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Mechanics of stretchable batteries and supercapacitors

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ABSTRACT

The last decade has witnessed fast developments and substantial achievements that have been shaping the field of stretchable electronics. Due to a persistent need of equally stretchable power sources, especially for some emerging bio-integrated applications enabled by this unusual class of electronics, stretchable energy storage systems have been attracting increasing attentions in the past few years. This article reviews the mechanics of stretchable batteries and supercapacitors that are enabled by novel structural designs of hard and soft components, involving four representative strategies (i.e., wavy, wrinkled design, origami design, serpentine bridge-island design, and fractal inspired bridge-island design). The key mechanics of each strategy is summarized, with focuses on the design concepts, unique mechanical behaviors, and analytical/computational models that guide the design optimization. Finally, some perspectives are provided on the remaining challenges and opportunities for future research.

1. Introduction

The field of stretchable electronics has been evolving very rapidly during the last decade, from the perspective of developing fundamental enabling technologies, exploring applicable device systems, and opening up new application opportunities. This class of electronics could offer the functionalities of established technologies [1,2], while with superior mechanical attributes that are inaccessible to traditional electronics, e.g., stretched like a rubber band, twisted like a rope, and bent around a pencil tip, without mechanical fatigue or any significant change in operating characteristics. Those superior mechanical characteristics pave the way to a range of innovative and realistic applications that could not be addressed with any other approach, such as "epidermal" health/wellness monitors [3–5], eyeball-like digital cameras [6,7], soft surgical instruments [8–10], and sensitive robotic skins [11–13].

To enable conformal integration of stretchable electronic devices with human tissues, there is a persistent need for developing equally stretchable energy storage systems to complete the entire package. However, the stretchable energy storage systems did not receive much attention until 2009 [14], partially due to the relative complex constructions, or the requirement of sufficiently large energy density. Many important progresses have been achieved in recent years with the development of new design concepts and enabling technologies. In general, there are two routes to stretchable energy storage systems: (1) developing novel materials that are intrinsically stretchable to serve as key components (e.g., electrodes and electrolytes) of the batteries/supercapacitors [15–20]; (2) devising novel structural designs for heterogeneous integration of hard and soft components to result in device systems that are stretchable [14,21–31]. This paper will focus on the latter route, aiming to provide a review on the recent advances in the mechanics of stretchable batteries and supercapacitors.

Fig. 1 summarizes four representative strategies of structural designs that have been exploited to achieve stretchable batteries/supercapacitors: (i) wavy, wrinkled design [14,21–25] through use of prestrain in soft elastomeric substrate; (ii) origami design [26,27] by exploiting predefined crease patterns; (iii) serpentine bridge-island design [28,29], and (iv) fractal inspired (or self-similar) bridge-island design [30], with the aid of photolithography technology. The subsequent Sections 'Wavy, wrinkled design', 'Origami design', 'Serpentine bridge-island design', and 'Fractal inspired bridge-island design' will give an overview of the key mechanics in each of those strategies, including the design concepts, superior mechanical performances, and analytical/computational models that guide the design optimization. Section 6 presents a brief

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discussion on the remaining challenges and opportunities for future research.

2. Wavy, wrinkled design

The wavy, wrinkled designs were exploited in several studies of stretchable supercapacitors and batteries to form stretchable electrodes made of single-walled carbon nanotube macrofilms [14,22], polypyrrole (PPy) [21], or graphenes [24,25]. The key of this strategy is to introduce an initial strain difference in the soft substrate (e.g., PDMS or ecoflex) and hard thin films (e.g., metal or semiconductor), either by thermally induced mismatch [32] or mechanical prestrain [33,34]. Fig. 2a presents schematically the fabrication procedure of wavy silicon ribbons that are fully bonded on an elastomeric substrate [34]. This strategy involves thin single-crystal Si ribbons or complete integrated devices (e.g., transistors, diodes) that are formed on a mother wafer by traditional lithographic processing, and a prestrained elastomeric substrate (PDMS). Etching of the top Si and SiO_2 layers of a SOI wafer could eliminate the bonding between the ribbon structures and the underlying wafer, such that contacting the prestrained PDMS to the ribbons leads to their transfer to the PDMS substrate. Releasing the prestrain in the PDMS substrate then leads to formation of highly periodic, stretchable wavy ribbon structures. During this procedure, UV/ozone activation of PDMS surface can be adopted to enable strong, covalent interfacial bonding between Si ribbons and PDMS substrate, because of silane coupling reactions between hydroxyl groups on the native oxide surfaces of Si ribbons [35]. Fig. 2b presents scanning electron micrographs (SEM) of wavy, single-crystal Si ribbons generated with the use of ~15% prestrain in the PDMS.

