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Perspective

Self-powered technology for next-generation biosensor

Han Ouyang [a,b,1], Dongjie Jiang [a,c,1], Yubo Fan [b], Zhong Lin Wang [a,c,d], Zhou Li [a,c,d,*]

[a] CAS Center for Excellence in Nanoscience, Beijing Key Laboratory of Micro-Nano Energy and Sensor, Beijing Institute of Nanoenergy and Nanosystems, Chinese Academy of Sciences, Beijing 100083, China

[b] Key Laboratory for Biomechanics and Mechanobiology (Ministry of Education), Beijing Advanced Innovation Centre for Biomedical Engineering, School of Biological Science and Medical Engineering, Beihang University, Beijing 100083, China

[c] School of Nanoscience and Technology, University of Chinese Academy of Sciences, Beijing 100049, China

[d] Center on Nanoenergy Research, School of Physical Science and Technology, Guangxi University, Nanning 530004, China

Owing to their potential for diagnosis and remote healthcare monitoring, biosensors are a major research focus for the medical industry. In general, biosensors contain two key components: a biological component and a physical or chemical transducing device. As a typical convergence technology, biosensor integrates the principles and technologies of biology, chemistry, physics, and other disciplines. Since the advent of the first biosensor in the 1960s, an amperometric enzyme electrode for monitoring glucose leverls [1], biosensors have developed rapidly in terms of design simplicity, sensitivity, feedback speed, and accuracy. They have broad application prospects, such as portable (including wearable) devices, 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 research has entered a new era, with the Internet of Things (IoT), big data, and artificial intelligence emerging as significant influences for next-generation biosensor technology, with a focus on miniaturized integrability, intelligentize, and wireless portability. Increased device intelligence often corresponds to greater energy consumption as the number of calculations involved in multiple signals acquisition and additional processing. Moreover, the tendency toward device miniaturization and the requirement for wireless capabilities have further limited the volume and weight of the power source. Powering billions of these distributed devices remains a huge challenge. To date, the limited capacity of battery-based power source has impeded the development of the intelligentization and wireless portability of next-generation biosensors.

At present, there is a drive to develop self-powered technology to overcome the challenges involved in powering distributed electronic devices [2–4]. Two main modes have been explored regarding self-powered technology for biosensors. The first concerns self-powered sensing systems that extract energy from the environment or organisms that rely on an energy harvesting unit to power the sensor. The second mode involves self-powered sensors that convert weak physical/chemical changes in the environment and organisms into electrical signals directly. Both modes 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 components of self-powered systems, converting energy from organisms or the enviroment into electrical energy. They can be divided into five categories: piezoelectric nanogenerator (PENG), triboelectric nanogenerator (TENG), enzymatic biofuel cells, thermoelectric generator/pyroelectric nanogenerator (TEG/PyNG), and solar cells.

Self-powered sensing system. Self-powered sensing systems comprise three main components, namely, the energy harvest, energy storage, and sensing units (Fig. 1a). External physical, chemical, or biological changes induce the energy harvesting unit to generate electrical power and then store it in the energy storage unit. Rechargeable lithium batteries are often used as energy storage units, with the energy generated by the energy harvesting device 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 TENG capable of driving 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) that functions as a self-powered wearable information system. For the latter, the instantaneous excitation of a single external force produces continuous electric energy output for 2 s, with its output power satisfying the requirements of most wearable electronic products. Alernatively, Nadeau et al. [7] developed an ingestible device that uses copper and zinc electrodes to harvest energy from gastric acid. The energy harvested by this device is sufficient to transmit data recorded by the built-in temperature sensor to a receiver a few meters away. This energy harvesting device has the potential to power the next generation of ingestible sensing devices. In addition, 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 is powered by a glucose fuel cell. This sensing platform monitors the subject's vital signs and provides other molecular information, with its development targeted at optimizing state-of-the-art

* Corresponding author.
E-mail address: zli@binn.cas.cn (Z. Li).

[1] These authors contributed equally to this work.

