temperature monitoring. Reliance on stable temperature gradient.	Human motion monitoring, fire alarm, and environment monitoring	[81–122]
	Pyroelectric effect	Temperature, light, and touch sensors	Suitable for monitoring rapid temperature changes. Reliance on rapid temperature fluctuations.	Human motion monitoring, respiration monitoring, and thermal imaging	[123–146]
Mechanical energy	Triboelectric effect	Pressure, gas, bio-, and wave sensors	Instantaneous pressure sensing and material selection diversity. Sensitive to moisture, temperature, discharging, and contact electrification.	Sleep monitoring, respiration monitoring, water height monitoring	[20,29,147,150–177, 179,180,182–187]
	Piezoelectric effect	Pressure, gas, and motion sensors	High sensitivity, fast response time, and compact size. Low deformation, inadequate gas permeability, and weak damage tolerance	Gait recognition system, pulse sensor, sweat sensor, sound monitoring sensor	[190–210]

Table 2
Recently Published Representative Examples in Self-Powered Physical and Chemical Sensors based on Electricity Generation in terms of Types and Performance of the Sensors.

Types of sensors	Self-powered mechanism	Sensing performance	Applications	References
Pressure sensor	Photovoltaic effect	Sensitivity: 0.101 kPa^{-1} Linearity: R^2 =0.995 Working range: 1–120 kPa	Mask for breathing monitoring Wind speed and direction detection	[219]
	Thermoelectric effect	Pressure sensitivity > 20 kPa^{-1} Pressure range: 0−20 kPa Temperature resolution < 0.1 K Temperature range: 0–100 K Seebeck coefficient: 200 μV K^{-1}	Touch sensor and artificial human skin	[93]
	Triboelectric effect	Sensitivity: 10.79 mV/Pa Working frequency bandwidth: 0–40 Hz	Human sleep monitoring	[189]
	Piezoelectric effect	Sensitivity: 0.018 kPa^{-1} Response time: 60 ms Working frequency bandwidth: 0.2–240 Hz	Pulse monitoring system and respiration monitoring sensor	[192]
Strain sensor	Photovoltaic effect	GF ≈ 10.5 Hysteresis: 0.508 % Linearity: R^2 > 0.997 Response time < 20 ms Working range: 0–30 %	Monitoring aerostat inflation/deflation, artificial satellite crack propagation, and human motion	[80]
	Thermoelectric effect	Strain range: 0–400 % Temperature range: 0–25 K Seebeck coefficient: 31 μV K^{-1}	Wearable electronics	[101]
	Piezoelectric effect	Maximum output voltage: 6 V Maximum output current density: 0.2 μA/cm^2 Sensitivity: 13 at 0.09 %	Wrist motion sensor	[205]
Temperature sensor	Pyroelectric effect	Open-circuit voltage: 42 V Short-circuit current: 2.5 μA Output power: 8.31 μW	Respiration monitoring	[129]
	Pyroelectric effect	Temperature range: −10–80 °C Output power: 14 mW cm^{-2}	Human motion monitoring	[142]
Gas sensor	Photoelectrochemical reaction	Working range: 200 ppb – 10 ppm Linearity: R^2 > 0.99 Sensitivity: 1.74 %/ppb Response time: 46.2 s Recovery time: 59.3 s	Wearable electronics (NO_2 gas sensing)	[70]
	Photovoltaic effect	Working range: 1–20 ppm	Self-powered gas sensor system in an indoor environment	[78]
	Thermoelectric effect	Response time: 17 s Output response: 42.4 μV Seebeck coefficient: 897 μV K^{-1}	Hydrogen monitoring at room temperature	[104]
	Triboelectric effect	Sensitivity: 20.13 ppm^{-1} Working range: 0.1–10 ppm Humidity range: 11.3–97.5 % RH	Wearable respiration sensor	[173]
Pollution sensor	Photoelectrochemical reaction	Linearity: R^2 = 0.9985 Working range: 0.5–4 × 105 pmol/L Working cycle: 10 on/off irradiation cycles	Environmental analysis (MC-LR detection in lake)	[68]
Biosensor	Photoelectrochemical reaction	Working range: 20–20,000 cell/mL Maximum change in power output: 0.974 μWcm^{-2} Maximum change in photocurrent density of the cytosensor: 9.74 μAcm^{-2}	Platform to detect CCRF-CEM cells and monitor the progression of leukemia.	[66]
	Piezoelectric effect	Resolution: 0.02 ± 0.005 mML^{-1} (Glucose) 0.01 ± 0.005 mML^{-1} (Uric acid) 0.5 ± 0.2 mML^{-1} (Urea)	Wearable noninvasive electronic skin	[203]
Light sensor	Pyroelectric effect	Response time: 15 μs Output current: 1.05 × 10^{-3} A Output power: 4.8 mW cm^{-2}	Near-infrared sensor for optothermal detection and biological imaging	[128]
Wave sensor	Triboelectric effect	Sensitivity: 23.5 mV/mm Frequency bandwidth: 0.6–1.2 Hz Working range: 0–0.035 gmL^{-1}	Smart marine equipment	[150]

self-powered photoelectrochemical sensors can detect glucose and hydrogen peroxide levels in medical diagnostics. [45] Similarly, sensors are used for the sensitive detection of sarcosine, a biomarker of prostate cancer.[46] These applications demonstrate the utility of light energy in continuous monitoring without requiring external power sources, enhancing the sustainability and efficiency in critical areas. Self-powered sensors that rely on sunlight offer significant advantages, including abundance, sustainability, and cost-effectiveness. Furthermore, the utilization of artificial light, which is prevalent in both indoor and outdoor environments, presents notable advantages in terms of environmental sustainability and cost-effectiveness because it obviates the need for supplementary devices or infrastructure. Light energy is typically utilized in sensing applications using two main approaches: observing alterations in light intensity transmitted through a functional film in response to external physical or chemical stimuli, or leveraging photochemical reactions triggered by light.

To further exploit these characteristics, future research should focus on optimizing the spectral sensitivity of sensors to maximize energy absorption across various light conditions. This involves the exploration of materials with broad-spectrum light absorption capabilities and the development of sensors that can adapt their performance based on ambient light conditions. While key avenues for future research have been briefly outlined above, detailed discussions on each specific area are provided in the following subsections.

2.1.1. Self-powered sensors based on photoelectrochemical reactions

A PEC sensor comprises a photoelectrode composed of a semiconductor material that serves as both a sensing element and an energy conversion element. Self-powered PEC sensors operate on the fundamental principle of harnessing solar light to induce photoelectrode activation. The target analyte, which can exist as a gas, liquid, or solid, interacts with the surface of the photoelectrode. When the photoelectrode is illuminated with ambient light, the semiconductor material becomes excited, facilitating redox reactions that involve the target material and the subsequent movement of electrons to generate a measurable sensing current. (Fig. 2**a**).

These sensors can achieve high selectivity for specific analytes through the integration of suitable surface functionalization or selective recognition elements. Several critical material and design considerations are essential in effectively designing and utilizing a photoelectrochemical (PEC) sensor. The choice of photoactive materials is crucial, with common options including semiconductor materials such as TiO_2, ZnO, CdS, and Fe_2O_3, as well as organic semiconductors such as P3HT and PCBM. The electrode material must exhibit high conductivity and transparency, with ITO, FTO, or graphene often used.[47] The electrolyte must facilitate efficient ion transport, with aqueous solutions, ionic liquids, and solid-state electrolytes being common choices. Design considerations include optimizing the interface between the photoactive material and the electrode for efficient charge transfer and ensuring that the architecture supports good light absorption and distribution. Self-powered PEC sensors, akin to PV cells, utilize abundant and renewable solar energy, eliminating the need for external energy sources. However, these sensors are susceptible to variations in solar light intensity and face challenges under low-light conditions, such as at night. Long-term stability and durability are also concerns as photoelectrodes can degrade due to corrosion, fouling, or other factors that affect the performance and lifespan of the sensor.

Therefore, it is necessary to consider both the sensitivity of the sensor to low solar irradiance and the susceptibility of the material to degradation during sensor manufacturing. Further, these materials pose challenges related to their complex synthesis, electrochemical reactions, and light absorption characteristics. Thus, the development of a facile material fabrication process is expected to facilitate the efficient replacement of degraded sensors and enable the simultaneous operation of multiple sensors, thereby capitalizing on the inherent advantages of self-powered PEC sensors. Recent advances have focused on developing new materials and fabrication techniques to enhance the performance of PEC sensors. For instance, Li et al. employed a cost-effective and controllable wax-printing technique to fabricate a paper-based PEC device, offering affordability, ease of control, and potential for large-scale production, as shown in Fig. 2**b**.[48] This approach offers advantages such as affordability, ease of control, and potential for large-scale production, and therefore, can be used for multiple sensors.

Substances that exhibit light-induced chemical reactions and aptamers have significant potential for detecting specific biomaterials and biological organisms. [49–65] For example, CCRF-CEM, a human T lymphoblast that is indicative of cancer based on its concentration in blood, can be detected through PEC analysis.[66] When exposed to visible light, electrons photogenerated from the g-C_3N_4 quantum dot (QD) material become excited and migrate to the conduction band, where they are easily injected into zinc oxide (ZnO) nanodisks (NDs) and subsequently transmitted to the external circuit. However, if a CCRF-CEM cell that serves as the sensing target is present, the electrons become obstructed because CCRF-CEM binds to the aptamer Sgc8c, which specifically reacts with this cell, resulting in a reduced power output (Fig. 2**c**). Pang et al. synthesized ZnO NDs and g- C_3N_4 QDs to enhance visible light absorption and increase the number of surface-active sites, thereby improving the separation of photogenerated electron-hole pairs.(Fig. 2**d-i)** [66] Consequently, a linear relationship is observed between the change in the power output and the logarithm of the CCRF-CEM cell concentration, indicating the selectivity of the sensor (Fig. 2**d-ii**).

Chemical contaminants in water can be detected using visible light. [67,68] Tao et al. synthesized a composite material for detecting MC-LR, which causes the eutrophication of freshwater and liver cancer in humans.[68] In_2S_3 nanosheets (NSs), In_2O_3 hollow tubules (HT), and Ti_3C_2 QDs were synthesized and used as photoanodes to create an S-scheme heterojunction that facilitated the separation of photogenerated charges with a large surface area (Fig. 2**f-i**). When the In_2O_3 HTs and In_2S_3 NSs are in close contact, an internal built-in electric field is generated from the In_2S_3 NSs to the In_2O_3 HTs at the interface. The photogenerated electrons in the In_2S_3 NSs spontaneously migrate to the surface of the Ti_3C_2 QDs. As different concentrations of the MC-LR solution are anchored on the photoanode, MC-LR molecules are oxidized by the photogenerated holes. The concentration of MC-LR is determined by monitoring the fluctuations in the anode photocurrent signal (Fig. 2**e**). High linearity is obtained using a calibration equation (Fig. 2**f-ii**).

The PEC principle can be employed for gas sensing without requiring external electric power.[69–71] Yue et al. developed a device for sensing NO_2 gas under visible-light irradiation.[69] When a p-n junction is exposed to light, electron–hole pairs are generated in both the MoS_2 and GaSe layers, and they tend to migrate to the interface. The electrons are transferred to MoS_2, holes are transferred to GaSe, and the current flows because of the built-in electric field between the two materials. NO_2 gas exhibits strong electron affinity, enabling it to readily capture electrons from the conduction band of the material. Consequently, the resistance of the heterojunction increases, and the current decreases upon exposure to NO_2 (Fig. 2**g**). The device incorporates a GaSe/MoS_2 heterojunction fabricated to provide high photoresponsivity and a short response time. The heterojunction is synthesized by overlapping MoS_2 and GaSe nanoflakes (Fig. 2**h-i**). The response to the NO_2 concentration conforms to the Langmuir isotherm and exhibits good recovery (Fig. 2**h-ii**).

Self-powered PEC sensors have applications in chemical fields that involve the control of electron movement, such as the detection of harmful gases and specific biomaterials. Furthermore, because these sensors rely solely on solar irradiation, they are useful for environmental analysis, particularly for the detection of contaminants in water bodies, such as lakes (see Fig. 2**i**).[68] The result of sensing lake contamination indicates that the higher the concentration of MC-LR, the greater the intensity of the photocurrent (Fig. 2**j-i**). The calibration equation demonstrates a linear relationship between concentration and current, enabling the sensor to achieve a wide detection range of 0.5–4 $\times$ 10^2 pmol/L. Within this range, the concentration and current exhibited high linearity, with an R^2 value of 0.9985. Additionally, the limit of detection (LOD) was confirmed to be in the pmol/L range, verifying the suitability of the sensor to detect water contamination (Fig. 2**j-ii**). In_2S_3 nanosheets (NSs), In_2O_3 hollow tubules (HT), and Ti_3C_2 QDs were selected to efficiently detect MC-LR in lakes. These materials form an S-scheme heterojunction, enhancing charge separation and increasing surface area. The contact between In_2O_3 HTs and In_2S_3 NSs creates an internal electric field, facilitating electron migration to the Ti_3C_2 QDs. It enhances the photocurrent response, enabling the photogenerated holes to oxidize MC-LR. The concentration is determined by monitoring the photocurrent signal, ensuring high sensitivity and specificity.

