Wearable microgrids empowered by single-atom materials

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Wearable microgrids, a wearable system with integrated energy harvesting, storage, and regulation modules, and sensors, have potential to support human healthcare. However, wearable microgrids have not reached viability due to their high costs and limited performance, stability, and biocompatibility, awaiting significant breakthroughs, especially in material science filed. Single-atom materials (SAMs), one of the most promising forefronts of material, can overcome the shortcomings mentioned above and provide many extra advantages in various harvesters, energy storage devices, and wearable sensors. Herein, we discuss the potential of using SAMs in wearable devices to meet the demands of building practical energy-autonomous wearable microgrids towards extended comprehensive self-monitoring and human-machine interfacing.

INTRODUCTION

Wearable technology has recently witnessed spectacular growth, providing possibilities and perspectives for personalized self-monitoring towards prognosis, diagnosis, and treatment of diseases and human-machine interfacing for control, communication, and entertainment purposes. The global wearable market is estimated at USD 52 billion in 2022 with a projected annual growth rate of 13.8% till 2028[1]. While existing wearable products still rely on rigid and bulky electronics, researchers are pursued next-generation wearable devices featuring thin, flexible, conformal, and wireless form factors. Various wearable modules integrate into a multifunctional wearable system, leading to the "wearable microgrid" concept. Like traditional microgrids, power is supplied to multiple loads within the grids through energy sources and energy storage facilities, all managed by supervisory controls. This "wearable microgrid" concept describes a multi-modular system with various wearable applications whose power is provided by various energy harvesters and regulated by energy storage devices[2]. Its implementation relies on the design of the system with compatible wearable form factors, complementary characteristics within the proposed use case, and most importantly, commensurate energy rating to ensure reliable operation. In particular, the energy harvesters provide energy inputs to extend the system runtime, thereby assisting or potentially obviating the need for external energy, which allows autonomous on-body operation. Energy storage modules provide power regulation for the reliable operation of different wearable applications. However, wearable microgrids still have limitations, including insufficient biocompatibility of the system, high device power consumption of applications, low efficiency of harvesters, low power density of batteries, and limited sensitivity of sensors. For develop the next-generation wearable microgrids, the biocompatibility of the devices should be guaranteed, and the runtime of need to be extend, and the performance are required to be enhanced. Hence, advanced materials should be involved to solve these limitations and extend the practicality in the whole wearable microgrids including sensors, batteries, and energy harvesters.

WHY SINGLE-ATOM?

Single-atom materials (SAMs), which consist of isolated active atom sties dispersed on the supports, have emerged as highly promising high-performance materials for various applications. Among them, single-atom catalysts (SACs) have already boosted the catalytic properties in various energy devices and sensors, which have significant potential to address the mentioned drawbacks in the wearable microgrids. As we know, catalysts are a series of essential substances that can participate in chemical reactions and increase reaction rates, which play essential roles in wearable microgrids in terms of sensing, energy conversion, and energy storage. The operation of wearable microgrids rely on various catalysts to facilitate reactions with desired specificity, selectivity, or efficiency. The rise of nanotechnology and material science has brought new insights into the design of nanomaterial-based catalysts, downsizing traditional catalysts from bulk-level to nano-/subnano-level to improve their efficiency, activity, and selectivity. However, the state-of-art nanocatalysts still use expensive noble metals for high-performance devices, whose performance is unmatched by non-noble metal alternatives. However, the high loading of the noble metal usually results in increased cost and potential toxicity. Many wearable electrochemical sensors also rely on noble metal catalysts that lack selectivity, or enzymatic catalysts, which have limited stability and may require toxic mediators. Nanocatalysts have multiple active centers and complex chemical or coordination environments, which result in undesirable and/or toxic side reactions, reducing their specificity, biocompatibility, and stability. To this end, a practical approach was proposed to anchor individual metal atoms to supporting materials, reducing the metal nanostructure into well-defined, atomically uniformly distributed metal active centers[3]. The bottom-up construction of atomic-level catalysts with well-defined single active centers and low-coordination conditions was thus applied, named SACs, which can offer accurately controlled catalytic performance superior to nanocatalysts. Unlike traditional nanomaterials whose surface atoms contribute most of the catalytic activity, SAMs require the atomic level design of catalysts for dispersing metal reaction sites precisely and homogeneously on the specific solid support with particular electronic/geometrical structures (Figure 1). This allows SAMs to achieve maximum utilization of metals while avoiding issues of low selectivity due to the inhomogeneous distribution of materials. The performance of transition metal-based SAMs thus can be comparable to expensive noble-metal-based catalysts but with a fraction of the cost. Besides, the active site of Fe-N-C-based SAM (Fe-N_x site) can mimic the structure of the heme-based natural enzyme's active center and show the potential to replace natural biocatalysts in related bio-applications[4]. These series of SACs are also named single-atom nanozymes (SANs)[5]. Based on these advantages, SAMs have potential to play a critical and versatile role in wearable microgrids towards components requiring performance, stability, selectivity, and compatibility.

