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Stretchable microbatteries and microsupercapacitors for next-generation wearable electronics

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Abstract

Stretchable energy-storage devices are required to power next-generation wearable electronics intimately integrated with the human body. The microbatteries and microsupercapacitors represent promising candidates featuring small footprints and facile system integration. This perspective reviews common strategies to convert conventional rigid devices into stretchable forms. Several prototype soft electronic systems are presented utilizing microbatteries and microsupercapacitors as power sources. We discuss the current challenges and perspectives of the stretchable microbattery and microsupercapacitor. Stretchable forms of miniaturized energy-storage devices often show a significant trade-off between mechanical deformability and electrochemical performances, which present attractive opportunities for the material and engineering community.

Keywords: Microbattery, microsupercapacitor, stretchable electronics, wearable electronics, energy-storage devices

INTRODUCTION

Various wearable electronic gadgets, such as smartwatches, wristbands, and Bluetooth earphones, are vital components of modern civilization. These devices continuously evolve toward reduced sizes, costs, and power consumption. In the coming decades, next-generation wearables are expected to adopt soft forms to seamlessly integrate with the human body, establishing robust interfaces for various sensing and stimulation functionalities[1,2]. The emerging stretchable electronics provide technology solutions to expand their application scopes toward healthcare monitoring, human-machine interfaces, and robotic prosthetics[3-5]. Typically, these devices utilize compliant materials and intelligent designs to achieve stable and persistent operations under bent, stretched, and twisted states. A key requirement for stretchable electronics is compatible and persistent energy supplies to form untethered systems. Soft energy harvesting systems may extract power from walking, finger motion, and sweat[6,7]. The intermittency of these renewable energy sources, unfortunately, hinders the continuous operations of wearable electronics over a prolonged period.

The electrochemical energy-storage devices are considered promising solutions to stably power smart wearables in terms of batteries and supercapacitors[8,9]. Batteries store energy via redox reactions of the active materials at electrodes to achieve high energy density. Supercapacitors exhibit high power density and superior lifetime through capacitive adsorption-desorption of ions or pseudo-capacitive Faradic reactions of the electrodes. To match the dimensions of next-generation wearables, miniaturized electrochemical energy-storage devices have been developed over the past decade, namely microbatteries and microsupercapacitors[10,11]. To date, these miniaturized cells are created with a typical footprint area below 1 cm^2 through advanced printing technologies, laser patterning, and lithographical techniques, resulting in superior energy-storage capability even after repeated mechanical bending[12-14]. The compact sizes of these miniaturized energy-storage devices facilitate their deployments over the target area on the substrate and monolithic integration with other functional electronic components. As-prepared microbattery/microsupercapacitor cells exhibit planar configurations for facile interconnection in series or in parallel, consequently adjusting output voltages and energy capacities to satisfy the corresponding electronic systems. The recent advancements in miniaturized energy-storage devices have already been covered in several reviews[15,16]. Stretchability is urgently required for microbatteries and microsupercapacitors to power soft electronic devices in on-skin wearable systems without constraining body movements. Currently, microbattery and microsupercapacitor cells are often constructed by patterning electrode materials on flexible substrates. As a practical challenge for sustainable energy supply, the electrodes are easily damaged upon external mechanical stretching. In this context, significant research efforts focus on materials innovations and cell designs for enhanced deformability in miniaturized energy-storage devices. The trade-off between electrochemical performances and mechanical stretchability provides enticing opportunities in these novel forms of energy-storage devices. In this perspective, we summarize the recent developments of stretchable microbatteries/microsupercapacitors and discuss the strength and weaknesses of the design strategies, as shown in Figure 1. The scientific and technical challenges for stretchable miniaturized energy-storage devices to compete against their rigid counterparts are outlined. Finally, various untethered wearable systems are discussed to illustrate the applications of microbatteries and microsupercapacitors as soft power sources.

ARCHITECTURE STRATEGIES TO ENABLE STRETCHABLE MINIATURIZED ELECTROCHEMICAL ENERGY-STORAGE DEVICES

A stretchable microbattery/microsupercapacitor comprises a positive electrode and a negative electrode, separated by an ionically conductive electrolyte. The stacked configuration has the potential risk of internal shorting under mechanical strains by continuously reducing the device dimensions. The mainstream design is in favor of planar configurations with interdigitated finger electrodes[17-19]. The positive and negative