PEC sensors exhibit high selectivity, sensitivity, and self-powered operation; however, the challenges related to the sensitivity to solar-light intensity and long-term stability remain unresolved. Addressing these limitations through ongoing research efforts holds promise for improving the sensor performance under various environmental conditions, including areas with weak sunlight. Future developments could also focus on synthesizing more robust materials to enhance the operational lifespan and reliability of these self-powered sensors in diverse settings.

2.1.2. Self-powered sensors based on photovoltaic effects

Self-powered sensors convert light energy into electrical energy

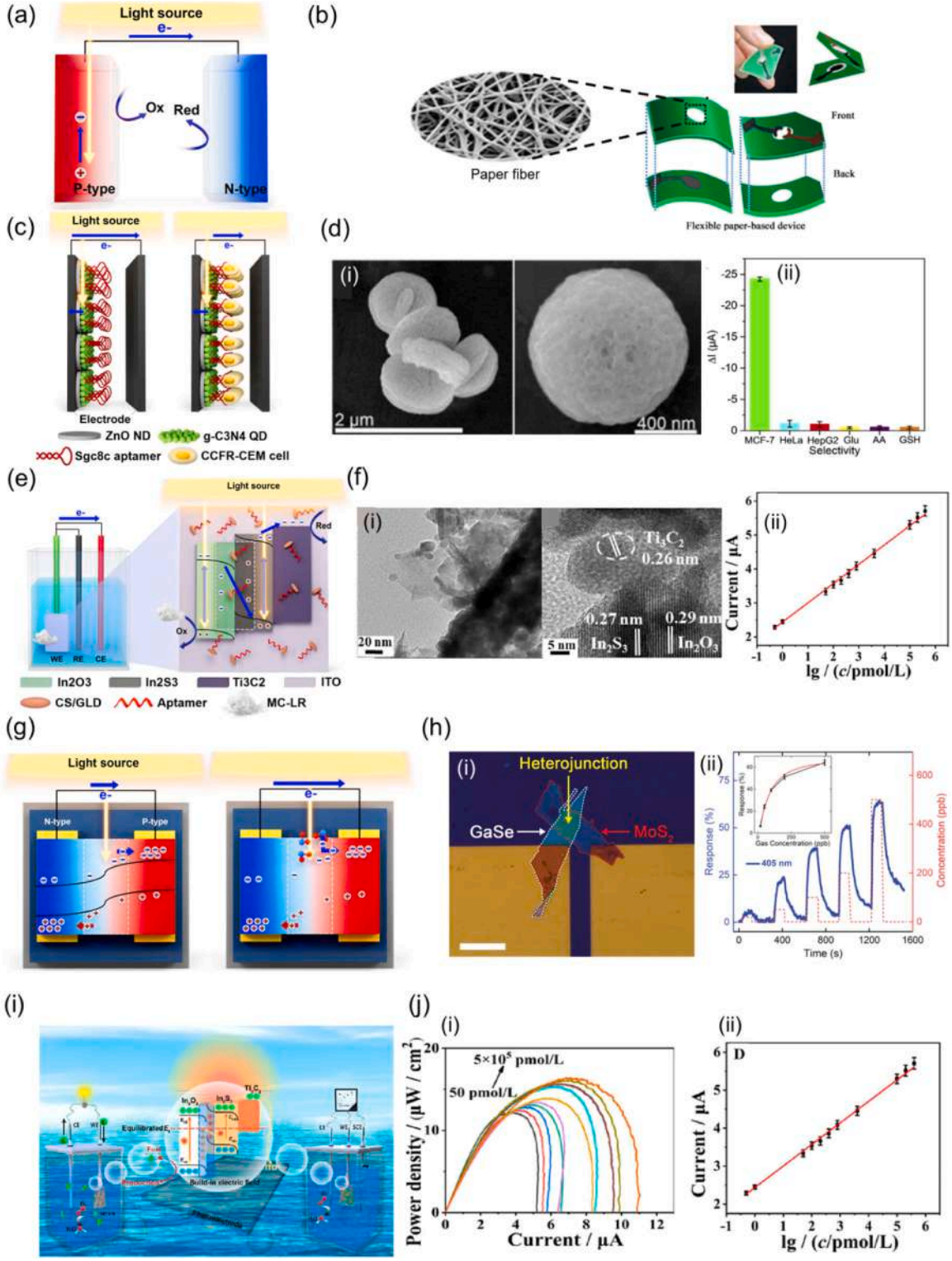


Fig. 2. Various Types of Photoelectrochemical Self-Powered Sensors. (a) Schematic of the working principle of a photodetector based on the coupling of photoelectrochemical reaction. (b) Image of the photoelectrochemical biosensor. Reproduced with permission.[48] 2023, The Authors. Published by WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim. (c) Schematic and (d) (i) scanning electron microscopy image of electrode material synthesized for biosensing, (ii) and the resulting calibration curve between pressure change and logarithm of the concentration of CCRF-CEM cells. Reproduced with permission.[66] Copyright 2018, Elsevier Ltd. (e) Schematic illustration and (f) (i) transmission electron microscopy image of the electrode material synthesized for contamination sensing, and (ii) the resulting calibration curve between maximum pressure and MC-LR concentrations. Reproduced with permission.[68] Copyright 2022, Published by American Chemical Society. (g) Schematic and (h) (i) optical image of the electrode material synthesized for gas sensing, and (ii) the resulting dynamic response of the heterojunction exposed to different NO_2 concentrations. Reproduced under the terms of the CC-BY-4.0 license,[69] Copyright 2021, The Authors. (i) Lake contamination sensing application. (j) (i) P–I responses at different MC-LR concentrations. (ii) Results of applying the calibration curve to the current at different concentrations. Reproduced with permission.[68] Copyright 2023, The Authors. Published by WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim.

through the PV effect, wherein photons are absorbed by a semiconductor material, generating an electric current. This review investigates a self-powered PV sensor that effectively harnesses ambient light (i.e., sunlight) as the primary source of light energy (Fig. 3**a**). Self-powered sensors can detect alterations in physical or environmental parameters, such as gas concentration, strain, or pressure. The variation in the quantity of sensing targets results in a corresponding change in the transmittance of the film, which consequently alters the incident light that reaches the underlying solar cell and subsequently modulates the current flowing through the sensor. To fabricate such sensors, materials such as responsive polymers, metal-organic frameworks, photochromic materials, nanocomposites, and liquid crystals, are key as they alter their optical properties in response to stimuli, such as humidity, temperature, or specific chemicals. Design features should include layered structures, micro/nano structuring, thin films, and flexible designs for enhanced sensitivity. The PV effect-based sensors leverage the abundant and sustainable power source of sunlight, obviating the need for external power supplies or frequent battery replacements, thereby ensuring prolonged sensor operation. Applications include environmental monitoring, healthcare diagnostics, smart windows, food quality control, wearable technology, and security screening, offering real-time detection and monitoring capabilities. Despite their notable advantages, PV effect-based sensors face two inherent challenges:

1) The sensors are sensitive to fluctuations in ambient light, which can unpredictably impact sensing outcomes. PV cells can only detect changes in incoming light, making it difficult to distinguish whether the change in light is owing to a change in the target physical quantity of the sensor or a change in the intensity of the external light source itself. For example, when utilizing ambient sunlight as the power source for sensing, changes in lighting conditions, such as cloud cover, shading, and nighttime periods, present additional challenges, affecting the reliability of the sensor.
2) In low-light conditions, such as nighttime operations, the current output can be constrained, which can pose difficulties in accurately measuring the current changes associated with variations in the sensing target. Therefore, the design of PV effect-based sensors must prioritize minimizing the influence of external power availability, and it is necessary to develop a sensor structure that enables continuous sensing even under scenarios of exceedingly low external light.

Several studies have proposed solutions to overcome these challenges. For example, Choi et al. incorporated a reference solar cell to minimize the effect of variations in the external power source to mitigate the influence of external factors on the performance of the PV sensor.[23] This reference cell served as a stable benchmark, allowing for the precise assessment and compensation of changes in the power generation process. Additionally, Choi et al. employed polydimethylsiloxane (PDMS) as a protective enclosure (Fig. 3**b**). This choice effectively shielded the PV cells from environmental phenomena, such as moisture, dust, and physical damage. Implementing PDMS enabled reducing the susceptibility of the sensor to external influences significantly, thereby ensuring reliable and accurate operation. Using these strategies, Choi et al. successfully enhanced the robustness and performance stability of PV sensors. Wu et al. proposed a novel approach involving the storage of solar energy in a battery through daytime energy harvesting to ensure accurate sensing under low-light conditions.[23] Subsequently, during nighttime operation, wind detection is activated by utilizing a light-emitting diode powered by the energy stored in the battery. Therefore, carefully considering these factors during the design phase can enable developing dependable sensors that exhibit reduced susceptibility to the effects of the external environment. Such sensors have the potential to be utilized across diverse fields of applications.

For example, the PV effect can be employed to sense pressure without using an external power source.[17,23] The amount of light reaching the PV cell can be altered by designing a sensor structure that changes in response to the applied pressure (Figs. 3**c,** 3**d-i**), thereby enabling the measurement of different pressure levels.[17] The sensitivity and sensing range of the sensor can be tailored by adjusting the structural parameters, with sensitivity values of 0.31, 0.094, and 0.0149 kPa^{-1} achieved for pressure ranges of 1, 10, and 65 kPa, respectively (Fig. 3**d-ii**). Thus, the self-powered pressure sensor has potential applications in wireless breath monitoring and wind detection.

Similarly, a strain sensor can be developed using the same principle as a pressure sensor, i.e., by utilizing changes in structure to detect strain [30] (Fig. 3**e**). Gu et al. developed a self-powered strain sensor by incorporating a light-blocking film and a PV cell. As the strain applied to the sensor changes, the structure of the light-blocking film undergoes alterations, resulting in variations in light transmittance. By utilizing a rotating square pattern for the light-blocking film structure (Fig. 3**f-i**), high sensitivity (GF $\approx$ 10.5) was achieved within a strain range of 0–30 % (Fig. 3**f-ii**). This strain sensor can be used for human motion monitoring, wireless aerostat inflation/deflation detection, and crack propagation detection in artificial satellites.

Furthermore, gas sensing can be achieved by combining chemical effects and PV effects.[72–77] The transmittance of the sensing film changes when a gas interacts with it (Fig. 3**g**), thereby varying the current generated by the organic PV cell. The sensing layer, composed of N,N,N',N'-tetramethyl-p-phenylenediamine (TMPD), responds to NO_2 gas, causing the TMPD molecules to undergo cationization, resulting in a color change (Fig. 3**h-i**).[78] Consequently, the current in the PV cell decreases as the transmittance decreases. The developed gas sensor system exhibits high selectivity to NO_2 against other gases, such as H_2S and CO (Fig. 3**h-ii**). This self-powered gas sensor has the potential to perform indoor NO_2 gas sensing using ambient light sources.

A self-powered humidity sensor was developed by combining a humidity sensor with a PV cell.[79] The sensing principle is based on the change in the transmittance spectrum of a metal-insulator-metal Fabry–Perot filter caused by variations in relative humidity (RH). The insulating layer, comprising chitosan, absorbs water molecules from the air and swells, which changes the optical resonance wavelength (Figs. 3**i,** 3**j-i**). The amount of light absorbed by the solar cell decreases as the relative humidity increases, thereby resulting in reduced current (Fig. 3**j-ii**). This self-powered humidity sensor can distinguish relative humidity changes of up to 5 % and be employed for both indoor and outdoor humidity measurements.

