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Perspective

Self-powered technology for next-generation biosensor

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The medical biosensor has received significant attentions from the medical and industry due to the powerful capability in diagnosis and healthcare. Biosensors generally contain two key components: biological components and physical or chemical transducing devices. As a typical convergence technology, biosensor integrates the principles and technologies of biology, chemistry, physics, and other disciplines. Since Clark et al. [1] first proposed and led to the advent of the first biosensor in the 1960s, which is an amperometric enzyme electrode for glucose. Over the past 60 years, biosensors have developed rapidly due to their simple, sensitive, fast and accurate characteristics, which showing broad prospects such as wearable and portable, point-of-care testing (POCT), noninvasive analysis, biopsy, online detection, on-site monitoring, ultra-high time-space resolution and single-cell biology applications.

Recently, the biosensor has entered a new era. The Internet of Things (IoT), big data, and artificial intelligence have become significant external powers for next-generation biosensor progress. The miniaturized integrability, intelligentize, and wireless portability are the main features of next-generation biosensors. Intelligence often means more energy consumption owing to the more calculations from multiple signals acquisition and further processing. However, wireless and miniaturization have further limited the volume and weight of the power source. It is a huge challenge to power billions of these distributed devices. Up to now, the limited capacity of power source based on battery has impeded the development of the intelligentization and wireless portability of next-generation biosensors.

In recent years, self-powered technology has been rapidly developed as an ideal solution for powering distributed electronic devices [2–4]. There are mainly two modes of self-powered technology for the next generation of biosensors. The first mode is the self-powered sensing system that extracts energy from the environment or organisms that rely on the energy harvesting unit to power the sensing unit. The second mode is a self-powered sensor that directly converts the weak physical/chemical changes in the environment and organisms into electrical signals. These proposals increase the energy supply or reduce the power consumption of the system and reveal broad prospects in sensor applications. Energy conversion devices are the core component of self-powered system. It can be divided into five categories: piezoelectric nanogenerator (PENG), triboelectric nanogenerator (TENG), enzymatic biofuel cells, thermoelectric generator/pyroelectric nanogenerator (TEG/PyNG), and solar cells. These devices can convert the energy from organisms or environmental into electrical energy based on the corresponding working mechanism.

Self-powered sensing system. The energy harvest unit, energy storage unit and sensing unit are the main three parts of the self-powered sensing system (Fig. 1a). External physical, chemical, or biological changes induce the energy harvesting unit to generate electrical power and then stored it in the energy storage unit. Rechargeable lithium battery is often used as energy storage units, and the energy generated by energy harvesting devices has been transformed electrochemically and stored in the energy storage unit. The sensing unit is powered by the energy storage unit and transforms the biological signal into an associated electrical signal. Recently, Lin et al. [5] developed a triboelectric nanogenerator that enables a self-powered wireless body sensor network (BSN) system for heart-rate monitoring. Jiang et al. [6] reported a human motion-driven wearable noncontact free-rotating hybrid nanogenerator (WRG) for a self-powered information wearable system. The instantaneous excitation of a single external force can produce continuous electric energy output for continuous 2 s. Its output power meets the requirements of most wearable electronic products. The further development of self-powered mobile sensing devices is expected to be promoted by this work. Nadeau et al. [7] developed an ingestible device that uses copper electrodes and zinc electrodes to harvest energy from gastric