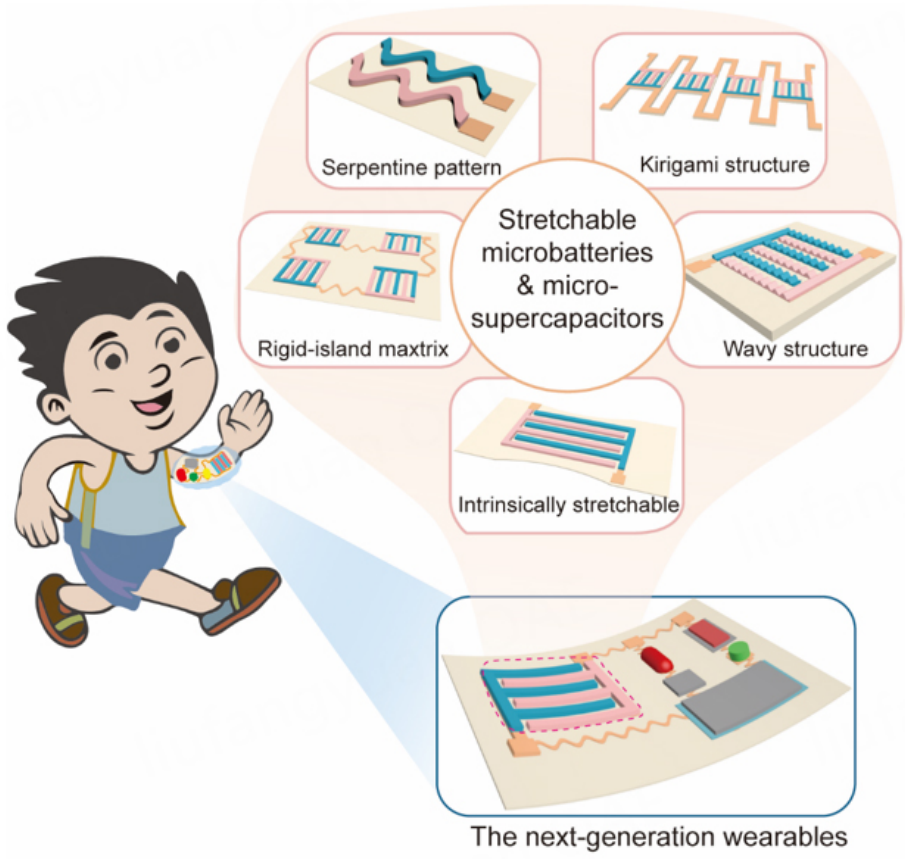

Figure 1. Schematic illustrating several designs of stretchable microbatteries and microsupercapacitors to power the next-generation wearable electronics.

electrodes are spatially separated and ionically connected by a liquid or gel electrolyte. Although the elastomer substrate and electrolytes are soft and deformable, the electrodes may experience fractures and delamination under large tensile strains[20,21]. Stretchable microbatteries and microsupercapacitors show a significant trade-off between electrochemical performances and mechanical deformability. Several design strategies have already been explored to create stretchable forms of miniaturized energy-storage devices, including a rigid-island matrix, serpentine patterns, kirigami configurations, wavy structures, and intrinsically stretchable structures, as shown in Figure 2 and Table 1.

Rigid-island matrix

The rigid microbattery/microsupercapacitor cells are distributed in island-like matrices on stretchable substrates and electrically interconnected by serpentine-shaped wires, as shown in Figure 2A. The tensile loads are primarily dissipated by straightening and bucking serpentine wires[22]. The design allows rigid cells to achieve appreciable deformability on the system level. In addition to uniaxial strain, the rigid-island matrix allows omnidirectional stretching by suitable integrated system designs[23,24]. Despite excellent electrochemical performances, the heterogeneously integrated cells suffer from delamination and fractures upon repetitive stretching due to large mechanical mismatches at material interfaces[25]. To overcome this limitation, the soft substrates are often locally stiffened for strain redistribution by embedding non-deformable materials at cell regions, such as polyethylene terephthalate and epoxy[24,26]. Liquid metals are also promising candidates for constructing ultrastretchable wires for electrical interconnection[27]. The corresponding rigid-island matrix achieves a superior stretchability of up to 400% strain[28]. The rigid-island