These sensors eliminate the need for external power sources or batteries, thereby effectively reducing the costs associated with their operation and maintenance. Moreover, PV sensors have emerged as a viable solution for outdoor environmental monitoring as they have the inherent benefits of harnessing natural light and exhibiting superior reliability compared to those of alternative renewable sources, such as wind. Furthermore, their applicability in space environments[80] characterized by the availability of abundant and uninterrupted light facilitates continuous and steady fast-sensing operations. The versatile employment of PV sensors extends across an extensive spectrum of domains, which encompasses industrial automation, healthcare, and infrastructure management. As shown in Fig. 3**k**, the strain sensor enables human motion monitoring without requiring batteries or external power.[80] To develop a strain sensor for wearable workout monitoring, a flexible substrate such as PDMS is used for comfort and durability, embedding conductive nanomaterials such as graphene for high sensitivity. A serpentine pattern enables it to stretch with body movements, and a rotating square pattern achieves high sensitivity. The exercise posture can be evaluated by measuring the strain value when the strain sensor is attached to the biceps and wrist (Fig. 3**l**). This strain sensor exhibits a stretchability of approximately 175 %. It features a high gauge factor (GF) of approximately 10.5 within a strain range of 0–20 %, and demonstrates a rapid response time of less than 20 ms during both loading and unloading processes. These specifications indicate its suitability for use as a wearable sensor. The potential for a wide range of

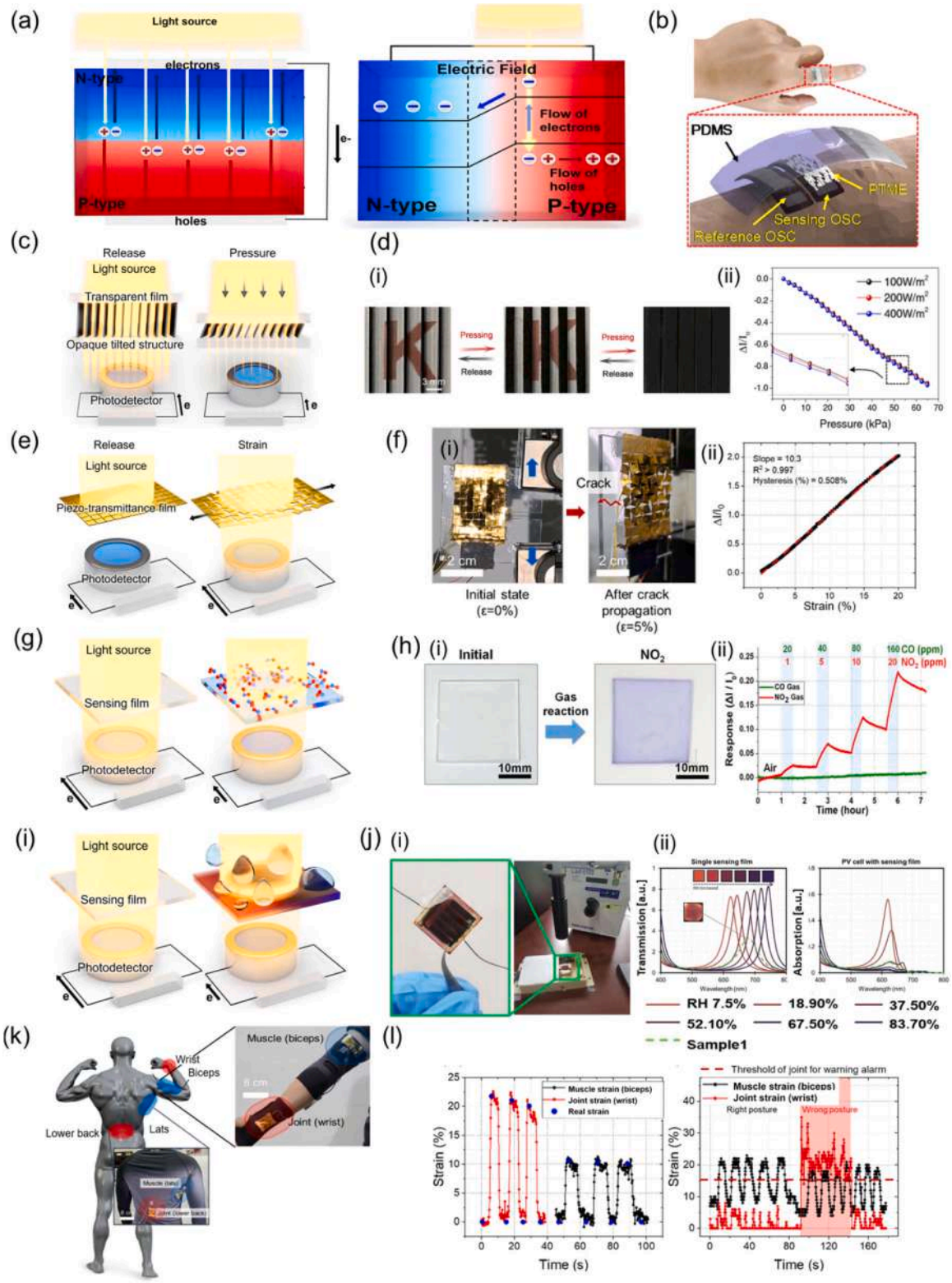


Fig. 3. Various Types of Photovoltaic (PV) Self-Powered Sensors. (a) Schematic of the operating principle of a photodetector based on the PV effect and (b) photograph of the PV pressure sensor. Reproduced with permission,[23] (Copyright 2020, Elsevier Ltd. (c) Schematic, (d) (i) top view of tilted structures for pressure sensing and (ii) detection of light transmittance change. Reproduced with permission,[17] Copyright 2023, Elsevier Ltd. (e) Schematic and (f) (i) image of strain sensor during stretching and releasing and (ii) response to input strain in the range of ε = 0–20 %. Reproduced with permission, [30] Copyright 2021, Elsevier Ltd. (g) Schematic and (h) (i) photos of the sensing layer before and after exposure to gas and (ii) concentration vs. response curve. Reproduced with permission,[78] Copyright 2020, Published by American Chemical Society. (i) Schematic and (j) (i) photos of humidity chamber and sensing device and (ii) calculated absorption spectra of the PV cell combined with the sensing films. Reproduced with permission,[17] Copyright 2021, The Authors. Published by WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim, (k) Application of the developed strain sensor to human motion monitoring. Reproduced with permission,[80] Copyright 2023, Elsevier Ltd. (l) Calibrated individual sensor signal for biceps and wrist motion monitoring and experimental results. Reproduced with permission,[30] Copyright 2020, Elsevier Ltd.

wearable applications, extending beyond just workout monitoring, has been confirmed.

PV sensors are currently undergoing extensive research to exploit their structural and chemical properties to modulate the current intensity of the sensor in response to variations in the sensed target. These sensors have diverse applications ranging from wearable devices to environmental detection systems. However, it is imperative to ensure uninterrupted and stable sensing capabilities, particularly under intermittent light conditions, to expand its utility across a broad spectrum of environments. Moving forward, enhancing the efficiency of light conversion and improving the resilience of the sensor materials could significantly broaden practical applications.

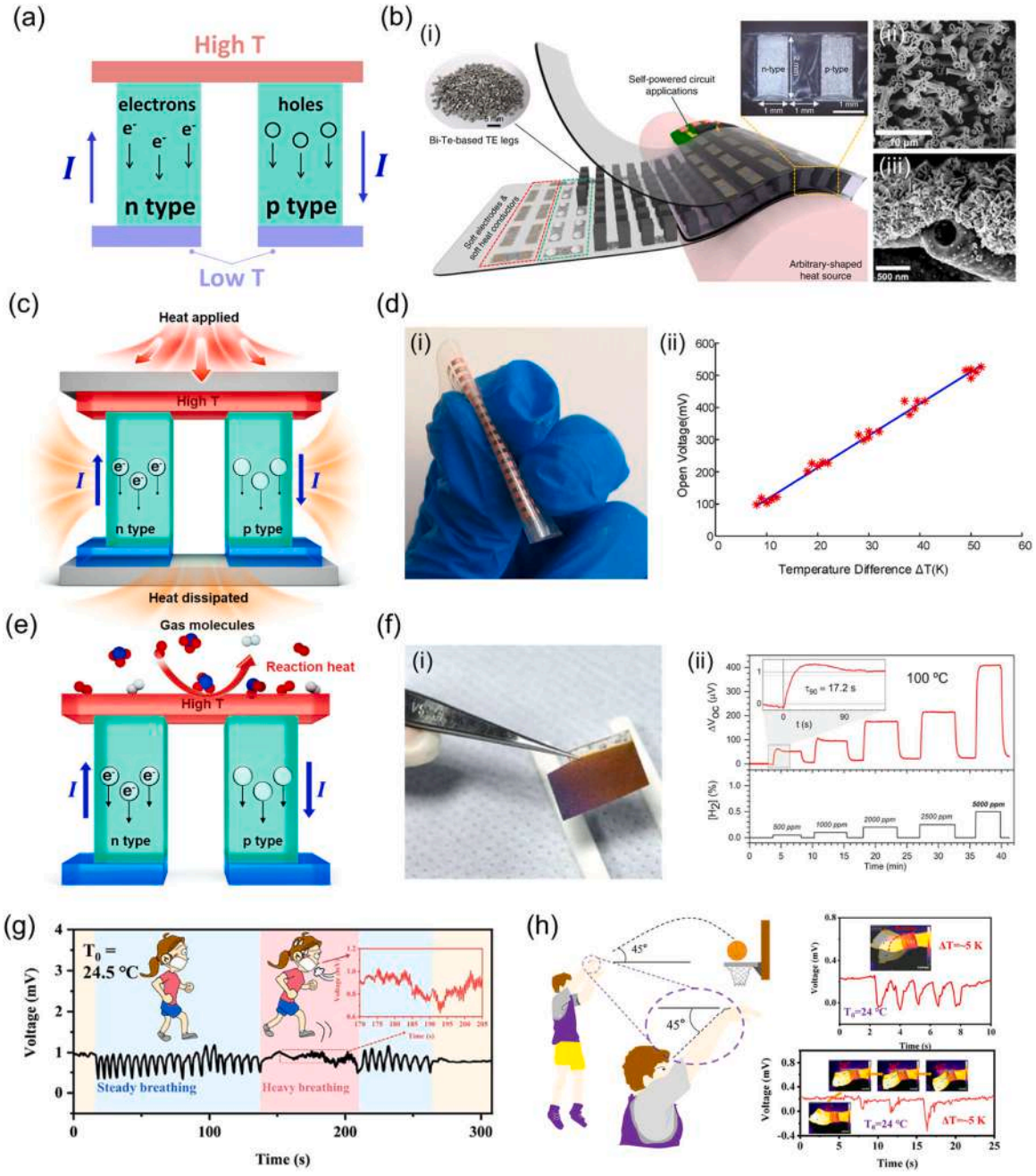


Fig. 4. Various Types of Thermoelectric-Effect-based Self-Powered Sensors. (a) Schematic of the working principle of thermoelectric effect-based self-powered sensors. (b) Photographs and image of thermoelectric self-powered devices. (i) Images of bismuth telluride based thermoelectric legs. (ii-iii) SEM image of the thermoelectric silicon fabrics. Reproduced with permission[86,92] 2020, Nature Research; 2020, WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim. (c) Working mechanism of the thermoelectric temperature sensors. (d) Photographs and response of the self-powered temperature sensor based on the thermoelectric effect. (i) Photographs of the bismuth telluride-based flexible thermoelectric sensor. (ii) Output power curve of the devices. Reproduced with permission.[99] 2017, WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim. (e) Working mechanism of thermoelectric gas sensors. (f) Photograph and response of gas sensor based on thermoelectric effect. (i) Photograph of gas sensor. (ii) Response of gas sensor with different H_2 concentrations. Reproduced with permission.[92] 2020, WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim. (g) Response of thermoelectric temperature sensors for breath monitoring. (h) Photographs and response of thermoelectric strain sensors for human motion monitoring. Reproduced with permission.[113]2022, Elsevier Ltd.

2.2. Self-powered sensors based on electricity generation from thermal energy sources

Thermal energy sources, including body heat, environmental temperature gradients, and chemical effect heat, are forms of energy that are appreciable to the surrounding environment. Self-powered sensors based on electricity generation from thermal energy sources have emerged as a promising technology in the field of green-energy-based physical and chemical sensors. Self-powered sensors that can harness and convert thermal energy into electricity offer numerous advantages, including sustainability, reliability, and widespread availability in the environment. Temperature changes from the thermal energy sources can be employed for sensing applications by generating electric power from temperature gradients (dT/dx) or by converting temperature changes over time (dT/dt) into electrical potentials. Following this, this chapter introduces sensors that make use of these two separate mechanisms. Here, we explore the core principles, design, and various applications of self-powered sensors that rely on electricity generation from thermal energy sources.

2.2.1. Self-powered sensors based on thermoelectric effects

The thermoelectric effect converts temperature differences caused by heat into electricity. This effect enables the conversion of heat energy wasted in nature and industrial sites into usable electricity.