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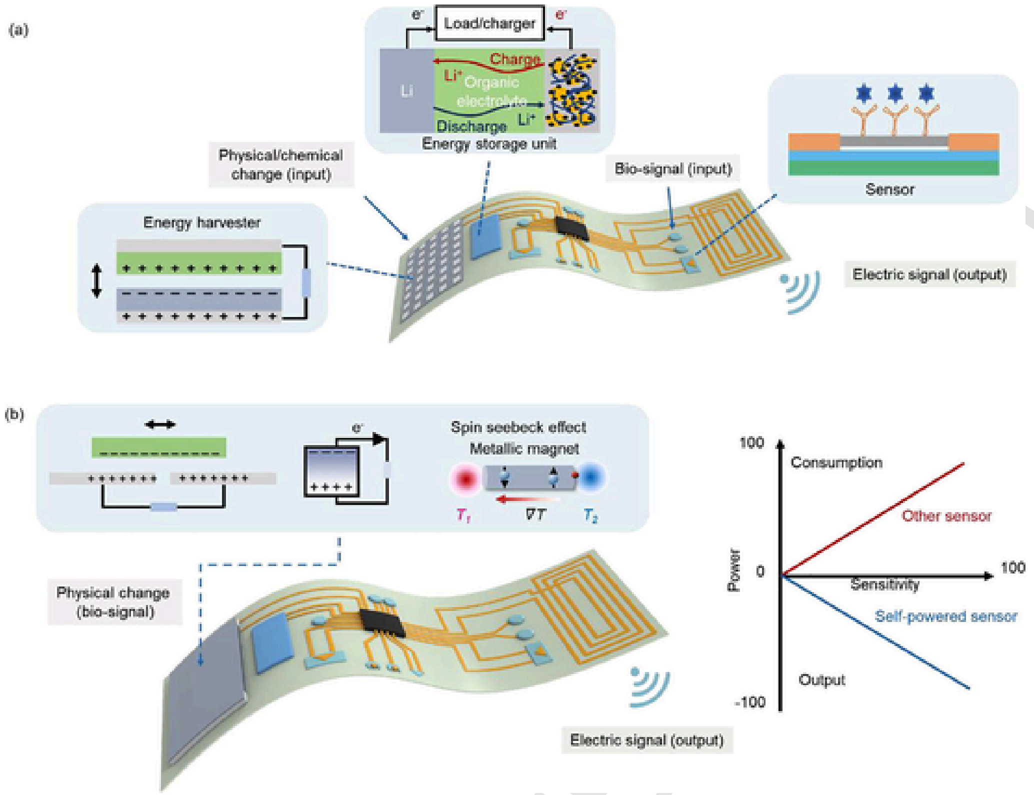

Fig. 1. Two typical modes of self-powered technology for the next generation of biosensors. (a) Diagram of the self-powered sensing system. (b) Diagram of the self-powered sensor.

acid. The energy harvested by this device is enough to transmit the measurement results from the built-in temperature sensor to a receiver a few meters away from the animals. This energy harvesting device has the potential to provide energy supply for the next generation of ingestible sensing devices. Yu et al. [8] proposed a multiplexed metabolic sensing system based on flexible perspiration-powered integrated electronic skin (PPES). This electronic skin can selectively monitor key metabolic analytes (such as urea, NH_4^+, glucose, and pH) and be powered by a glucose fuel cell. This vital signs and molecular information sensing platform can be applied in optimizing of next-generation prostheses. To satisfy the balance between energy production and consumption, energy sources and utilization efficiency are critical issues for most of the self-powered sensing systems. Generally, energy conversion and management efficiency are important to improve usage efficiency.

Self-powered sensor. The sensitivity of self-powered sensor is positively related to the electrical signal output since the sensor can directly transform external changes into associated electrical signals without additional electrical energy supply. For other types of sensors, sensitivity is the derivative of the output to the stimulus. To achieve higher sensitivity, higher output and power consumption are required. As an active device, self-powered sensors generally do not consume additional electrical power (Fig. 1b). The greater output electrical signal is, the higher sensitivity of the sensor is. Thus, self-powerability has been considered to be the key problem of achieving the compatibility of ultra-high sensitivity and low power consumption for next-generation of biosensors. Self-powered sensors based on nanogenerators and EBFS (enzymatic biofuel cells) show powerful capabilities in detecting pulse, respiration, heart beating, limb motion, facial movement, and even metabolic monitoring, etc. In addition, the TENG's friction layers can be modified by biological or molecular recognition elements or receptors to realize a self-powered biosensor [9].