Table 1. Literature survey of stretchable microbatteries/microsupercapacitors

Cell design	Anode//Cathode	Specific capacity	Voltage window	Stretchability	Ref.
Rigid-island matrix	MWCNTs/PANI// MWCNTs/PANI	16.1 F/cm^3 at 5 mA/cm^3	0-1.2 V	50%, uniaxial 96%, biaxial	[22]
Rigid-island matrix	MXene/BC@PPy//MXene/BC@PPy	232.79 mF/cm^2 at 0.75 mA/cm^2	0-1.2 V	100%, uniaxial 300%, biaxial	[23]
Rigid-island matrix	MWCNTs// MWCNTs	13.2 F/cm^3 at 1 V/s	0-1.5 V	100%, uniaxial 125%, biaxial	[24]
Rigid-island matrix	MWCNTs/PPy/I^-//MWCNTs/PPy/I^-	5.17 mF/cm^2 at 0.1 mA/cm^2	0-0.8 V	69%, biaxial	[26]
Rigid-island matrix	Zn//O_2	29.54 mAh/g at 2 mA/cm^2	NA	400%, uniaxial	[28]
Serpentine	MWCNTs/PANI// MWCNTs/PANI	44.13 mF/cm^2 at 0.2 mA/cm^2	0-0.8 V	40%, uniaxial	[30]
Serpentine	MWCNTs/MnO_2// MWCNTs/MnO_2	12.59 mF/cm^2 at 0.01 mA/cm^2	0-0.8 V	69%, biaxial	[31]
Kirigami	MXene/BC// MXene/BC	112.2 mF/cm^2 at 1 mA/cm^2	0-0.6 V	100%, uniaxial	[34]
Wavy structure	rGO//rGO	0.54 mF/cm^2 at 500 mV/s	0-0.8 V	100%, uniaxial	[35]
Wavy structure	GO//GO	10.8 mF/cm^2 at 0.025 mA/cm^2	0-0.8 V	200%, uniaxial	[36]
Wavy structure	MWCNTs// MWCNTs	9.5 F/cm^3 at 0.036 A/cm^3	0-0.9 V	400%, biaxial	[37]
Wavy structure	MXene//MXene	185 mF/cm^2 at 2.0 mV/s	0-0.8 V	800%, biaxial	[17]
Wavy structure	MWCNTs/Mn/Mo//MWCNTs/Mn/Mo	7.5 mF/cm^2 at 0.3 mA/cm^2	0-2.0 V	50%, biaxial	[18]
Wavy structure	rGO/PEDOT:PSS// rGO/PEDOT:PSS	2.50 mF/cm^2 at 0.1 mA/cm^2	0-0.8 V	220%, uniaxial	[40]
Intrinsically stretchable	AuNW/PANI// AuNW/PANI	5.03 mF/cm^2 at 20 mV/s	0-0.8 V	50%, uniaxial	[41]
Intrinsically stretchable	Au@MnO_2// Au@MnO_2	0.53 mF/cm^2 at 0.01 mA/cm^2	0-0.8 V	60%, uniaxial	[42]
Intrinsically stretchable	Ag/Fe//Ag/Ni	2.9 mF/cm^2 at 10 mV/s	0-1.6 V	20%, uniaxial	[44]
Intrinsically stretchable	Graphene/PEDOT:PSS//Graphene/PEDOT:PSS	23 mF/cm^2 at 5 mV/s	0-1.0 V	100%, uniaxial	[45]
Intrinsically stretchable	MXene/AgNW/MnO_2/C_{60}//MXene/AgNW/MnO_2 /C_{60}	247.8 mF/cm^2 at 10 mV/s	0-0.8 V	50%, uniaxial	[46]
Intrinsically stretchable	Zn//MnO_2	0.51 mAh/cm^2 at 0.2 mA/cm^2	0.8-1.7 V	200%, uniaxial	[47]

PANI: Polyaniline; BC: bacterial cellulose; PPy: polypyrrole; I^-: iodide; AuNW: Au nanowire; AgNW: Ag nanowire; NA: not available.

pattern demonstrates appealing compatibility to the active materials widely used in currently studied energy-storage systems, but their further implementations into wearable electronics may be burdened by sophisticated manufacturing procedures. Additionally, the interconnect wires in rigid-island matrix inevitably occupy extra area within the whole device and, unfortunately, result in relatively low areal energy density.

Serpentine pattern

The serpentine pattern endows stretchability to miniaturized energy-storage devices by dissipating the imposed tensile strain by bending or buckling its meandering structure [Figure 2B]. For example, a simple serpentine metal film can realize a stretchability of ~30%[29], which matches the stretchability of skin. By virtue of the extension of the serpentine pattern, stretchable microbattery or microsupercapacitor cells can