A self-powered thermoelectric sensor operates by utilizing charge carriers in doped semiconductor materials to convert temperature differences generated by target parameters (e.g., heat, chemistry, pressure, and strain) into electricity. Fig. 4**a** shows the operating principle of a self-powered sensor based on thermoelectric mechanisms. Thermoelectric materials generate electric power from temperature gradients (dT/dx) via the Seebeck effect. Electrons and phonons diffuse when one side of a p-type or n-type material is heated and the other is cooled by the target parameters of a sensor, such as gas, heat, or body temperature. An array of doped semiconductor legs forms a thermoelectric device to provide sufficient power output. The legs are electrically connected in series and thermally connected in parallel. A small voltage is generated across each leg within the module because of the dissimilar semiconductor junctions. These low voltages are added to produce a significantly higher usable voltage. These electrical signals can then be interpreted to measure the target parameters of the self-powered sensors. Self-powered sensors based on thermoelectric effects can provide a sustainable solution for powering sensing devices, without requiring external power sources.[81–84]

The performance of thermoelectric materials is often evaluated using a dimensionless figure of merit, ZT, which is defined as $ZT = \frac{S^2\sigma T}{\kappa}$, where S is the Seebeck coefficient, σ denotes the electrical conductivity, T denotes the absolute temperature, and κ signifies the thermal conductivity. This relationship implies that to achieve a high ZT, it is crucial to increase the Seebeck coefficient and electrical conductivity while reducing the thermal conductivity. Efforts to enhance ZT values have focused on strategies to reduce thermal conductivity and improve the Seebeck coefficient. One approach is to use nano structuring to scatter phonons and reduce thermal conductivity without significantly affecting electrical conductivity. Another approach involves doping and alloying to increase the Seebeck coefficient by optimizing the carrier concentration and band structure of the materials. These advancements in thermoelectric material research are promoting the development of more efficient self-powered sensors that can operate under a wide range of environmental conditions and provide reliable power output for various applications.

Recent research has focused on developing self-powered TEGs that can be attached to the human skin by combining inorganic-based thermoelectric devices with stretchable substrates to utilize these devices for various applications.[84–86]. (Fig. 4**b**). Most early self-powered wearable thermoelectric sensors used solid metal-based electrodes and inorganic p-n type semiconductors with limited flexibility and bulky form factors.[81,87] Consequently, research aimed at innovating a new type of thermoelectric sensors by integrating both brittle and flexible materials hold significant importance. The selection of materials for thermoelectric sensors requires an approach that considers flexibility, efficiency, cost, toxicity concerns, and suitability for specific applications. The most widely used inorganic-based material for p-n type semiconductors is bismuth-telluride. (Bi_2Te_3), which exhibits excellent thermoelectric efficiency (ZT) at room temperature.[86,88–91] However, despite its high ZT, Bi_2Te_3 suffers from several limitations, including limited flexibility, mechanical brittleness, high production costs, and toxicity concerns. Therefore, recent research has been increasingly focusing on alternative materials that offer better flexibility, environmental stability, and cost-efficiency without compromising thermoelectric performance. Silicon-based materials are being studied owing to their low price, wide availability, non-toxicity, and excellent compatibility with existing semiconductor technologies.[92] Organic-based substances, such as conducting polymers and organic-inorganic hybrid materials, are also gaining attention for their inherent flexibility, lightweight nature, and ease of processing. [93–96] Additionally, nanocomposites, which combine inorganic nanoparticles with organic matrices, offer a promising approach to enhance the thermoelectric efficiency while maintaining flexibility and mechanical robustness.

The main application of self-powered thermoelectric sensors is temperature sensing based on the change in the temperature of the object in contact with the sensor.[93,97–110] Fig. 4**c** shows the operating mechanism of a self-powered temperature sensor based on thermoelectric effects. When heat is applied to one side of a self-powered thermoelectric sensor, it dissipates across the legs and electrodes of the sensor, resulting in a temperature difference between the top and bottom surfaces. Following the Seebeck effect, charge carriers diffuse from the hot side to the cold side, generating a heat-induced current. Thermoelectric temperature sensors are well suited for steady-state temperature monitoring because they rely on a stable temperature gradient generated by the Seebeck effect. Fig. 4**d** displays photographs of a self-powered thermoelectric temperature sensor with a flexible polyethylene terephthalate (PET) film.[99] The temperature sensor has an open-circuit voltage that increases proportionally with the temperature difference between the electrodes. These temperature sensors are scalable for various applications, including wearable sensors and fire alarms.[106,107,110]

Gas sensors that utilize the heat generated from effects with gas molecules are another type of TEG-based self-powered sensors.[92,104,111,112] Fig. 4**e** illustrates the working mechanism of a self-powered chemical sensor based on a thermoelectric effect. A chemical effect occurs between the gas molecules and a catalyst-coated electrode, thereby leading to a thermal gradient across the sensors. The heat generation caused by the gas molecules produces an electrical signal that can be employed to measure the gas concentration. Fig. 4**f** shows a self-powered hydrogen sensor based on a silicon-based fabric coated with a metal catalyst.[92] The open-circuit voltages of the sensor are dictated by both the temperature elevation induced by the gas effect and the Seebeck constant. Elevated concentrations of H_2 instigate substantial heat from the effect, thereby leading to higher open-circuit voltages. Lin et al. proposed a mercury-ion monitoring sensor based on the chemical effect of Hg^{2+} ions and Te nanowires with a thermoelectric effect.[112]

Another application of self-powered thermoelectric sensors is human motion monitoring, wherein temperature changes generated by the heat produced by the human body and breathing patterns are detected. [113–116] Such sensors can be used to monitor physical stimuli, such as strain and pressure, based on changes in the area of contact with a heat source and the thermoelectric current generation by a temperature gradient.[101,113,117,118] (Fig. 4**g-h**) Moreover, the simultaneous monitoring of multimodal factors has implications in a variety of fields, including e-skins, machine learning, and various other areas.[93,97,

101,107,119–122] Wan et al. proposed a self-powered multimodal sensor for monitoring the strain, visible light, and humidity using stretchable n-type material based on a polyurethane (PU) film.[110] The multimodal sensor can sense strain, light, and humidity at a constant temperature gradient ($\Delta T \approx 50$ °C) and exhibit high strain sensitivity (GF ≈ 13), particularly at high tensile strains ($\varepsilon \approx 300$ %). Zhang et al. proposed a self-powered temperature-pressure sensor using organic thermoelectric materials (PEDOT: PSS) combined with a porous structure (PU).[93] The self-powered pressure sensor exhibits a sensitivity up to 28.9 kPa^{-1}, whereas its temperature sensing capabilities boast a resolution of less than 0.1 K.

Self-powered thermoelectric sensors convert thermal gradients directly into electrical energy, offering a sustainable method to harvest waste heat with high durability but suffering from high materials costs. Ongoing research into new materials and nanostructures promises to improve the efficiency and reduce the cost of thermoelectric materials, expanding with a wide range of applications. For example, as chemical sensors, they play a pivotal role in detecting environmental pollutants and in monitoring temperature changes in the environment or devices. Additionally, they can be used for human motion monitoring by enabling the use of touch and respiration sensors. The potential for such diverse applications signifies the crucial role that thermoelectric-

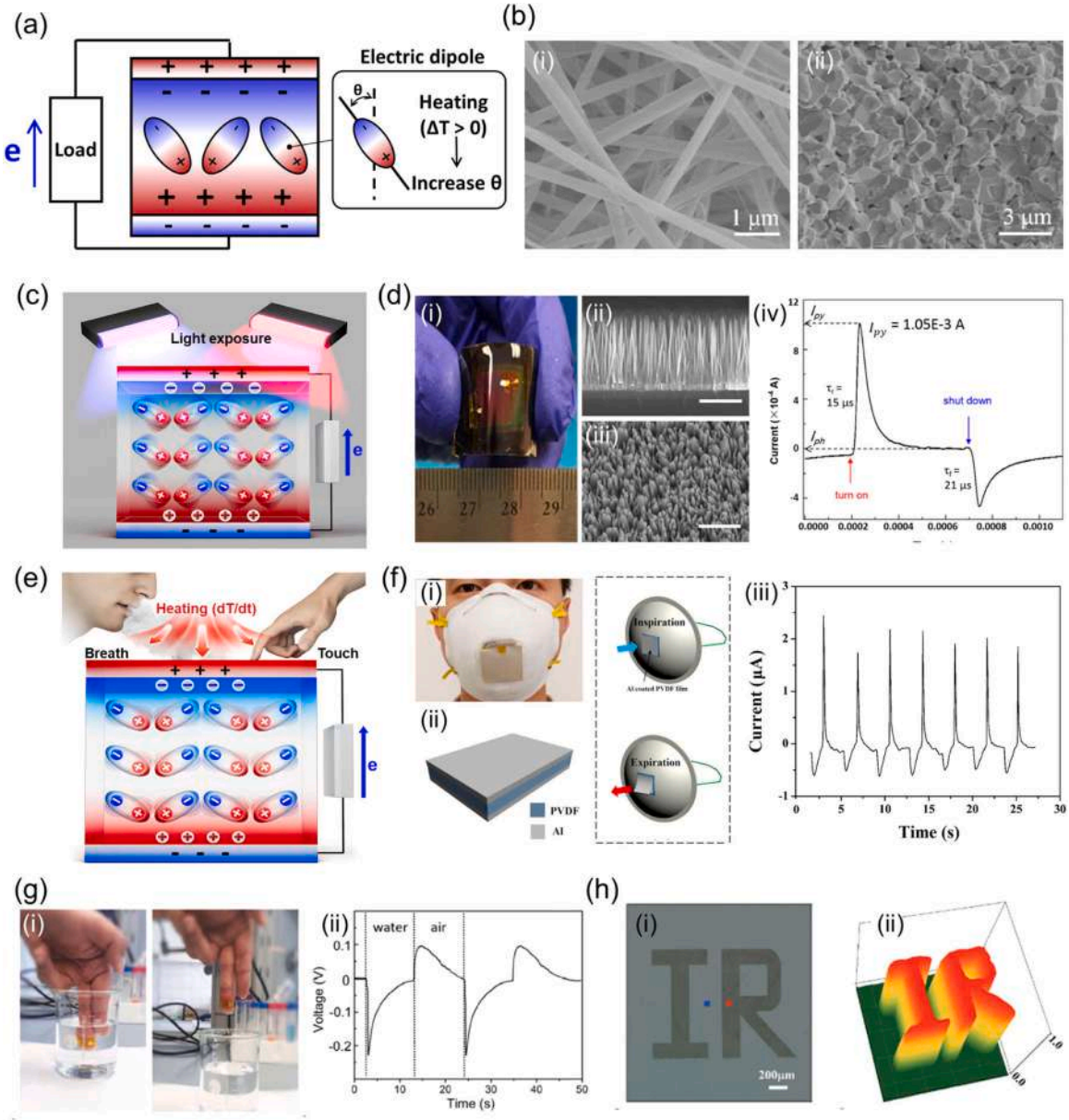


Fig. 5. Various Types of Pyroelectric Effect-based Self-Powered Sensors. (a) Schematic of the operating principle of pyroelectric effect-based self-powered sensors. (b) SEM images of synthesized materials for pyroelectric self-powered sensors. (i) BTO nanowires. (ii) BTO ceramics. Reproduced with permission.[136] 2017, Elsevier Ltd. (c) Operational mechanism of the pyroelectric effect-based light detection sensors. (d) Photographs and response of self-powered light sensor based on pyroelectric reaction. (i) Photograph of p-Si/n-ZnO-based sensor. SEM image of ZnO nanowires with scale bars of 500 nm. Cross-section-view (ii) and tilt-top-view (iii) (iv) Response circle of the short-circuit curve. Reproduced under the terms of the CC-BY-4.0 license.[128] 2017, American Chemical Society. (e) Operating mechanism of the pyroelectric sensors for human monition detection. (f) (i) photograph, (ii) schematic, and (iii) response of self-powered breath monitoring sensor based on pyroelectric reaction. Reproduced with permission.[129] 2017, Elsevier Ltd. (g) (i) photographs and (ii) response of pyroelectric sensors for temperature monitoring. Reproduced with permission.[134] 2017, WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim. (h) photographs of pyroelectric sensors for IR monitoring (i) Microscope image (ii) 3D images of experimental absorption peak wavelength of 980 cm−1. Reproduced with permission.[133] 2018, WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim.

powered sensors can play in the industry and everyday life.

2.2.2. Self-powered sensors based on pyroelectric effects

The pyroelectric effect is the spontaneous polarization of certain anisotropic solids under temperature fluctuations (dT/dt).[123] This effect is observed in specific materials and can be used to generate electric charge in response to temperature changes. Polarization aligns electric dipoles within a material in a particular orientation, which serves as the foundation for self-powered sensors that harness pyroelectric responses. Fig. 5**a** illustrates the working principle of pyroelectric effect-based self-powered sensors. Pyroelectric sensors are commonly composed of thin films of pyroelectric materials and metal films as the top-bottom electrodes. The mechanism is based on the random wobbling of an electric dipole induced by ambient heat. The wobble of the dipole relative to the equilibrium axis increases in magnitude as the temperature increases. The crystal lattice structure of the pyroelectric material expands or contracts when a pyroelectric sensor encounters a temperature change such as body heat or an abrupt shift in the external temperature, which cause electric dipoles within the material to shift, thereby generating an electric charge. The magnitude and direction of this signal depend on the direction and rate of temperature change. The increase in temperature causes a large range of oscillations of the electric dipoles to their aligning axes and reduces the total average spontaneous polarization. The reduced quantity of induced charges in the electrodes causes a flow of electrons in the load with the external circuit. The amassed electric charge is gathered by electrodes on the surface of the pyroelectric material, and consequently, this accumulated charge yields a voltage across the electrodes, generating an electrical signal from the self-powered pyroelectric sensors.