Recently, Dagdeviren et al. [10] demonstrated an ingestible sensor that can be rolled into a capsule based on piezoelectric materials which can operate without a battery. The flexible device is based on piezoelectric materials, which can operate without the battery. The sensor also uses a polymer to adapt to the skin and stretch and move with the intestine. Zhang et al. [11] develop flexible temperature-pressure sensors based on the microstructure-frame-supported organic thermoelectric (MFSOTE) materials. The Sub 0.1 K temperature resolution and up to 28.9 kPa^{-1} pressure-sensing sensitivity has been achieved. The MFSOTE materials are expected to apply in health-monitoring and e-skin due to excellent sensing properties, large-area fabrication, and low cost. Ouyang et al. [12] proposed a flexible self-powered ultrasensitive pulse sensor (SUPS). This research work not only reports the pulse sensor based on self-powered technology for early disease detection capabilities. It also reveals that the self-power sensor can realize the compatibility of low power consumption and high sensitivity at the same time. Zou et al. [3] developed a bionic stretchable nanogenerator (BSNG) which can be used for underwater sensing and energy harvesting. In this work, the ion channel on the cell membrane of the electric eel's power generating organ has been imitated and constructed. The mechanically sensitive bionic channel controls the reciprocating movement of the electrifying liquid inside the generator, thereby realizing the conversion of electrical energy. The BSNG provides a promising alternative to a new generation of wearable electronic devices in dry and liquid environments power supply. The integration of miniaturization, durability and multi-function are the significant trends of development in the self-powered sensors.

Self-powered sensor for closed-loop control system. The intelligentization and integration of personal devices and bionic robots provide unprecedented opportunities and challenges for the development of biosensors [13]. In order to perform tasks effectively without manual intervention, the integration of sensory information and artificial intelligence is necessary. Sensors are not treated individually, which is core element of its closed-loop control system and also the part of the intelligent system. It is crucial for control and automation systems that the biosensors detect and measure physical, chemical or biological changes and provide this information to the control system. The closed-loop control system always consists of controllers, sensors, transducers, final control elements or actuators, and transmitters. Here, the sensor can convert a physical, chemical, or biological stimulus into a readable output electrical signal.

Self-powered sensors can directly convert physical, chemical or biological changes into electrical signals and control closed-loop systems that respond to external stimuli (Fig. 2a) [14]. The system maintains near-zero power consumption when in standby mode due to the sensor has no energy consumption. However, the other sensing technology to provide continuous power is required to maintain sensing capabilities. Self-powered sensors will greatly extend the service life of closed-loop systems, such as wearable/implantable biological therapeutic devices and bionic robots.

Furthermore, it is essential to achieve a perfect closure by harvesting energy from the surrounding environment and organisms for powering closed-loop control systems based on biosensor (Fig. 2b). These closed-loop control systems realize a self-powered operation, independent of external supply power. However, for other sensor systems that rely on battery power supply, the battery capacity will reduce until it is exhausted. Eventually, the battery had to be replaced. That will destroy the perfect closure to a certain extent. Self-powered technology is expected to be applied to a broad field such as intelligent robots, environmental monitoring, and healthcare [15].

Sufficient and sustained energy supply is a key issue to realize the miniaturized integrability, intelligentize, and wireless portability of the next-generation biosensors. It is a great practical significance that utilizes energy from organisms and the environment to power biosensors. Various kinds of technologies are proposed to utilize these energies, such as triboelectric nanogenerator, piezoelectric nanogenerator, thermoelectric generator/pyroelectric nanogenerator, enzymatic biofuel cells, and solar cells. These self-powered technologies have been realized in different sensing areas such as pulse sensors, metabolic sensing, temperature sensors, etc.