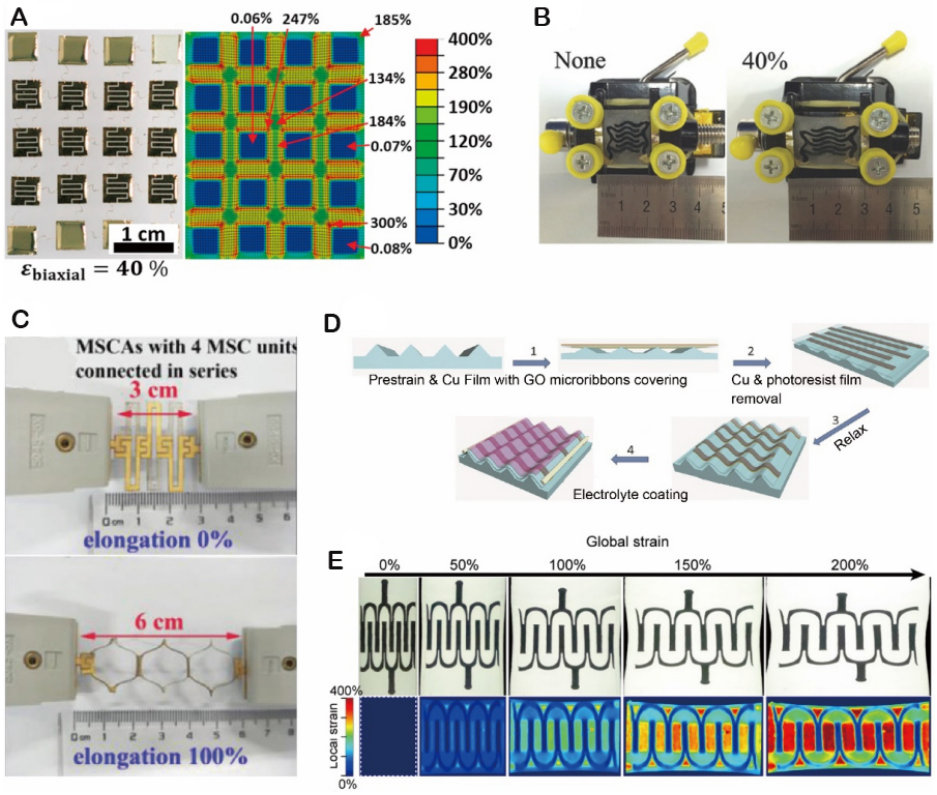

Figure 2. Design strategies to create stretchable microbattery and microsupercapacitor cells. (A) Optical image (left) and corresponding strain distribution (right) of a rigid-island matrix of microsupercapacitors under a 40% biaxial strain. Reprinted with permission from Yun *et al.*[22]. Copyright 2016 Elsevier. (B) Optical images showing stretchable microsupercapacitor in serpentine pattern design under 0% (left) and 40% (right) uniaxial strains. Reprinted with permission from Li *et al.*[30]. Copyright 2017 Wiley-VCH. (C) Optical images revealing Kirigami microsupercapacitors at 0% (top) and 100% (bottom) uniaxial tensile strains. Reprinted with permission from Jiao *et al.*[34]. Copyright 2019 Wiley-VCH. (D) Schematic illustration of the fabrication process for a wavy microsupercapacitor. Reprinted with permission from Qi *et al.*[35]. Copyright 2015 Wiley-VCH. (E) Optical images (top) and corresponding strain distributions (bottom) of intrinsically stretchable microelectrodes to illustrate the strain redistribution strategy. Reprinted with permission from Bai *et al.*[47]. Copyright 2022 American Chemical Society.

be achieved by directly preparing a positive electrode and a negative electrode on serpentine current collectors[30,31]. The matured slurry comprising of rigid granular active materials, conductive additives, and stiff polymeric binders for conventional electrodes can also be utilized to construct stretchable electrodes. The stretchability of the serpentine pattern can be further improved by tailoring its in-plane design and structural flexibility in the out-of-plane direction, such as the sinusoidal wave structure, the adhesion energy between wires and soft substrate, and the stiffness of the soft substrate[32]. One drawback to this technique is that the delaminations of active materials layer at large tensile strains. Recently, vertical microarrays have been intently created to replace the continuous film for the active materials layer, which improves the stretchability to 70% strain[33].

Kirigami configuration

Kirigami is a traditional form of paper art involving folds and cuts to allow a change in geometry. Kirigami patterns are often introduced into microbattery/microsupercapacitor cells for a high level of stretchability. Despite some undesirable out-of-plane deformations, the Kirigami pattern transforms global tensile strains into localized bending motions (see Figure 2C)[34]. The energy-storage components are subjected to minor stresses under large global strains, thereby largely preserving their electrochemical performances. The excellent deformability allows the devices to be worn as a wristband. The out-of-plane buckling of these

devices, on the other hand, often precludes conformal and seamless integration with the human body. Additionally, the deformation direction of these devices is usually defined by the Kirigami pattern, so that the energy-storage devices may demonstrate anisotropic stretchability.