The selection of materials for pyroelectric sensors is crucial to balance various factors, such as flexibility, efficiency, cost, and toxicity concerns, as well as their suitability for specific applications. Pyroelectric materials such as lead zirconate titanate (PZT),[124,125] ZnO, [126–128] polyvinylidene fluoride (PVDF),[129–133] lead magnesium niobite-lead titanate (PMN-PT),[134] barium titanate (BTO),[135–137], and polyacrylonitrile[138] exhibit polarization changes when exposed to temperature variations. Among these, PVDF and its copolymers are widely used owing to their high flexibility, low production costs, and ease of processing. PVDF materials can be processed into thin films or nanofibers, making them ideal for flexible and wearable applications. ZnO and PZT nanowire-based structures are favored for their mechanical flexibility and higher power efficiency. In particular, ZnO offers the advantage of being non-toxic and environmentally friendly, making it suitable for eco-friendly applications. Additionally, materials such as BTO and ZnO exhibit photoelectric effects and are used in photonic applications where heat can be induced by light illumination. Fig. 5**b** shows an SEM image of the BTO nanowire array for pyroelectric effect-based self-powered devices.[133] Pyroelectric materials and composites with different morphologies have been used as self-powered sensors for various applications.[139–141]

Pyroelectric sensors are based on temperature changes over time (dT/dt), whereas thermoelectric sensors are based on changes in temperature with distance (dT/dx). Unlike thermoelectric sensors that require a temperature difference between two electrodes to generate an electrical signal, pyroelectric sensors do not require additional spatial provisions to uphold temperature differences or extensive heat dissipation considerations for their design. Therefore, pyroelectric sensors can be configured in smaller form factors because of their intrinsic mechanism of responding to temperature changes directly within a material. Based on their working mechanism and material properties, pyroelectric sensors are frequently employed for practical applications related to temperature detection, such as light-detection sensors used in security systems, wearable sensors for breath monitoring and touch detection, and even in certain types of thermal imaging cameras. These sensors are ideal for detecting rapid temperature changes and identifying moving objects or changes in thermal radiation.

Light-detection sensors that contain pyroelectric layers have attracted considerable research attention owing to their simplified structures and pyropolarization with photoactivation.[127,128,136,137,142–144] A pyroelectric light-detection sensor comprises a layer of pyroelectric material sandwiched between the upper and lower electrodes. Upon exposure to a specific light, the sensor promptly undergoes pyroelectric polarization and photoexcitation, thereby generating an electrical signal (Fig. 5**c**). This principle has been demonstrated in a self-powered near-infrared detection sensor composed of a thin film of a p-silicon (Si) /n-ZnO nanowire heterostructure with good flexibility (Fig. 5**d**). The sensor exhibits a power density of 4.8 mW·cm−2 with one typical cycle under near-infrared light (λ=1064 nm) and an exceptionally high pyroelectric current of $1.05 \times 10-3$ A with a 45 μm thick Si substrate. Qi et al. proposed a $BiFeO_3$ film-based self-powered sensor to detect visible light (λ=450 nm) range, which showed an output voltage of 0.13 V and output current of 8.8 nA under light illumination at λ=450 nm.[143] These examples support the core principle of using pyroelectric materials for efficient light detection by showcasing their performance metrics and practical applications.

Wearable devices, such as cough and touch sensors, can be utilized for human motion detection and monitoring.[129–132,134,135,138, 145] Fig. 5**e** illustrates the working mechanism of a self-powered pyroelectric sensors that harvests thermal energy from the human body. These devices work based on the temperature difference between the human body and the surrounding environment or on temperature changes caused by physical activities. When the device is exposed to ambient heat from the human body, the electric dipoles in the device wobble to a large degree relative to the equilibrium axis. The reduction in the induced charges in the electrodes causes electrons to flow from the bottom electrode to the top electrode. Human activities such as breathing cause temperature fluctuations around the mouth, enabling the operation of the pyroelectric sensor. Integrated with a respirator, the pyroelectric self-powered sensor harvests energy from breathing and simultaneously monitors human breathing based on the temperature difference inside the respiratory tract [129] (Fig. 5**f**). Roy et al. proposed a pyroelectric breathing sensor based on graphene-oxide-doped PVDF nanofibers that exhibited a maximum output power density of ~ 1.2 nW/m^2.[130] The sensors can measure periodic temperature fluctuations during continuous respiration. Another application of self-powered pyroelectric sensors is a direct temperature sensor based on the temperature change of the object in contact with the sensor.[134,135,145] Chen et al. proposed a pyroelectric-based wearable sensor that measures the temperature change of an object in contact with a sensor composed of PMN-PT[134] (Fig. 5**g**). The devices attached on a finger shows a negative voltage peak when the finger is dipped in warm water (~40 °C) and an opposite peak when the finger is taken out and exposed to air. Furthermore, pyroelectric materials are often used in thermal imaging, which extends beyond the temperature detection applications mentioned above.[133,146] Fig. 5**h** shows a photograph of the printed thermal imaging device and a three-dimensional (3D) image of the absorption data at a wavelength of 10.2 μm. Pang et al. used a pyroelectric thin film and proposed a plasmonic metasurface-based absorber using a PVDF film for thermal imaging in the infrared spectral region.[133]

In summary, pyroelectric effect-based self-powered sensors respond to temperature changes by generating electrical charges, thereby producing electrical signals. Pyroelectric sensors offer the advantage of not requiring additional spatial allowances to maintain temperature gradients or extensive considerations for heat dissipation in their design. This advantage enables the creation of these sensors in more compact sizes, primarily owing to their inherent capacity to directly detect temperature changes within the material. However, their performance is contingent on environmental temperature changes, which may not be consistent or predictable in all conditions, and the performance is sensitive to mechanical and electrical noise, potentially affecting sensor accuracy. Future improvements in materials and integration with IoT could unlock broader applications in smart environments and healthcare.

2.3. Self-powered sensors based on electricity generation from mechanical energy sources

Mechanical energy sources, such as pressure, vibration, and temperature variations, are ubiquitous in our daily lives and serve as readily available forms of energy for powering innovative, self-sustainable sensors. Such sensors can capitalize on the mechanical energy derived from these sources for effective operation. Self-powered sensors harness the inherent energy of pressure fluctuations, tension, or vibrations, thereby translating these mechanical changes into electrical energy and offering a multitude of advantages. The adaptability and abundance of mechanical energy sources make these sensors highly versatile and applicable in various applications, including wearable devices and environmental detection. This chapter delves into the fundamental principles that govern the conversion of mechanical energy into electricity, with a particular focus on the design intricacies and diverse applications of self-powered sensors that utilize mechanical energy sources. By e exploring the utilization of mechanical energy sources, ranging from detecting structural deformation induced by applied pressure to discerning surface chemical modifications resulting from dynamic responses to gases such as oxidation and absorption, this chapter aims to shed light on the innovative mechanisms that underlie the functionality of these sensors.

2.3.1. Self-powered sensors based on triboelectric effects

The triboelectric effect, also known as the triboelectric effect, is the fundamental principle underlying electricity generation through the interaction between two different materials. Electron transfer occurs when materials with distinct affinities for electrons interact with other, which results in a positive charge on the electron donor material and a negative charge on the electron acceptor material, thereby establishing an electric potential between them (Fig. 6**a**). The generated voltage, when manifested by a sensing target, can be measured and utilized as a sensor. The mechanical actions responsible for the contact and separation of materials can manifest in various modes.[147] In the contact-separation and single-electrode modes, the triboelectric effect is generated by the contact and separation of two different materials from above and below. The linear sliding and freestanding modes generate an electric potential by changing the contact area as the material slides from side to side while in contact. These distinct modes of operation highlight the versatility of the triboelectric sensor in response to various mechanical actions, thereby exhibiting adaptability to different applications (Fig. 6**b**). For example, the triboelectric sensor can be utilized in medical diagnostics, such as real-time platelet count monitoring. [148] Additionally, environmental applications involving TENGs are expanding. [149]

Sensors that utilize the triboelectric effect exhibit versatility in material applicability, with performance outcomes contingent on the specific materials used.[150,151] Further, their applicability extends across diverse sensor types because electrostatic signals can be influenced by various external stimuli. The efficacy of these sensors is highly dependent on the careful selection and design of materials on the contact surface, coupled with the consideration of surface structure design (nano-[152,153], microstructure[154–156], etc.). Selecting the interface material (solid–solid contact and solid–liquid contact) and contact method (sliding, contact and separation, single electrode, and free-standing mode) is critical in defining both the material and operational method to be used. Therefore, well-selected and designed materials can be used to measure physical and chemical changes through sliding and contact, thereby facilitating the use of sensors without an external power source.

With the well-designed contact mechanisms and materials, triboelectric sensors are applicable in self-powered pressure sensors.[20,154,156–170] When an external force is exerted on a sensor composed of different materials, their physical contact induces the triboelectric effect. This effect involves the transfer of electrons between materials during the contact and deformation processes. Upon releasing the pressure, the potential difference magnitude varies owing to the distinct charge distribution that corresponds to the applied pressure. Measuring this electrical potential difference enables the sensing of the applied pressure. (Fig. 6**c**). A notable application example is a smart textile pressure sensor developed for sleep monitoring (Fig. 6**d-i**). In the developed sensor, charge transfer is detected as a result of the change in distance between silicone rubber and polyester fiber **(**Fig. 6**d- ii)**. As a biomechanical signal (i.e., human motion) of the body induces pressure and brings the two materials into contact, electrons migrate from the polyester surface to the silicone rubber, creating an electrical potential. The sensor proved to be reliable even in the low-pressure range of 0–2 kPa, exhibiting a sensitivity of 10.79 mV/Pa through adjustments in the contact areas **(**Fig. 6**d- iii)**.

Additionally, variations in surface electron affinity caused by changes in gas molecules can modify the voltage output through the triboelectric effect in the presence of continuous mechanical forces, thus enabling the development of gas sensors.[171–176] The attachment of gas molecules to a material induces an electron transfer, altering the permittivity of the sensitive material and consequently modifying the magnitude of the voltage generated by the triboelectric effect (Fig. 6**e**). For instance, NH_3 gas concentration can be quantified by the triboelectric effect induced by breathing-based deformation, as shown in Fig. 6**f-i**. The potential arises from the charge transfer during the contact and separation of the Ce-doped ZnO and PDMS layers by respiration. In the presence of NH_3 molecules, the electrons from NH_3 migrate to Ce-doped ZnO, diminishing the permittivity of the material and consequently reducing the output voltage. This principle enables the determination of the NH_3 concentration through the output voltage of the triboelectric effect, as demonstrated in Fig. 6**f-ii**, where the response is reduced with an increasing NH_3 concentration. A linear relationship between the NH_3 concentration and response, derived through the fitting process, enables determining the NH_3 concentration from the response.

Water waves can also be detected by utilizing the charges generated through the motion of the liquid, which creates contact-separation between the water and PTFE film.[150,177] Owing to the presence of abundant ions, seawater exhibits relatively positive triboelectric properties compared to PTFE (Fig. 6**g**). Therefore, upon contact with seawater, the surface groups on the PTFE induce a negative charge, leading to the formation of an electrical double layer (EDL) for charge neutralization. Waves prompt positive charges in the solution to counterbalance the negative charge on the PTFE surface (Fig. 6**h-i**). The amount of transferred charges depends on the contact force, which correlates with the wave intensity, and the contact area, which correlates with the height of the wave. Therefore, the obtained sensor response can be used to infer the input wave with high sensitivity (Fig. 6**h-ii**).

Self-powered triboelectric sensors have practical applications in robotics[152,165,169,178] and wearable devices.[162,172,173,179,180] Fig. 6**i** shows a triboelectric sensor that surpasses human tactile perception and is suitable for integration into intelligent robots or artificial prosthetics.[20] The array comprises discrete sensors that utilize materials such as polyamide, polyethylene terephthalate, polystyrene, and polytetrafluoroethylene, each operating in a single-electrode vertical contact separation mode and generating unique voltage signals that reflect triboelectric interactions with different materials. The sensor can distinguish between a variety of materials, including acrylic, EVA, glass, PU, PVC, silicone, wood, and metal, with an accuracy rate of 96.8 %. The response time is 1.23 ms, making it ideal for use with artificial skin.