There are still some challenges of the self-powered technology required to be overcome for next-generation biosensing applications. (1) Output improvement. Energy harvesting units for self-powered systems are often difficult to achieve compatibility between the high output voltage and high output current. The output of these devices is expected to be improved by the optimization of materials and structures. (2) Efficient energy storage. Nowadays, self-powered sensing devices can't achieve real-time monitoring and communication due to the limited energy storage efficiency. It is urgent to develop a more efficient energy management unit for the self-powered system. Some novelty and self-charging strategies of the self-powered system have been demonstrated, which are expected to promote energy management efficiency in self-powered sensing devices. (3) Minimization. Device miniaturization is an important issue, especially for mobile medical devices. New material synthesis and processing technologies are expected to provide more opportunities for miniaturization. (4) Long-term operation. It is a challenge to achieve long-term work and maintain excellent performance under service conditions. Nanotechnology and flexible packaging strategies are expected to provide some solutions for long-term operation challenges.

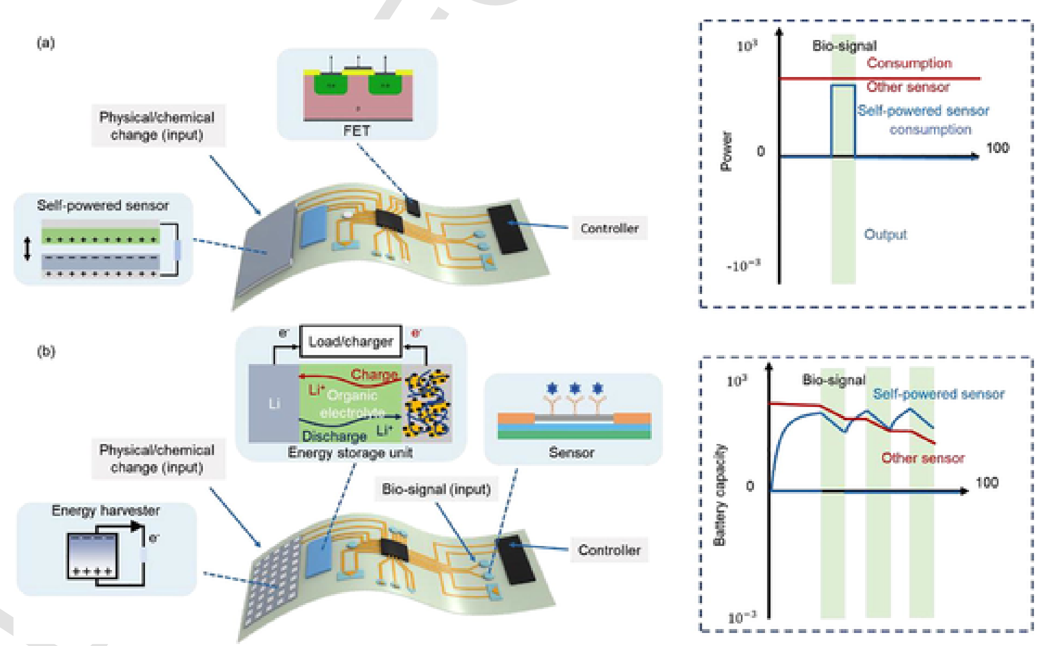

Fig. 2. Two typical modes of closed-loop system based on self-powered technology. (a) Diagram of a self-powered sensor for closed-loop control system. (b) Diagram of a closed-loop self-powered sensing and controlling system.

With the widespread applications of next-generation biosensors based on self-powered technology, it can potentially revolutionize the early detection capabilities in the biomedical field. It is expected to influence our daily life in the future, from intelligent electronics to healthcare.

Declaration of Competing Interest

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

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Biography

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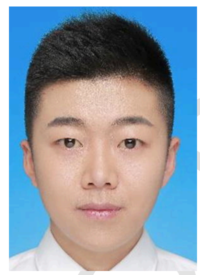

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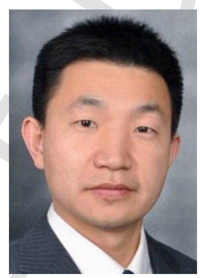

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