Wavy structure

The wavy structure accommodates tensile loads on the electrodes into the expansion of the waves. As regards the preparation procedure, a thin electrode layer is laminated onto a pre-stretched elastomer substrate and then buckled into wavy structures by releasing the strain (see Figure 2D)[35]. The strategy utilizes flexible materials to create stretchable electrodes with highly textured surfaces. Carbon nanotube sheets and graphene films have often been utilized to create wavy microelectrodes for microsupercapacitors due to their excellent mechanical flexibility and decent electrical conductivity of ~100 S/cm[36,37]. Two-dimensional transition metal carbides (MXenes) are alternative candidate materials for wavy microelectrodes featuring high electrical conductivity (20,000 S/cm) and outstanding theoretical capacitance (> 900 F/cm^3)[38,39]. Our group recently reported a MXene microsupercapacitor based on wavy-like microelectrodes that exhibits a high areal capacity of 185 mF/cm^2 and ultrahigh stretchability of up to 800% area strain[17].

As a major limitation, the electrode design requires flexible material candidates to avoid severe fractures upon mechanical buckling for the wavy surface textures. The wave dimension should be carefully regulated to achieve intimate interfaces with the human skin. The electrode thickness is commonly within several micrometers, resulting in a relatively low areal capacity[18,37,40]. By raising the electrode loading, the increased dimension of the wavy structures may present practical challenges for assembling compact cells.

Intrinsically stretchable structure

Intrinsically stretchable devices harness all compliant material components to achieve skin-like mechanical deformability. As liquid or gel electrolytes are mechanically compliant, the majority of research effects focus on preparing soft and stretchy microelectrodes[41,42]. Conventional active material layers are rigid and brittle composites made from slurries. To overcome the limitations, active materials and conductive additives are blended with elastomer or gel binders to improve the mechanical deformability of active material layers[21,43]. An alternative approach is coating a thin film of active materials onto intrinsically stretchable current collectors[20]. A series of intrinsically stretchable microsupercapacitors based on various active materials have already been realized[44-46]. However, due to the significant discrepancy in mechanical properties between active materials and the soft matrix, the microelectrodes endure server delamination if the bonding energy between active materials and a soft matrix is insufficient, thus resulting in energy-storage performance fading. Additionally, the degraded electronic conductivity of stretchable electrodes in response to high tensile strains leads to increased impedance and overpotential for the charging/discharge processes. The field of intrinsically stretchable miniaturized energy-storage devices is relatively nascent compared to rigid-island, Kirigami, and wavy architectures discussed previously. Intrinsically stretchable microelectrodes require proper strategies to address issues associated with poor structural stability and suppressed electronic conductivity at stretched states.

Our group recently proposed a self-adaptive strain redistribution design to improve the deformability of intrinsically stretchable microbatteries[47]. The interdigitated current collector utilizes high-modulus conductive nanocomposites to achieve local stiffening effects. The tensile deformations are mainly accommodated by expanding interdigitated gaps, thereby protecting the active electrodes from potential damage [Figure 2E]. The local strain on finger electrodes is 47% at a high global strain of 200%, representing quadrupled mechanical deformability.

CHALLENGES AND PERSPECTIVE

In the past decade, we have witnessed persistent research efforts to improve the mechanical deformability of microbatteries and microsupercapacitors. The electrochemical performances of stretchable miniaturized energy-storage devices remain inferior to their rigid counterparts. Continuous research efforts may shrink the performance gap through improved materials and cell architectures. It is also vital to identify application settings with low-energy consumption suitable for current microbatteries and microsupercapacitors. In addition, these devices are often fabricated on the laboratory scale and via unconventional processes. In the coming decades, this technology may become the mainstream energy supply for soft wearables. The demand for pilot-scale production may open up a broad range of opportunities in device designs with scaling-up viability. Here, we identify four key aspects to optimize stretchable microbattery/microsupercapacitor cells for next-generation wearable electronics, as shown in Figure 3.

Energy density

Some modern sensors may have power consumption in the order of 1 nW. Miniaturized energy-storage devices with a typical capacity above 1 μWh are sufficient to low-power devices for over a month. In contrast, a typical neural recording device consumes up to 100 μW through continuous data recording and transmission[48]. High capacity is crucial for small footprint energy-storage devices to sustain the long-term operation of corresponding devices. Currently, the energy density of stretchable microbattery/microsupercapacitor is still lower than rigid devices. The issue is largely associated with either limited electrode mass loading or significant inactive areas. In addition, the energy density of microbatteries/microsupercapacitors is rarely reported by counting on the overall mass or volume. It is understandable for prototype devices with unoptimized cell components (encapsulation, stretchable substrates, and interconnect wires) to occupy extra weight and volume. Several strategies are available to enhance the energy density of the stretchable devices, as listed in the following:

(1) The high energy density is essential for miniaturized energy-storage devices to achieve decent capacity at a low footprint. Intuitively, the electrode mass loading can be improved by increasing the layer thickness or active material concentration. The modified microelectrodes should retain compliant mechanical properties for stretchable cell applications.