A self-powered triboelectric sensor can be adapted for medical diagnostic applications, such as cough detection.[29] Fig. 6**j-i** shows a TENG-based cough detection sensor affixed to a reusable mask. During exhalation, the airflow opens the exhalation valve by applying pressure to the TENG, whereas during inhalation, air enters and induces charge transfer. This sensor is a morphology-controllable wrinkled hierarchical

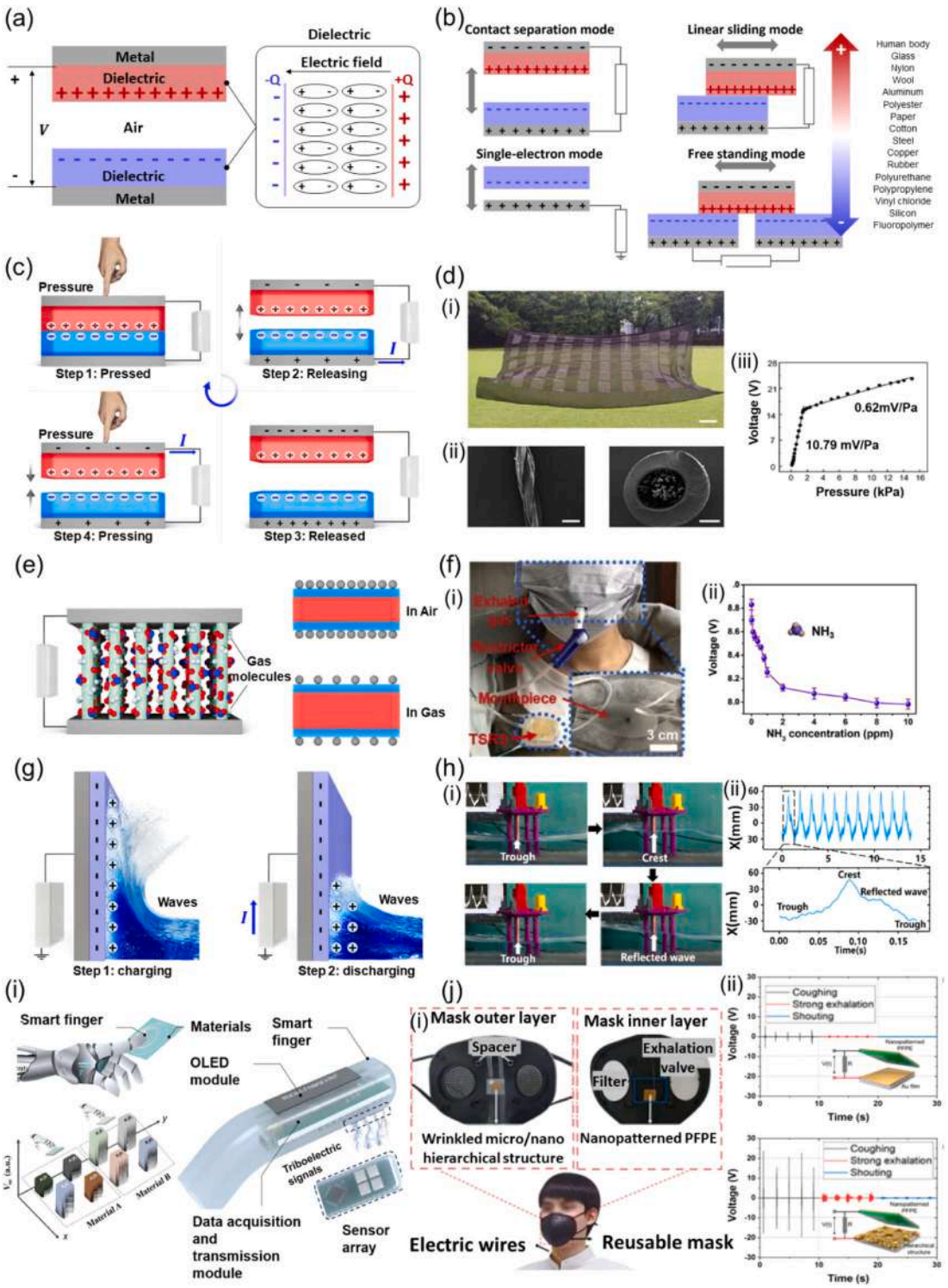


Fig. 6. Various Types of Triboelectric-Effect-based Self-Powered Sensors. (a) Schematic of the working principle of triboelectric self-powered sensors. (b) Classification of triboelectric self-powered sensors based on modes and materials. (c) Working mechanism of triboelectric effect-based pressure sensors. (d) Photographs and response of self-powered pressure sensor: (i) Photographs of the smart textile and (ii) SEM images of the sensor, (iii) relationship between voltage and pressure and frequency. Reproduced with permission[189] Copyright 2019, Elsevier Ltd. (e) Working mechanism of the triboelectric effect-based gas sensors. (f) Photographs and response of self-powered gas sensor: (i) Photographs of the gas sensor and (ii) relationship between NH_2 concentration and output voltage. Reproduced with permission[173] Copyright 2019, Elsevier Ltd. (g) Working mechanism of triboelectric effect-based ocean wave sensors. (h) Photographs and response of self-powered wave sensor: (i) Photographs of the sensor according to the waves and (ii) sensor output results as waves. Reproduced under the terms of the CC-BY-4.0 license.[150] Copyright 2020, The Authors, Published by AAAS. (i) Triboelectric sensor for integration into intelligent robots and artificial prosthetics. Reproduced under the terms of the CC-BY-4.0 license[20] 2020, The Authors, Published by AAAS. (j) Triboelectric cough detection sensor: (i) Photograph of the mask capable of sensing coughing and (ii) Output voltage during coughing, strong exhalation, and shouting. Reproduced with permission[29], Copyright 2021, Elsevier Ltd.

structure (WHS) owing to its enhanced hydrophobicity and triboelectric effects. This structure integrates micropatterns for mechanical strength and elasticity, nanopatterns for increased surface area and triboelectric efficiency, and wrinkles for amplified surface roughness and hydrophobicity. The materials used, such as the superhydrophobic PFPE, ensure water resistance and durability, making the sensor ideal for reliable cough detection in humid conditions. This configuration allows the sensor to effectively detect coughing events. The fluctuating pressure on the TENG during breathing cycles yields distinct triboelectric signals, facilitating cough detection based on the response of the sensor to respiratory patterns. This sensor demonstrated high sensitivity, exhibiting an output of 5–24 V during coughing, 3 V during strong exhalation, and 1 V during shouting (Fig. 6**j-ii**). It had a short response time of 65 ms and maintained stability even after 50,000 tests, while demonstrating excellent water resistance. Therefore, it is suitable as a cough sensor. Extending beyond medical diagnostics, recent research has further expanded the scope of TENG applications into the field of drug discovery. Here, their unique properties are harnessed to develop label-free sensing platforms, demonstrating the broad potential of TENG technology in various biotechnological fields [181].

Although the method has several advantages, it has practical challenges that require careful consideration; for example, the sensor

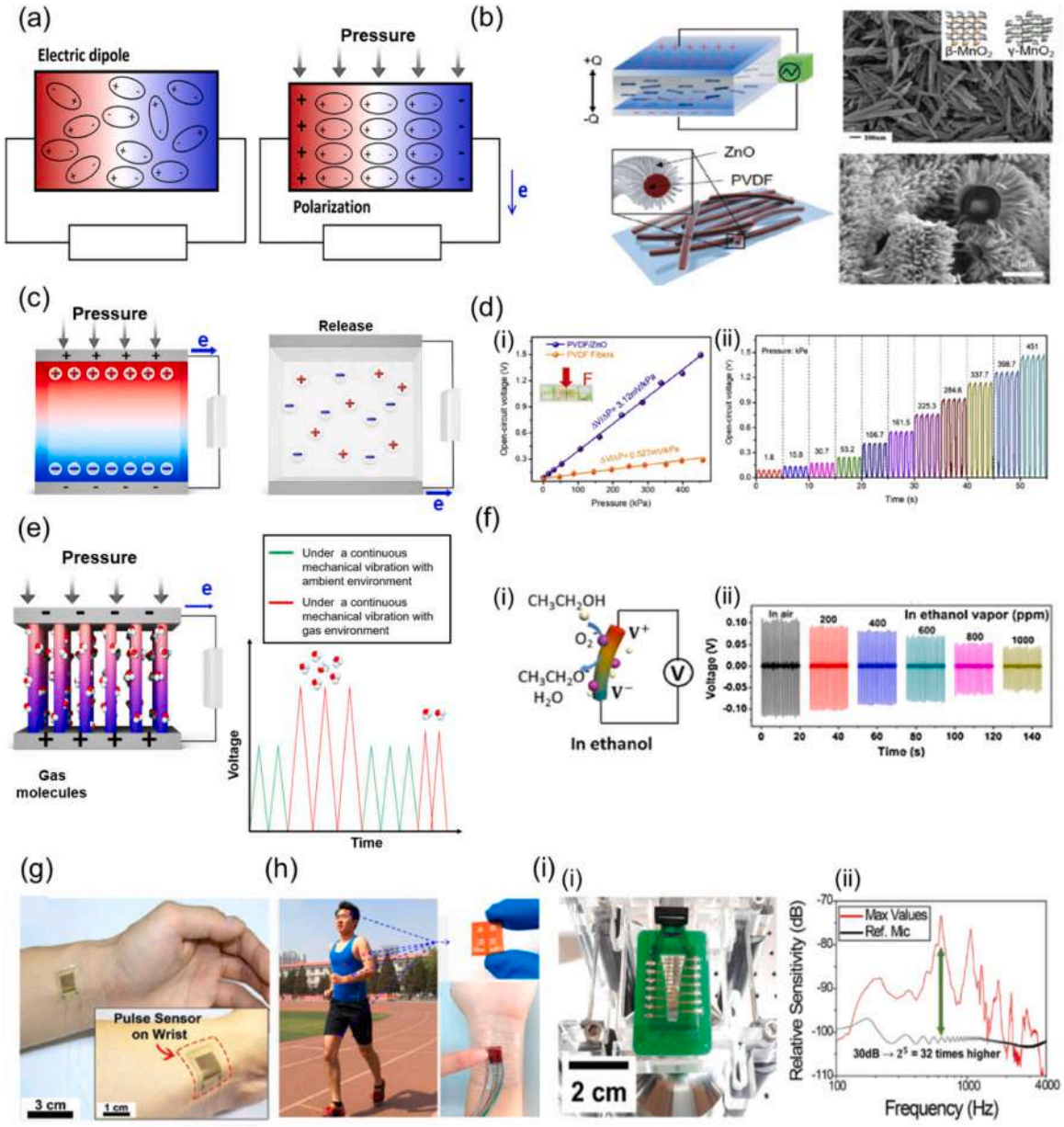


Fig. 7. Various Types of Piezoelectric Effect-Based Self-Powered Sensors. (a) Schematic of the operating principle of piezoelectric effect-based self-powered sensors. (b) SEM image of piezoelectric self-powered sensors. Reproduced with permission.[190] Copyright 2019, Elsevier Ltd; Reproduced with permission.[193], Copyright 2020, Elsevier Ltd. (c) Operating mechanism of piezoelectric effect-based pressure sensors. (d) Self-powered pressure sensor based on piezoelectric effect of PVDF/ZnO: (i) Dependence of the open-circuit voltage on pressure and (ii) enlarged view of the open-circuit voltage under different pressures. Reproduced with permission.[193] Copyright 2020, Elsevier Ltd. (e) Operating mechanism of piezoelectric effect-based gas sensors. (f) Self-powered gas sensor based on the piezoelectric effect of Fe/ZnO: (i) Operating mechanism of Fe/ZnO against ethanol and (ii) performance of gas sensor [198] (g) Photograph of piezoelectric sensor for pulse monitoring. Reproduced with permission.[192] Copyright 2019, Elsevier Ltd. (h) Photographs of piezoelectric sensor for sweat monitoring. Reprinted with permission[203] Copyright 2017, American Chemical Society. (i) (i) Photographs of the piezoelectric sensor for sound monitoring. (ii) Relative sensitivity of the sensor and reference microphone over a voice frequency. Reproduced with permission[191], Copyright 2018, Elsevier Ltd.

accuracy is compromised by various factors, including moisture, temperature, discharge, and contact electrification, which pose significant challenges.[182–186] Efforts to address these problems involve employing two TENG devices simultaneously and implementing self-calibration through signal processing.[162] The TENGs in this study are designed to function without manual calibration, despite environmental changes. The algorithms used can detect anomalies or shifts in baseline readings that could be caused by factors such as humidity or temperature. Employing two TENG devices simultaneously enhances the accuracy and reliability of the readings. Feedback loops are integral to this self-calibration process, providing continuous feedback based on the output signals and adjusting the system settings to mitigate distortions, thus maintaining optimal performance. In addition, while proficient in measuring instantaneous stimuli, the triboelectric sensors lack the capability to measure static stimuli, often requiring additional challenges,[169,185,187] and successful solutions are expected to enhance the applicability of sensors in environmental monitoring, smart fabrics, and textiles[188], with promising prospects for the future.