Many mechanics models have been developed to describe, in a quantitative manner, the formation of wavy ribbon structures, as well as their stretchability and compressibility, which have been summarized in two review papers [36,37]. As such, only the key results will be mentioned herein. In the regime of small prestrain (e.g., $0.5\% < \varepsilon_{pre} < 5\%$), an energy approach was developed [38,39] based on small-deformation theory to determine the buckling geometry, in which the linear, elastic substrate is modeled as a

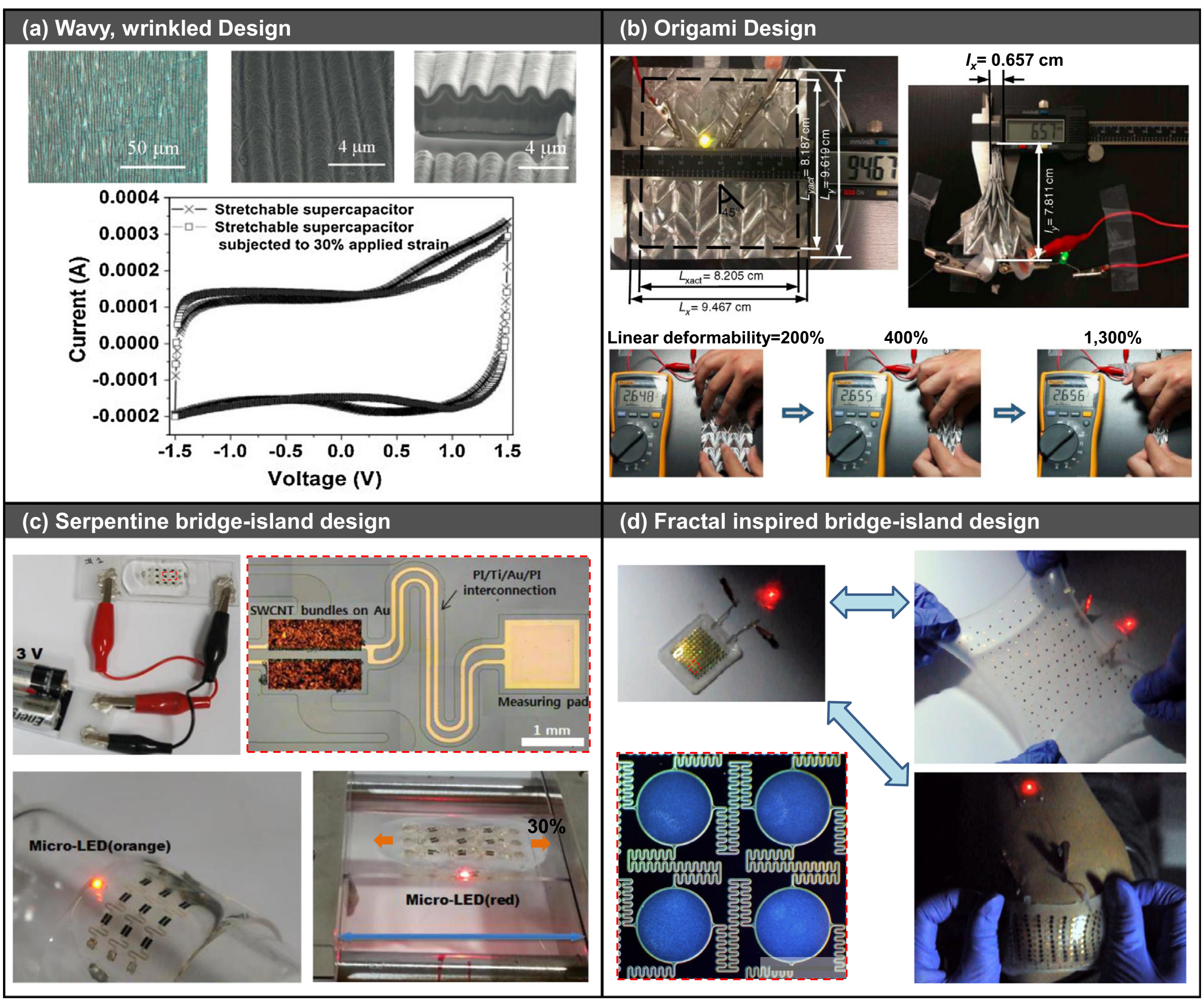

Fig. 1. Four representative mechanics-guided design strategies to enable stretchable batteries and/or supercapacitors. (a) Wavy, wrinkled design: optical microscopy and SEM images (top panels) of a 50-nm-thick, buckled SWNT macrofilm on a PDMS substrate with 30% prestrain, and cyclic voltammograms (bottom panel) of the stretchable supercapacitors under 0% and 30% unaxial strain, along with traditional supercapacitors using the pristine SWNT film for comparison. (b) Origami design: photographs (top panels) of the origami batteries operating a light-emitting diodes (LED), in the completely unfolded and compressed states, and the images (bottom panels) of linear deformation of an origami battery connected to a voltmeter. (c) Serpentine bridge-island design: photographs of stretchable supercapacitors under the charging state at 3 V (left top panel) and discharging state lighting a LED under bent (with a bending radius of ~2.5 cm, left bottom panel) and 30% stretched state (right bottom panel), and optical microscope image (right top panel) of an individual micro-supercapacitor with serpentine interconnections. (d) Fractal inspired bridge-island design: operation of a battery connected to a red LED, while undeformed (left top panel), biaxially stretched to 300% (right top panel), and mounted on the human elbow (right bottom panel), and optical image (scale bar, 2 mm) of the Al electrode pads and self-similar interconnects (left bottom panel). (a) is adapted with permission from Ref. [14], Copyright 2009, WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim. (b) and (d) are adapted with permission from Refs. [27] (Copyright 2014) and [30] (Copyright 2013), Nature Publishing Group. (c) is adapted from with permission from Ref. [28], Copyright 2013, American Chemical Society.