(2) Three-dimensional porous structures may facilitate ion transports of high-loading microelectrodes, consequently improving the rate capability and areal capacity. On the other hand, the internal voids inevitably occupy the precious volume for active materials. The porous electrode design should balance gravimetric (Wh/kg) and volumetric (Wh/L) energy density.

(3) Materials engineering strategies toward novel active materials are encouraged. The active materials with high theoretical capacities may enhance the total capacity of the stretchable microbatteries/microsupercapacitors.

(4) Innovative electrolytes, such as water-in-salt systems, can expand the electrochemical stability windows and encourage high-voltage operations. The selected electrolyte should be compatible with the elastomer packages to avoid swelling or dissolving issues.

On-skin wearability

Softness is highly desired for electronic devices and systems to achieve conformal and intimate interactions with the human skin. Innovative designs are the enabler of the device-level stretchability in microbatteries/microsupercapacitors. Kirigami configuration allows miniaturized energy-storage devices to accommodate

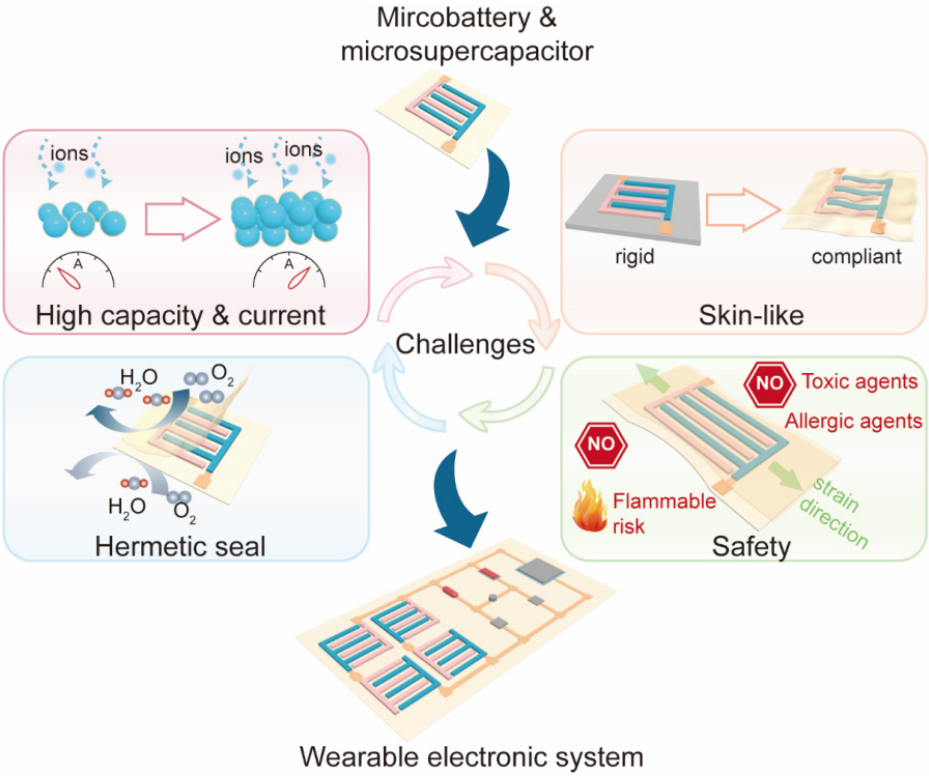

Figure 3. Challenges and opportunities of stretchable microbatteries and microsupercapacitors for next-generation wearable electronic systems.