2.3.2. *Self-powered sensors based on piezoelectric effects*

A self-powered piezoelectric sensor is based on the principle of the piezoelectric effect, generating a voltage in response to mechanical changes applied to a specific material. Upon the application of an external mechanical stress or deformation, the crystal lattice undergoes distortion, resulting in the exhibition of an electric dipole moment. Consequently, positive and negative charges are displaced, thereby creating an electric potential (Fig. 7**a**). Piezoelectric sensors offer notable advantages, such as high sensitivity, fast response time, and compact size.[190–192] As the characteristics of piezoelectric sensors are intrinsically tied to the properties of the piezoelectric material, meticulous consideration in material selection is imperative. Designing and fabricating a piezoelectric sensor involves selecting materials such as PZT, $BaTiO_3$, KNN, or flexible PVDF. The geometry affects the sensitivity, with thin films offering high sensitivity and larger areas detecting more force. Conductive electrodes, typically gold or silver, are crucial for performance. Proper packaging protects the sensor from environmental damage, ensuring durability. Optimizing these elements results in a high-performance, reliable piezoelectric sensor. Despite their advantages, many piezoelectric films encounter challenges, such as low softness, inadequate gas permeability, and weak damage tolerance, which limit their suitability and compatibility in various applications. Addressing these concerns requires the development of novel flexible piezoelectric materials or the transformation of brittle materials into flexible materials at the nanoscale.

For example, Yang et al. successfully overcame these problems (i.e., low softness and permeability) by creating extremely thin, coaxial, aligned, and hierarchically interlocked 3D PVDF/ZnO nanofibers through the epitaxial growth of ZnO NRs on the surface of electrospun PVDF nanofibers (Fig. 7**b**).[193] Considering these advantages and disadvantages, the upcoming section elaborates on the development of several piezoelectric-based self-powered sensors achieved through the innovation of appropriate materials and structures.

Thus far, several studies have explored combining the piezoelectric effect with pressure sensors to enable sensor operation without an external power source.[194–197] The application of pressure induces mechanical deformation of the piezoelectric material, which alters its crystalline lattice structure. The resulting electric dipole moment and electric field across the material are proportional to the extent of crystal lattice distortion (Fig. 7**c**). Yang et al. utilized core-shell PVDF/ZnO nanofibers to achieve a highly sensitive sensor with a linear relationship between pressure and voltage, thereby demonstrating consistent performance under various pressure loading/unloading conditions (Fig. 7**d-i, ii**)[193] This sensor was used for a gait-recognition system for human physiological monitoring.

Gas detection using the piezoelectric effect involves the adsorption of gas on the material surface, which results in swelling or contraction, causing changes in the mass and mechanical properties.[198,199] This mechanical deformation induces a piezoelectric effect, which generates an electric potential (Fig. 7**e**). Effectiveness relies on the careful selection of piezoelectric materials and surface treatment to optimize the gas adsorption characteristics. He et al. synthesized a gas-sensing material targeting ethanol and demonstrated effective gas-sensing capabilities with a significant decrease in the piezoelectric voltage output at higher ethanol vapor concentrations (Fig. 7**f-i, ii**).[198] In addition, the synthesis of other materials (bare ZnONWs, CuO/ZnO NWs, and TiO_2/ZnO NWs) enabled the sensing of RH, H_2S, and CH_4.

Piezoelectric sensors find applications in wearable[195,200–206] and environmental[191,198,207,208] monitoring. For instance, an ultrathin epidermal piezoelectric pressure sensor facilitates real-time arterial pulse monitoring without power consumption problems. Constructed by transferring a PZT($Pb[Zr_x,Ti_{1-x}]O_3$) film onto an ultra-thin PET substrate, this sensor detects radial/carotid artery pulses, respiratory activities, and trachea movements when conformally attached to human epidermis (Fig. 7**g**). The PZT film was transferred onto an ultrathin polyethylene terephthalate (PET) plastic substrate (4.8 μm thick), which provided flexibility and enabled conformal attachment to the complex texture of the skin. This ensures accurate pulse detection. The laser lift-off (ILLO) process preserves the properties of the PZT film, and the integration of gold interdigital electrodes enhances signal collection efficiency. [192] Han et al. fabricated a piezoelectric biosensor using enzyme/ZnO nanoarrays that actively detected various substances during perspiration while serving as a power supply and carrying valuable biosensing data (Fig. 7**h**).[203] The sensor exhibited a pressure sensitivity of 0.018 kPa^{-1} within a pressure range of up to 30 kPa and a response time of approximately 60 ms, making it suitable for wearable applications for pulse detection. A piezoelectric acoustic sensor inspired by a basilar membrane in the human cochlea covered a frequency range of 100−4000 Hz for speech and speaker recognition applications (Fig. 7**i-i**).[191] The sensor demonstrated a sensitivity of 0.018 kPa^{-1}, which enabled it to detect bio-signals within both low-pressure (1–10 kPa) and medium-pressure (10–100 kPa) ranges (Fig. 7**i-ii**). The sensor exhibited a response time of 60 ms, which enabled it to perform for real-time monitoring of bio-signals. Furthermore, the sensor maintained stable signal output even after 5000 repetitive tests, proving its suitability for use as an sound sensor.

Piezoelectric sensors offer high sensitivity, quick response, and compact size for pressure and gas sensing in wearables like pulse and respiration monitors. Their self-powered operation eliminates the need for external power sources, enhancing their applicability. However, self-powered piezoelectric sensors have certain disadvantages.[209,210] Notably, their susceptibility to temperature variations poses a profound concern, as this fluctuation distort measurements and compromise accuracy. Furthermore, the reliance on mechanical deformation for signal generation can lead to signal drift over time, necessitating frequent recalibration. Moreover, the intricate fabrication processes required for high-quality piezoelectric materials contribute to elevated production costs and scalability limitations. Addressing these fundamental drawbacks necessitates concerted efforts in material engineering, sensor design optimization, and calibration techniques to fully harness the potential of piezoelectric sensors across diverse applications. Currently, numerous researchers are actively working to address these challenges and are making strides toward developing self-powered sensors based on piezoelectric materials that can be reliably deployed in industrial settings, wearable environments, and beyond.

2.4. *Hybrid self-powered sensors*

As self-powered physical and chemical sensors that generate electricity from wasted or renewable energy sources have made significant progress, the development of hybrid devices that integrate two or more self-powered mechanisms to utilize their synergistic effects has become increasingly common. Two main strategies exist, based on their

intended purpose: 1) Combining multiple mechanisms within a single sensor to synergistically enhance the sensing performance, including sensitivity and working range.[144] 2) Integrating various self-powered sensors to develop multimodal sensors.[137,211–216]

This chapter presents a range of recently reported hybrid devices that integrate the abovementioned mechanisms in diverse ways and their practical applications.

As the first example, one promising approach involves coupling the

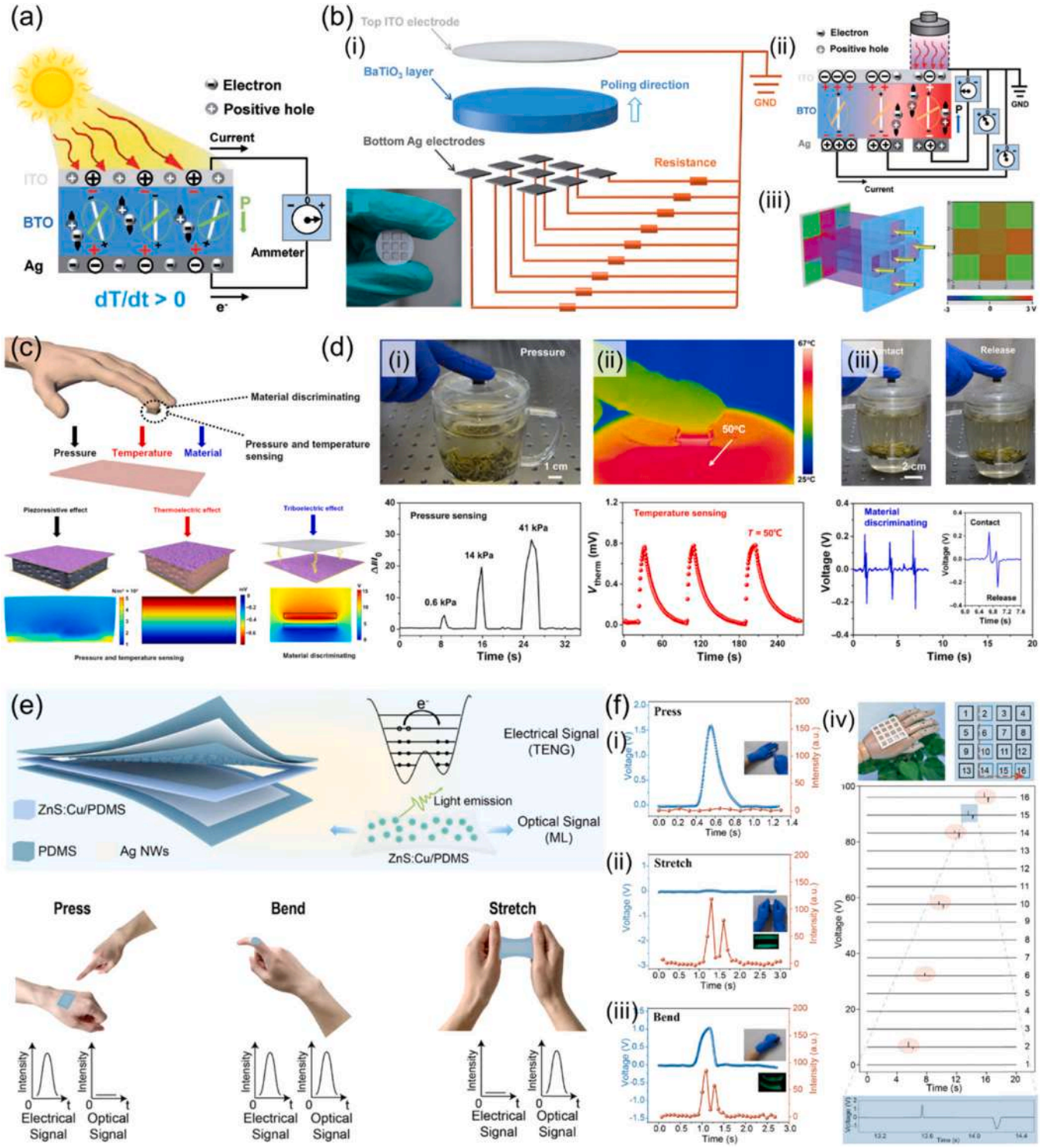


Fig. 8. Various Hybrid Self-Powered Sensors. (a) Schematic of the operating principle of a photodetector based on the coupling of the PV and pyroelectric effects in ferroelectric materials and (b) its application to a self-powered photodetector array system: (i) structure, (ii) charge transfer process, and (iii) the mapping image of photodetector array. Reproduced under the terms of the CC-BY-4.0 license.[144] 2017, Wiley-VCH GmbH. (c) Schematic and (d) demonstration of self-powered multimodal sensor based on the combination of piezoresistive, thermoelectric, and triboelectric effects to detect (i) pressure, (ii) temperature, and (iii) material identification. Reproduced under the terms of the CC-BY-4.0 license.[217] 2020, The Authors. (e) Schematic and (f) demonstration of self-powered electronic skin constructed by combining a contact-separation mode TENG with a mechanoluminescent spacer layer for sensing multiple mechanical stimuli, including (i) pressing, (ii) stretching, and (iii) bending, and (iv) for its array system. Reproduced with permission.[218] 2022, Elsevier Ltd.

PV effect and pyroelectric effect in ferroelectric materials, as shown in Fig. 8**a**.[144] Ma et al. demonstrated a ferroelectric $BaTiO_3$ (BTO) film-based photodetector that can operate without external power and can sense 405 nm light illumination with fast sensing capabilities. The developed indium tin oxide (ITO)/BTO/Ag photodetector works based on both the pyroelectric effect and PV effect, resulting in a positive pyroelectric current observed under light illumination and a PV current flow from the ITO to Ag electrode. Therefore, the responsivity and specific detectivity of the photodetector are enhanced by more than 260 % owing to the light-induced PV-pyroelectric coupled effect. In addition, as shown in Fig. 8**b-i, ii, and iii**, they present a self-powered photodetector array system capable of achieving spatially resolved light intensity detection by recording the output voltage signals as a mapping figure. Overall, the paper provides a novel design approach to achieve sensitive light detection using a self-powered sensor system based on the PV-pyroelectric coupled effect.