THE PERSPECTIVE OF SAMS FOR INTEGRATED WEARABLE MICROGRIDS

SAMs can exhibit their unique role in wearable microgrids in different applications (Figure 1). Some of wearable devices can harvest energy directly from the human body [6]. For example, bioenergy-powered wearable harvester systems like biofuel cells (BFCs) can provide regulated power with voltage to typical electronics. However, wearable BFCs are limited by low power density and instability for both the anode and cathode reactions. Specifically, the sluggish ORR at the cathode hinders the output performance of BFCs. Pt-based catalysts or bilirubin oxidase (BOD) are usually used for the cathode sides of BFCs. Precious Pt metals has cost issues, and the BOD have to integrate with mediators, enzyme direction-directing agents, and copping regents to enhance the power density. The long-time stability is the issue owing to the stability of a natural enzyme and the leaking of complex small molecule

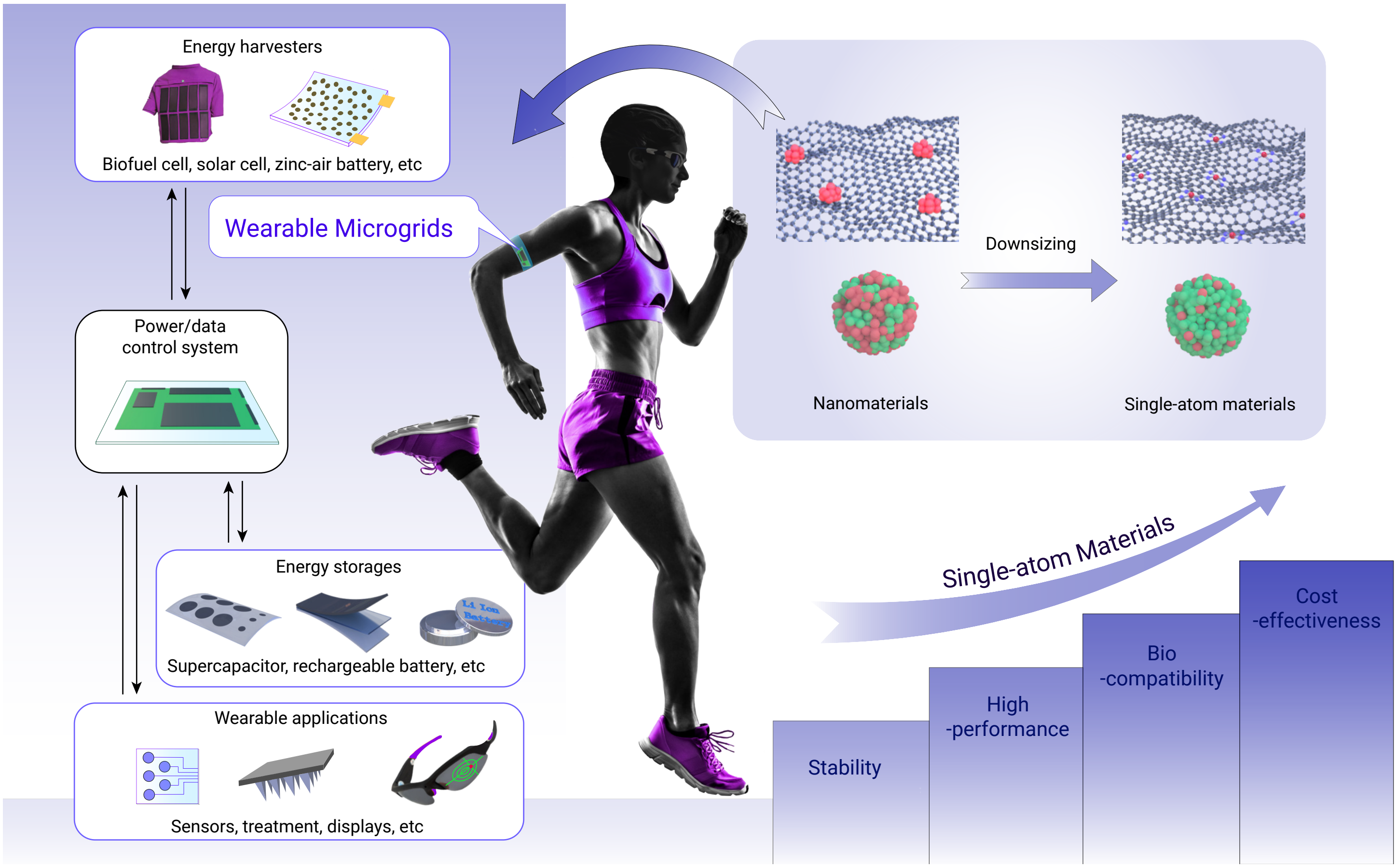

Figure 1. Opportunities for single-atom nanomaterials use in wearable microgrids.