spatial elongation through local bending and buckling. A large amount of out-of-plane deformation, unfortunately, renders a seamless interface with human skin challenging. In rigid-island matrices, the serpentine-shaped interconnection wires exhibit out-of-plane buckling under external tensile loading to compromise the skin conformability. Recently, liquid metals have been proposed as promising intrinsically stretchable conductors to address this practical challenge[24,28]. Similarly, the out-of-plane deformations also plague stretchable energy-storage devices using wavy electrodes. Intrinsically stretchable microbatteries/microsupercapacitors allow in-plane deformations for reliable lamination onto curvilinear and dynamic surfaces, such as human skin. Ideally, intrinsically stretchable cells require all compliant components to achieve skin-like deformability, including current collectors, electrode layers, electrolyte/separators, and encapsulations. Unfortunately, the large modulus contrast between active materials (10^7 to 10^8 kPa) and biological tissues (< 10^2 kPa) represents a practical challenge for conformal lamination of stretchable cells onto the skins. The elastomer binders may effectively reduce the mechanical stiffness of corresponding electrodes. The new binders should allow facile ionic and electrical transports for excellent electrochemical performances. Another promising approach fills rigid granular active materials into the crosslinked hydrogel to form tissue-like electrodes[49,50]. These electrodes adhere to hydrogel electrolytes with robust interfaces, enabling reliable energy-storage performances of corresponding cells during mechanical deformations. All these strategies focus on regulating the local modulus of skin-interfaced cell components for a seamless interface with human skin. Currently, intrinsically stretchable microbatteries/microsupercapacitors still require optimizations to suppress the degradation of energy-storage performances upon repetitive tensile deformations. In addition, the washability of microbattery/microsupercapacitor cells is a desired attribute for the hygiene requirement.

Encapsulation materials

Conventional energy-storage devices harness metal foil laminated films as hermetic seals for stable operations. Soft elastomers are often directly used for encapsulation in stretchable energy-storage devices. The inherent permeability of elastomers for oxygen and moisture represents a practical challenge due to the rich free volume in the polymer networks. Sheet-like materials, such as graphene and montmorillonite clay, are filled into elastomers to achieve ~80% reduction in gas permeability by constructing tortuous pathways for gas molecule transports[51,52]. The limited stretchability of up to 15% is insufficient for wearable applications. Recently, liquid metals have been incorporated into an elastomer film to achieve superior gas barrier properties comparable to a commercial aluminum-laminated film[53,54]. The low permeability is well preserved at a mechanical strain of up to 20%. These advancements may be adopted in stretchable microbatteries/micro-supercapacitors for long-term practical applications.

Safety

Safety is a prerequisite for stretchable microbattery/microsupercapacitor cells in the context of on-skin applications. Despite excellent electrochemical performances, organic electrolytes pose safety concerns due to their flammability and toxicity. A potential avenue is to replace organic electrolytes with solid electrolytes for all-solid-state energy-storage devices. Currently, the available solid electrolytes of ceramics and polymers struggle to achieve notable stretchability. Aqueous electrolytes are the most promising candidates featuring high ion conductivity, environmental friendliness, and affordable costs. The narrow electrochemical stability window of aqueous electrolytes (~1.2 V) may still limit the energy density of corresponding devices. The recent concept of "water-in-salt" electrolytes significantly widens the operating windows, supporting long-term reliable operations of high-energy microbattery/microsupercapacitor cells[55]. Additionally, conventional liquid electrolytes are vulnerable to leakage problems during repetitive cell deformations. Hydrogel electrolytes in crosslinked polymer networks are preferred options with structural stability for safe handling. Another critical issue of skin-attached applications is the biocompatibility requirement. Innovative materials should be screened with *in vitro* cell viability tests before wearable applications to avoid allergies and other adverse reactions.

INTEGRATION FOR WEARABLE ELECTRONIC SYSTEMS

Stretchable and wearable electronic systems have been extensively studied in the recent decade featuring multifunction, comfortability, and on-skin usage[19,56]. The electronic devices are driven by stretchable miniaturized energy-storage devices, forming self-powered or self-charging systems. Stretchable energy-storage devices favor high energy density and stable operations for practical deployment in wearable electronic systems. Moreover, stretchable microbatteries and microsupercapacitors should be capable of monolithic integration with other deformable forms of electronic devices. Various techniques are available to fabricate miniaturized energy-storage devices in targeted areas on the stretchable substrate, such as screen printing, inkjet printing, and laser patterning[15,57,58]. Stretchable microbattery/microsupercapacitor cells allow monolithic integration in series or in parallel to satisfy the power/energy requirement of corresponding electronic components. Several prototype self-powering systems have already been demonstrated in the context of on-skin applications for healthcare, environment monitoring, and wearable displays (see Figure 4A and B)[19,47,59].