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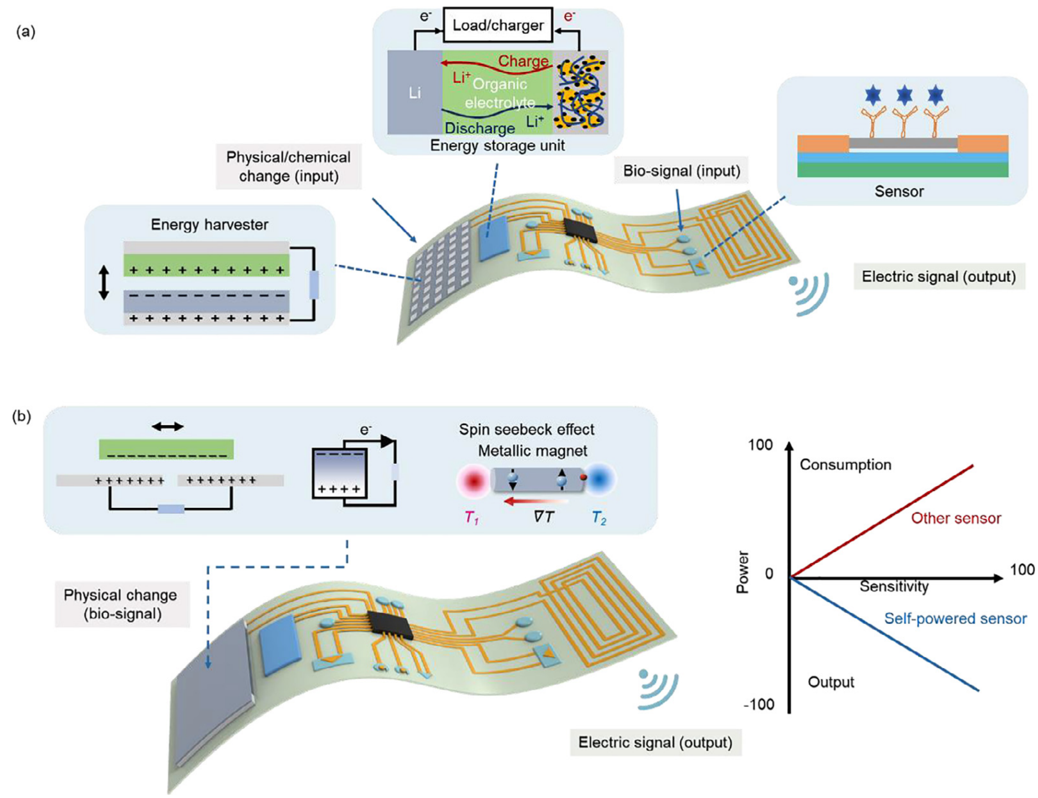

Fig. 1. Schematics of the two main modes of self-powered technology for the next generation of biosensors. (a) The self-powered sensing system based on an energy-harvesting unit. (b) The self-powered sensor based on the direct conversion of chemical/physical environmental changes.

prostheses. To satisfy the balance between energy production and consumption, the utilization efficiency of the energy source is the most critical issue for most self-powered sensing systems, with energy conversion and management efficiency both influential factors regarding utilization efficiency.

Self-powered sensor. As self-powered sensors can transform external changes into associated electrical signals directly without a separate supply of electrical energy, the sensitivity of self-powered sensors correlates positively to the electrical signal output. For other types of sensors, the sensitivity is the derivative of the output to the stimulus, with higher sensitivity achieved via higher output and power consumption. As active devices, self-powered sensors do not consume additional electrical power as a general rule (Fig. 1b). The greater the output electrical signal, the higher the sensitivity of the sensor. Consequently, the capacity for sensors to power themselves is considered key to balancing ultrahigh sensitivity and low power consumption. Self-powered sensors based on nanogenerators and enzymatic biofuel cells (EBFs) show powerful capabilities regarding pulse, respiration, heart beating, limb motion, and facial movement detection, as well as metabolic monitoring. In addition, self-powered biosensors can be realized by modifying the friction layers in TENGs using biological or molecular recognition elements or receptors [9].