reagents. Undoubtedly, advanced SACs will demonstrate their value in wearable energy harvesters. SAMs with various metals (Fe, Co, Mn, etc.)-N-C sites have huge progress in the ORR due to their maximization atom utilization, low cost, outstanding stability, and excellent activity. SAMs-based electrodes have better robustness in harsh environments than the enzyme electrodes and do not require additional small molecules to act as co-factors and mediators owing to their direct catalytic reaction mechanisms, thus addressing possible performance deterioration and toxicity due to chemical leaching. Besides, SANs can substitute or assist the natural enzymes (e.g., glucose oxidase) in enhancing the reaction efficiency on the anode side. Wearable solar cells are a series of green and inexpensive self-powered electronic devices. SACs can play different roles in photovoltaics and enhance solar-to-electric power conversion efficiency, which could be applied in wearable systems for energy harvesting. For example, SACs can replace Pt counter electrodes in dye-sensitized solar cells, which increases the collection of electrons from external circuits and enhance the catalytic efficiency of the triiodide/iodide redox reaction[7]. Other SAMs boost thermoelectric power generators and can be used in electronic devices and thermal-based energy harvests.[8]

Wearable energy storage devices like batteries or supercapacitors can power wearable applications. Wearable batteries feature better safety, high energy density, and a small device footprint, which are ideal for wearable applications. However, it would still require high-performance electrode materials to meet the rising power consumption of electronics. SAMs have the potential to boost electrochemical conversion reactions in batteries. Transition metal-N-C SAM has already been arranged in the rechargeable metal-air batteries. Other examples of using SAMs include decomposing H_2O_2 in lithium-oxygen batteries and boosting the electrochemical conversion kinetics, as well as providing super pseudocapacitive behavior in solar cells. For supercapacitors, carbon-based SAMs proposed that single-atom sites may catalyze some surface redox reactions or play other beneficial roles, which increase pseudo-capacitance, leading to higher energy-storage density.[9] Hence, synergistic SAMs will lead to exciting breakthroughs, find applications in a wide range of wearable energy storage devices, and potentially shift the paradigm in wearable energy systems with new reaction mechanisms that were once thought impossible.

Wearable sensors have seen tremendous commercial success for their ability to continuously monitor users' vital signals and biomarkers and provide feedback toward improved quality of life. Meanwhile, the frontier research of wearable sensors has focused on the non-invasive continuous monitoring of various signals towards obtaining a comprehensive closed-loop picture of personal well-being. SAMs with unique electronic/geometric structures and superior catalytic activity can boost signal amplification in colorimetrical, electrochemical, photoelectrochemical biosensing, etc[10]. For instance, the Fe-N-C SAMs can substitute the natural heme enzymes (with pentacoordinate heme iron active sites) for highly sensitive and stable sensing. Introducing SAM into wearable sensors could further achieve continuous operation and accurate measurements. Furthermore, SAMs with tailored reaction pathways can eliminate the need for small-molecule co-factors or mediators and rely on direct electron transfer for signal amplification, thereby boosting the sensing sensitivity, selectivity, and stability.

SAMs also show exciting potential in other wearable applications, including skin drug delivery, antimicrobials, wound treatment, and wearable displays. Specific SAMs with the catalytic process to produce reactive oxygen species in the aimed areas for antimicrobial and therapy. Besides, the biocompatibility performance of SAMs could allow the use of metal catalysts with minimized cytotoxicity for improved biocompatibility required in epidermal and textile-based devices.

CONCLUSION AND PERSPECTIVE

Wearable microgrids have promised an attractive future where comprehensive monitoring and human-machine interaction are seamlessly integrated into our daily lives with unparalleled convenience and autonomy. Nevertheless, it is still hard to reach sufficient technical readiness for commercialization. This perspective primarily introduces the state-of-the-art of SAMs in establishing wearable microgrids potentially. Incorporating SAMs into wearable microgrids offers possibilities in tailoring reaction mechanisms, performance, stability, and selectivity for desired applications. The continuous design of advanced SAMs as well as nanoengineering fabrication will also boost the wearable microgrids in various filed.

Although the SAMs boost various biomedical and energy harvesting properties, several challenges must be addressed before they can be widely used in wearable microgrids. These challenges include low-metal content, oxidic electronic states, poor biocompatibility, and instability. Also, advanced strategies need to achieve the large-scale synthesis of stable single atoms, like atomic layer deposition, etc. The improvements should meet the high demand for wearable sensors, and achieve continual surveillance, multi-task quick diagnosis, data/biomarker collection, and comparison for study/better understanding, and look forward to building SAM-boosted wearable sensors for more comfortable physical/medical monitoring for humans. There will also be great prospects in athletics and health, not only for vital signals or biomarkers continuous monitoring, but collecting sweat or other related biofluids for self-power support. Besides, the success of SAMs in the energy field will also suggest revolutionary new ideas in the field of wearable energy harvesting. The wearable self-powered integrated microgrids can also be used in the environmental area, like monitoring animal population status and their reproductive capacity, even in monitoring deep-sea animals. All in one, we believe that SAMs can boost next-generation wearable electronics for improving the quality of human life.

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DECLARATION OF INTERESTS

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