Energy harvesting devices are also integrated into stretchable electronic systems to improve power sustainability. A variety of devices are available to generate electricity out of environmental energy sources, including wireless coils from electromagnetic flux, photovoltaic cells from solar irradiation, triboelectric nanogenerators from mechanical friction/vibrations, and biofuel cells from chemicals[6]. The electricity is then stored in chemical forms inside microbattery/microsupercapacitor cells. The intermittency and uneven distribution of renewable energy are addressed through the design of systems. Due to the high rate

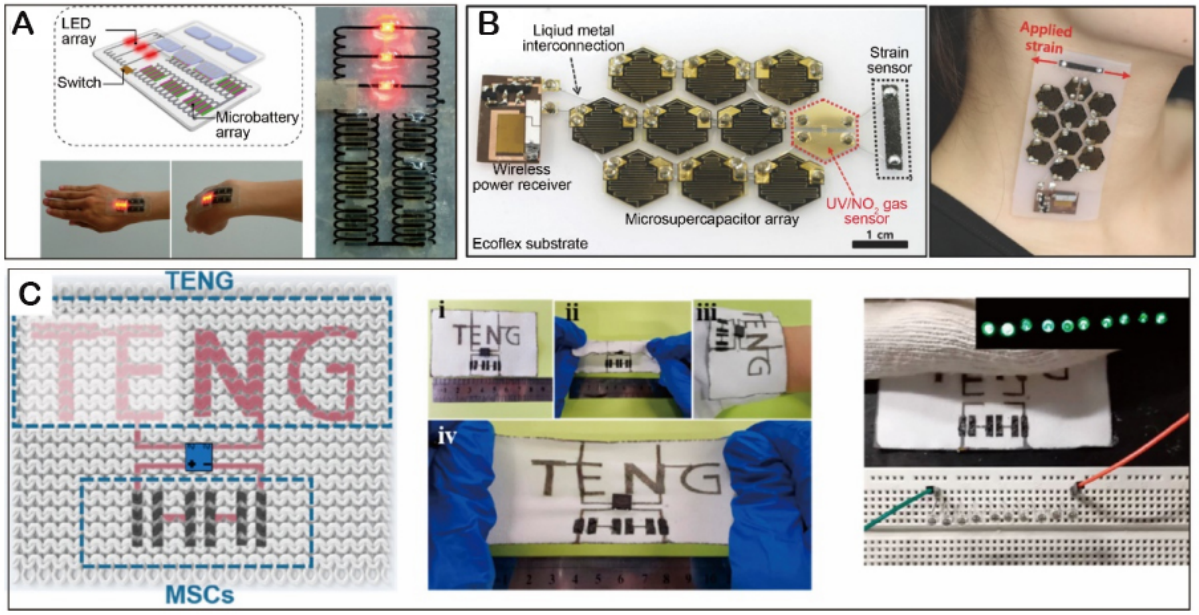

Figure 4. Wearable electronic systems powered by stretchable miniaturized energy-storage devices. (A) Soft LED array powered by a pack of intrinsically stretchable microbattery cells. Reprinted with permission from Bai *et al.*[47]. Copyright 2022 American Chemical Society. (B) Multi-functional wearable system for on-skin applications comprising an RF power receiver, a rigid-island matrix of microsupercapacitors, a strain sensor, and a gas sensor. Reprinted with permission from Kim *et al.*[19]. Copyright 2016 Wiley-VCH. (C) A stretchable self-charging electronic system constructed on soft textiles by integrating microsupercapacitor cells, triboelectric nanogenerator units, and LED array. Reprinted with permission from Cong *et al.*[60]. Copyright 2020 American Chemical Society.

capability and ultrahigh lifetime, stretchable microsupercapacitor cells are often used to bridge functional electronic components and energy-harvesting devices (see Figure 4C)[19,26,56,60,61]. Hitherto, self-charging wearable technology is still in its infancy. All components in self-charging systems are supported to be thin and soft to facilitate seamless on-skin applications. Reliable conversion is critical for energy-harvesting devices under mechanical manipulations, such as stretching, bending, and twisting. The balanced voltage and current settings between energy-harvesting and energy-storage devices are essential to reduce the energy loss of the wearable system. Power management components are often necessary to address the mismatch for optimized energy efficiency.

Stretchable microbatteries/microsupercapacitors are attractive components for next-generation untethered soft electronic systems. Several design strategies are available to achieve notable deformability in miniaturized energy-storage devices. Despite significant progress, stretchable microbatteries/microsupercapacitors still lag behind their rigid counterparts in energy-storage performance. Continuous effects are still required for material innovations and device optimizations. The research in this area is highly interdisciplinary in nature, calling for inputs from material sciences, chemistry, mechanical engineering, and electrical engineering. The breakthroughs may unravel the potential of stretchable miniaturized energy-storage devices for smart electronic wearables.

DECLARATIONS

Authors' contributions

Conceptualization and funding acquisition: Bai C, Kong D

The investigation, visualization, and writing-original draft: Bai C, Li S, Ji K, Wang M

Writing-review & editing, and supervision: Kong D

Availability of data and materials
Not applicable.

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Conflicts of interest
All authors declared that there are no conflicts of interest.

Ethical approval and consent to participate
Not applicable.

Consent for publication
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