Recently, Dagdeviren et al. [10] reported an ingestible sensor based on battery-independent piezoelectric materials that can be rolled into a capsule. In addition, the sensor uses a polymer to adapt to the skin and stretch and move with the intestine. Elsewhere, Zhang et al. [11] develop flexible temperature-pressure sensors based on microstructure-frame-supported organic thermoelectric (MFSOTE) materials, which demonstrate sub-0.1 K temperature resolution and a pressure sensitivity of up to 28.9 kPa^{-1}. The MFSOTE materials are promising candidates for applications in health-monitoring and e-skin owing to their excellent sensing properties, scalable fabrication, and low cost. Other notable contributions include the design of a flexible self-powered ultrasensitive pulse sensor (SUPS) by Ouyang et al. [12]. Not only does this SUPS exhibit early disease detection capabilities, it also demonstrates the desirable combination of low power consumption and high sensitivity. In addition, Zou et al. [3] developed a bionic stretchable nanogenerator (BSNG) capable of underwater sensing and energy harvesting. This BSNG involves an ion channel on the cell membrane that imitates the power generating organ of an electric eel. This 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 for wearable electronic devices that perform in both dry and liquid environments. In summary, current self-powered sensors research is focused on refining the integration of miniaturization, durability and multifunctionality.

Self-powered sensor for closed-loop control system. The intelligence and integration of personal devices and bionic robots provide unprecedented opportunities and challenges for the development of biosensors [13]. To perform tasks effectively without manual intervention, it is necessary to integrate sensory information and artificial intelligence. Sensors are not treated individually in closed-loop control system. Control and automation systems require biosensors to detect and measure physical, chemical, or biological changes and relay this information to the control system. Closed-loop control systems consist of controllers, sensors, transducers, final control elements or actuators, and transmitters in which the sensor converts 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]. Because the sensor does not consume energy, the system maintains

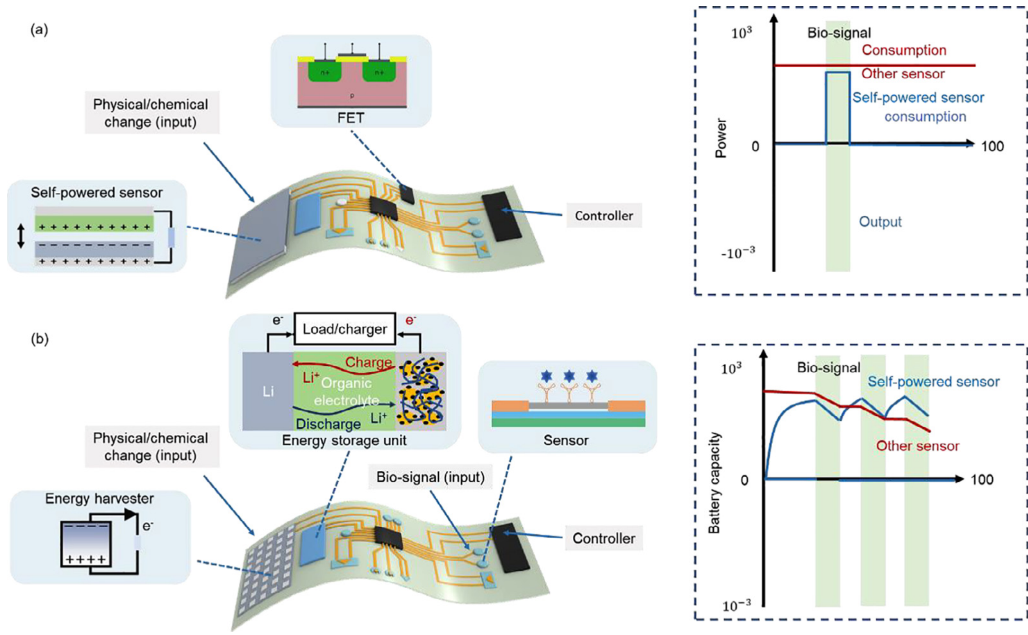

Fig. 2. Two typical modes of closed-loop system based on self-powered technology. (a) Diagram of a self-powered sensor for closed-loop control system. (b) Diagram of a closed-loop self-powered sensing and controlling system.