Second, Wang et al. developed a self-powered multimodal sensor that combines piezoresistive, thermoelectric, and triboelectric effects to detect pressure, temperature, and material identification. The sensor is fabricated using hydrophobic polytetrafluoroethylene (PTFE) films and graphene/polydimethylsiloxane sponges, which enables high pressure sensitivity and high temperature sensing resolution even for a liquid droplet, as shown in Fig. 8**c**.[217] In addition, the sensor can generate output voltage signals that can be used to infer material properties. The triboelectric voltage generated when an arbitrary material is pressed by a PTFE reference film with a constant force depends on the intrinsic properties of the material. Therefore, if pre-existing data on the voltage output of various materials is available, the voltage output generated when any material is pressed by a PTFE film can be utilized to infer the identity of the pressed material. Moreover, potential biomedical applications were demonstrated for the sensor by affixing it to a finger as a wearable electronic device, showcasing its individual capabilities for pressure sensing (e.g., measuring pressure when pressing a cup), temperature sensing (e.g., measuring temperature when holding a hot cup), and material identification (e.g., displaying a unique voltage output when pressure is applied to a cup), as shown in Fig. 8**d-i, ii, and iii**. Although the presented sensor cannot operate entirely on its own because the piezoresistive-based pressure sensor incorporated in it requires a power source, this integration could potentially lower the total power consumption of the multifunctional sensor, paving the way for the development of fully self-powered sensors in the future.

Third, as a transitional stage, the self-powered sensor based on electricity generation can also be integrated with other types of sensors that have the potential to be developed as self-powered sensors. Zhang et al. introduced a self-powered electronic skin (STMES) that can sense and differentiate multiple mechanical stimuli, such as pressing, bending, and stretching, as shown in Fig. 8**e**.[218] The STMES was constructed by combining a contact-separation mode TENG with a mechanoluminescent spacer layer. The TENG generated electrical signals in response to normal pressure or bending stress, while the mechanoluminescent spacer layer produced optical signals in response to bending or lateral strain, without requiring external power. By using both electrical and optical signals, the STMES can differentiate among various mechanical stimuli. The device is highly durable and stable and can be attached to the finger for continuous tracking of finger movements and external mechanical stimuli. A 4 × 4 sensor array demonstrated the position-sensing ability of the STMES, making it promising for applications such as soft robots, wearable electronics, and human-machine interactions, as shown in Fig. 8**f-i, ii, iii, and iv**. It is expected that further study to integrate a PV cell, instead of the used spectrometer, with the current mechanoluminescent material will enable a fully self-powered sensor.

In conclusion, hybrid self-powered sensors that integrate multiple self-powering mechanisms have shown great potential in enhancing the sensing performance and realizing multimodal sensing capabilities. Through the integration of different self-powering mechanisms, these sensors can operate autonomously without needing an external power source, making them ideal for remote and harsh environments. While many challenges, when the device is exposed to ambient heat from the human body, remain, the development of these hybrid sensors is expected to continue to grow and expand into new and exciting applications in the future.

3. Challenges and perspectives

Self-powered physical and chemical sensors have several practical advantages such as compatibility with electronic components and lower power consumption. However, several challenges must be addressed for their effective implementation. In this chapter, we will discuss these challenges and potential solutions, including the prospects of advanced self-powered sensing technology.

1) Self-powered sensors that rely on wasted or natural energy sources are often limited in their continuous operation. For instance, sensors powered by thermal energy sources require temperature differences to operate, which restricts their functionality in environments without heat sources. Therefore, to ensure continuous operation, self-powered systems that utilize external power sources when there is no natural or wasted energy source or systems that store energy during the presence of energy sources and use it later must be developed.
2) Natural energy is introduced as a sensing signal in self-powered sensors, which makes the sensor signal highly dependent on the external environment. For instance, in the case of self-powered sensors that use the PV effect and light energy sources, the signal changes not only when there is a change in the physical quantity to be detected but also owing to a change in the intensity of external light. To compensate for this, a reference sensor must be utilized.
3) The downscaling of the self-powered sensor is limited. To create an electrical signal with a detectable size in an electronic device, the device that converts energy must be relatively large, which increases the overall size of the sensor. Synergistic hybridization of multiple mechanisms is being investigated to increase efficiency, but this approach is currently limited to certain sensors, such as photodetectors.
4) Despite its inherent capability to transduce external physical stimuli into electrical responses, a self-powered sensor requires an external electrical circuit to quantify and present these responses to end users. Consequently, achieving complete autonomy in terms of the power supply for the entire system, including the measurement components of the sensor, remains a challenging endeavor. To address this challenge effectively, an ultralow-power external electrical circuit integrated with a compact energy-harvesting unit that can provide the required power to drive this circuit needs to be developed.
5) Multifunctional hybrid systems have many complex limitations that make them difficult to implement in practical devices. One general limitation of hybrid self-powered sensors is their reliance on multiple energy harvesting mechanisms, which can lead to increased complexity and potential interference among the different sensing modalities. For instance, integrating piezoresistive, thermoelectric, and triboelectric effects into a single sensor may cause cross-talk between the signals, complicating the data interpretation and reducing the overall reliability of the sensor. A potential solution to this problem entails the implementation of advanced signal processing algorithms and calibration techniques that can effectively separate and compensate for the overlapping signals. Additionally, designing the sensor architecture to physically isolate the different sensing elements could minimize interference and enhance the clarity of the output signals.

Another significant challenge is the physical size and scalability of hybrid self-powered sensors. The need to incorporate multiple energy

conversion and sensing components often results in larger sensor dimensions, which can limit their applicability in compact and portable devices. To address this, ongoing research is focused on developing miniaturized and integrated sensor systems through the use of advanced materials and fabrication techniques. For example, nanomaterials and flexible substrates can be utilized to create more compact and lightweight sensors without compromising their performance. Furthermore, exploring novel energy harvesting materials with higher efficiency can reduce the size of individual components, enabling the overall downsizing of hybrid self-powered sensors. This approach enhances their practicality for a wider range of applications and paves the way for their integration into next-generation wearable and portable electronic devices.

Overall, self-powered sensors face the predicament of relatively cumbersome sizing, which is partly attributed to the requirement of supplementary components, such as reference sensors or calibration circuits, to combat the aforementioned challenges. The incorporation of these components increases the overall size of the sensor despite the simplicity of the parts of the sensing mechanism. Despite the urgency to tackle this problem, it is essential to consider the potential utilization of niche applications where the presence of substantial centimeter-scale sensors does not pose a hindrance. Notwithstanding these obstacles, the advancement of self-powered sensors that utilize residual or renewable energy remains crucial, given the persistent concerns regarding environmental pollution and energy challenges. With the development of new sensing mechanisms and sensor structures that can overcome the limitations mentioned above and increase efficiency, self-powered chemical and physical sensors have the potential to replace a significant portion of existing sensors that require constant electrical power.

4. Conclusion

This review article provided a comprehensive overview of the recent progress in self-powered physical and chemical sensors based on electricity generation. The sensors were classified into three categories based on the type of wasted or renewable energy sources they use, and each category was further divided into subcategories to provide comprehensive explanations regarding the working mechanisms for generating electricity. Chapter 2.1 discussed sensors that use light energy sources, such as the PV and photoelectrochemical methods. PV and photoelectrochemical sensors capitalize on ambient light as a readily available power source for sensing applications, with solar light being particularly abundant. This characteristic renders them suitable for monitoring in various outdoor environments, including space and outdoor environments. However, the influence of the surrounding environment, particularly the intensity and direction of light, significantly impacts the sensor performance. Thus, further research focused on effectively managing and mitigating the environment-induced variations in sensor values holds potential for expanding their utilization across diverse fields. Chapter 2.2 covered sensors that use thermal energy sources, such as the thermoelectric and pyroelectric methods. Thermoelectric sensors operate through the Seebeck effect, converting a temperature gradient into an electric voltage. This generated voltage is directly proportional to the temperature difference between the ends of the conductors. These sensors have diverse applications, serving as temperature sensors, wearable physical sensors, and gas sensors. On the other hand, pyroelectric sensors function based on detecting temperature alterations using specialized materials known as pyroelectric crystals. These sensors produce a voltage when the temperature of the crystal changes. Pyroelectric materials exhibit a rearrangement in their crystal structure in response to temperature fluctuations, resulting in a change in polarization and the generation of an electric signal. Pyroelectric sensors find utility in various applications, such as temperature sensors for human motion monitoring, light detection sensors, and more. Self-powered sensors relying on thermal energy sources offer several advantages, including prolonged lifespan, absence of moving parts, emission-free operation, no operational or maintenance costs, and the utilization of low-grade thermal energy potential.

Chapter 2.3 described sensors that use mechanical energy sources, such as the triboelectric and piezoelectric methods. TENGs excel in self-powered sensing by efficiently converting ambient mechanical energy through the triboelectric effect. Their versatility and sensitivity make them ideal for applications like self-powered pressure sensors, smart textiles for sleep monitoring, and environmental monitoring. Piezoelectric sensors, leveraging the piezoelectric effect, function by converting mechanical energy into electrical power. The intrinsic characteristics of piezoelectric sensors facilitate their deployment as highly sensitive instruments in diverse applications, including motion detection and pressure sensing. Both TENGs and piezoelectric sensors face challenges, prompting ongoing research endeavors aimed at refining their accuracy and overcoming obstacles. Chapter 2.4 introduced recently reported hybrid devices that combine multiple self-powered sensing mechanisms to utilize their synergistic effects, which will enhance sensing performance and enable multimodal sensing. Chapter 3 discussed the summary and current limitations of self-powered sensors and provided an insight into future research areas that could overcome these limitations.

In the modern era, where energy consumption management is becoming increasingly important with the rapid increase in the usage of electronic devices, reducing the power consumption of sensors is crucial. Although efforts to improve conventional sensors, such as making them smaller, should continue, developing new self-powered sensing mechanisms to reduce the power consumption of next-generation sensors will be a breakthrough in addressing energy and environmental problems. As discussed in Chapter 3, there are still issues related to the size and reliability of self-powered sensors, but the current stage of development is noteworthy given that self-powered sensors have only just begun to be developed. Therefore, it is anticipated that further active and in-depth research will resolve the limitations mentioned above, and self-powered sensors will emerge as a powerful tool for the era of the advanced IoT and metaverse.

CRediT authorship contribution statement

Hyeonseok Han: Resources, Methodology. **Kichul Lee:** Visualization, Investigation. **Inkyu Park:** Writing – review & editing. **Donho Lee:** Formal analysis, Data curation. **Ji-Hwan Ha:** Supervision, Resources. **Soon Hyoung Hwang:** Validation, Resources. **Byeongmin Kang:** Validation, Software. **Yeongjae Kwon:** Supervision, Project administration. **Junseong Ahn:** Writing – review & editing, Writing – original draft. **Lei Wu:** Formal analysis, Data curation. **Jun-Ho Jeong:** Investigation, Funding acquisition. **Xuan Li:** Resources, Conceptualization. **Sohee Jeon:** Resources, Project administration. **Jihyeon Ahn:** Writing – review & editing, Writing – original draft. **Bingjun Yu:** Resources, Methodology. **Seokjoo Cho:** Writing – review & editing, Writing – original draft.

Declaration of Competing Interest

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

Data Availability

The data that has been used is confidential.

Acknowledgments

Jihyeon Ahn and S. Cho contributed equally to this work. This work was supported by the Basic Research Program of KIMM (Korea Institute

of Machinery and Materials, NK248B) and a National Research Foundation of Korea (NRF) grant funded by the Korean government (MSIT, No. 2021R1A2C3008742). This work was also supported by the Korea Evaluation Institute of Industrial Technology (KEIT) grant funded by the Korean government (MOTIE, Grant No. RS-2022-00154781, Development of large-area wafer-level flexible/stretchable hybrid sensor platform technology for form-factor-free highly integrated convergence sensor).

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Jihyeon Ahn is a master's student at the Korea Advanced Institute of Science and Technology (KAIST). She received her BS degree from Korea University (2023). Her current research interest focuses on wearable sensors for healthcare applications.



Seokjoo Cho is a PhD candidate at the Korea Advanced Institute of Science and Technology (KAIST). He received his BS and MS degrees from KAIST in 2020 and 2022, respectively. His current research interest focuses on wearable sensors for biomedical and healthcare applications.



Junseong Ahn is an assistant professor in the Department of Electro-Mechanical Systems Engineering at Korea University. He received his BS, MS, and PhD degrees from Hanyang University (2017), KAIST (2019), and KAIST (2023), respectively. His current research interests include micro/nano structuring and its application to sensors and energy harvesting devices.



Jun-Ho Jeong is a principal researcher at the Korea Institute of Machinery & Materials (KIMM). He is also a faculty member of the Department of Nano-Mechatronics at the University of Science and Technology (UST). He received his BS, MS, and PhD degrees from Hanyang University (1990), KAIST (1993), and KAIST (1998), respectively, in Mechanical Engineering. His research interests include nanoimprinting, nanofabrication, holograms, microneedles, and drug delivery.



Professor Inkyu Park received his BS, MS, and PhD from KAIST (1998), UIUC (2003), and UC Berkeley (2007), respectively, in mechanical engineering. He has been a faculty member of the Department of Mechanical Engineering at KAIST since 2009 and is currently a full professor and KAIST Endowed Chair Professor. His research interests include nanofabrication, smart sensors for healthcare, environmental and biomedical monitoring, nanomaterial-based sensors, and flexible/wearable electronics. He has published over 180 international journal articles (SCI indexed) and holds over 40 registered domestic and international patents in MEMS/NANO engineering.