near-zero power consumption when in standby mode. However, the other sensing technology that provides continuous power is required to maintain sensing capabilities. Self-powered sensors extend the service life of closed-loop systems, such as wearable/implantable biological therapeutic devices and bionic robots, considerably.

Furthermore, when powering biosensor-based closed-loop control systems, it is essential to achieve perfect loop closure by harvesting energy from the surrounding environment and organisms (Fig. 2b). Although such closed-loop control systems realize a self-powered operation independent of an external power supply, for sensor systems that rely on battery power supply, the battery capacity is reduced until it is exhausted. Consequently, the battery eventually requires replacing, which causes disruption to the perfect closure. Closed-loop control systems featuring self-powered sensors have attracted interest for applications involving intelligent robots, environmental monitoring, and healthcare [15].

The sufficient supply of sufficient energy is a key issue to realizing biosensors with miniaturized integrability, intelligence, and wireless portability. Among the technologies proposed to satisfy this demand are TENGs, PENGs, TEGs/PyNGs, EBFs, and solar cells. These self-powered technologies have been utilized in sensing areas ranging from pulse and temperatures sensors to metabolic sensing.

Several remaining challenges face the widespread implementation of biosensores driven by self-powered technology. (1) Output improvement. Energy harvesting units for self-powered systems often struggle to achieve compatibility between the high output voltage and high output current. Materials and structural optimization is considered the best strategy to overcome this issue. (2) Efficient energy storage. At present, self-powered sensing devices cannot achieve real-time monitoring and communication owing to the limited energy storage efficiency. As such, the development of more efficient energy management unit for the self-powered system is a high-priority objective of current research. Several novel strategies for fabricating self-charging self-powered system have been demonstrated, which are expected to promote efficient energy management efficiency in self-powered sensing devices. (3) Minimization. Device miniaturization has particular importance for mobile medical devices. New material synthesis and processing technologies are expected to overcome many obstacles to further miniaturization. (4) Long-term operation. Guaranteeing both device logevity and sustained excellent performance remains challenging. However, advances in nanotechnology, coupled with flexible packaging strategies, are expected to resolve these issues.

The widespread applications of next-generation self-powered biosensors has the potential to revolutionize the biomedical field in terms of early disease detection and diagnosis. From intelligent electronics to healthcare, over the next few decades, biosensors are expected to become an increasingly common feature of daily life.

Declaration of Competing Interest

The authors declare that they have no conflict of interest.

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Han ouyang is a postdoctoral research fellow at Beijing Advanced Innovation Centre for Biomedical Engineering, Beihang University. He received his Ph.D. degree at Beijing Institute of Nanoenergy and Nanosystems, Chinese Academy of Sciences and School of Nanoscience and Technology, University of Chinese Academy of Sciences in 2019. His research interest includes nanoenergy, biosensors, and medical electronics.

Dongjie Jiang received his Bachelor's degree at Light Chemical Engineering (Excellence Program), Zhejiang Sci-Tech University in 2017. He is pursuing the Ph.D. degree at Beijing Institute of Nanoenergy and Nanosystems, Chinese Academy of Sciences. His interest includes implantable self-powered systems and applications based on nanogenerators.

Zhou Li received his Ph.D. degree from Department of Biomedical Engineering, Peking University in 2010, and Bachelor's Degree from Wuhan University in 2004. He joined School of Biological Science and Medical Engineering, Beihang University in 2010 as an associate professor. Currently, he is a professor at Beijing Institute of Nanoenergy and Nanosystems, Chinese Academy of Sciences. His research interest includes nanogenerators, *in vivo* energy harvesters, self-powered medical devices, and biosensors.