Stretchable electronic devices using novel material and structural approaches

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ABSTRACT

Stretchable electronics are emerging as a new type of devices with their exceedingly robust mechanical compliance compared to the rigid or flexible devices. Many emerging electronic applications require distortions in shapes and forms, which could not be met with existing structural rigid devices. Stretchable electronics are poised to be essential in the development of the next generation electronic systems. Yet, there are still many challenges to be addressed before the realization of truly and imperceptible stretchable electronics. In this paper, we introduce the recent works in our group with the aim of realizing stretchable electronic devices based on novel material and structural approaches.

Keywords: stretchable electronics, e-skin, sensors, photodetector, electroluminescent devices

1 INTRODUCTION

Stretchable electronics is deemed to be a breakthrough innovation in the industry of electronics that typically rely on scaling with Moore's Law. It is envisaged that the day-to-day consumers could benefit from it in the form of wearable devices, smart clothings and connecting to internet of things via robotic sensory skins or bio-integrated devices.

The earlier development commences with the concept of materials in sufficiently thin form are flexible. The structural strategy to pattern thin and flexible metal film into a "wavy" or serpentine structures were developed by Rogers and co-workers to impart stretchability to the thin-film materials that could achieved excellent stretchability and were used as stretchable electrical interconnects.[1-7] With the structural strategy, stretchable photodetectors and light-emitting diodes (LEDs) were demonstrated by assembling small and rigid devices onto rubber substrates with the "wavy" electrical interconnections, yielding stretchable device systems.[1,8] Subsequently, a significant amount of stretchable electronic devices were studied and demonstrated based on different approaches and strategies. In general, the approaches can be categorized into two strategies. The first approach utilizes the "Structure That Stretch".[9] The materials in their thin film structures were patterned into "wavy" or buckling structures and bonded onto elastic substrates. The "wavy" or buckling structures are amenable to accommodate the mechanical strains under stretching. The limited mechanical stretchability in the thin-film materials can be compensated by the flexibility of selected materials. This approach has the advantage of leveraging on well-developed technologies in the conventional device fabrication, minimizing the gap by the assembly of the rigid components onto a stretchable substrates. Early works have been demonstrated by Rogers's group and Someya's group based on the strategy.[8,10-13] However, as a complicated patterning process is required to achieve the stretchable structure, the mechanical mismatch between the rigid and soft components in the same system needs to be carefully tailored. It is therefore still quite difficult to develop an effective and low-cost approach with the route. Besides, most of the demonstrations are still limited to stretchable electrical interconnections. Stretchable functional components have not been widely explored and still remain challenging with the structural approaches.

The other strategy focuses on "Materials That Stretch".[9] In this approach, new materials with intrinsic stretchability are developed for the functional device components. Different from the structural approach, it eliminates the complicated patterning process, which simplifies the fabrication process. Moreover, the functional components and the electrodes are both fabricated with stretchable materials which can be strained simultaneously under mechanical deformations. Fully stretchable electronic devices can be achieved. Challenges in the material approach lie in the daunting difficulty in developing the stretchable and functional materials. Pei's group has reported a few works on stretchable electroluminescent devices based on light-emitting electrochemical cells,[14-16] although the stretchability, mechanical stability, operating life-time, and switching speed of these devices still need to be further enhanced in these devices.

In this paper, we focus on several critical components that play a vital role in the technology, including stretchable conductors, stretchable photodetectors, sensors, and light emitting devices, to expand the possibilities of stretchable electronic devices. We embrace hybrid integrated strategies to resolve some of the challenges in these devices by improving their fabrication approaches and mechanical performance.

2 STRETCHABLE ELECTRONICS

2.1 Stretchable Photodetector

Among many electronic devices, stretchable photodetectors can convert light stimuli information into electrical signal. They can be integrated with textiles, incorporated as the active components in bionic eyes, and mounted onto biological systems as monitoring devices on special curvilinear surfaces, and achieving wearable night vision device for infrared light detection systems, and many other applications as well. However, research works which have been demonstrated to construct stretchable photodetectors are still quite limited. Earlier reported studies include hemispherical imaging systems which patterned thin and wavy metal thin films for stretchable interconnects and assembled conventional rigid silicon photodetection elements onto elastic substrates.[1,7] However, the fabrication process for these stretchable photodetection systems required complicated lithography and transfer steps. There is a lack of fully stretchable and transparent photodetectors being developed, which could serve as components in foldable display and other transparent electronic devices.

We have fabricated photodetectors which could be flexed, twisted or stretched with well-maintained photodetection performance.[17,18] The fully embedded NW structure in the elastic polymer matrix was found to be critical to maintain the NW network structures and hence sustain the device performance.

2.2 Strain sensor and temperature sensor

Strain sensors allow detection of electrical modulation upon mechanical deformations. Strain sensors have broad applications including strain monitoring on architectures or automobiles, strain control on soft robotics, and health monitoring. It is reckoned that human motions can result in high strains (e.g., the strains above 55% upon stretching and contracting of the human joints) that require highly stretchable strain sensors. This are primarily of interest for sportsman or athletes performance monitoring, physical motions monitoring in physical therapy and rehabilitation. Existing strain sensors are mainly based on bulky structures with limited stretchability (a few percent of strains). We have developed a high-strain sensor based on crumpled graphene embedded in elastomer matrix.[19] The strain sensor film was fabricated with a solution filtration method, similar to the stretchable photodetector fabrication. It was discovered that by combining the graphene and nanocellulose, a uniform composite film can be easily formed. After the composite was successfully embedded into the PDMS, the strain sensor could be used to detect strains up to 100%. Taking advantages of the excellent stretchability in the strain sensors (as shown in Figure 1a), a prototype device was demonstrated by implanting the strain sensors on a data glove which could provide real-time feedback on the finger movements, as shown in Figure 1b. Graphene is also an interesting material with its extraordinary electrical and thermal properties. The semiconducting behavior of the crumpled graphene enables changes in its resistivity under different temperatures, making it an ideal candidate for temperature sensing. Stretchable thermistors were also demonstrated with the crumpled graphene embedded in elastomers, as shown in Figure 1c.[20] The thermistor can be strained to 50% with maintained functionality.

2.3 Electrochromic (EC) devices

Electrochromism is a technology based on materials which change their optical properties under electrical bias. These non-emissive devices have wide application in low-power display, anti-glare rear-view mirrors in automobiles and energy-saving windows in architectures etc. Realizing soft electrochromics help to extend their applications in wearable and implantable smart electronic systems. The conventional indium tin oxide (ITO) typically used as the transparent conductors in the electrochromics encounter significant challenges to achieve good flexibility or stretchability due to their brittleness and rigid nature.

To circumvent the above-mentioned problem, we have developed a highly deformable and conductive electrodes for

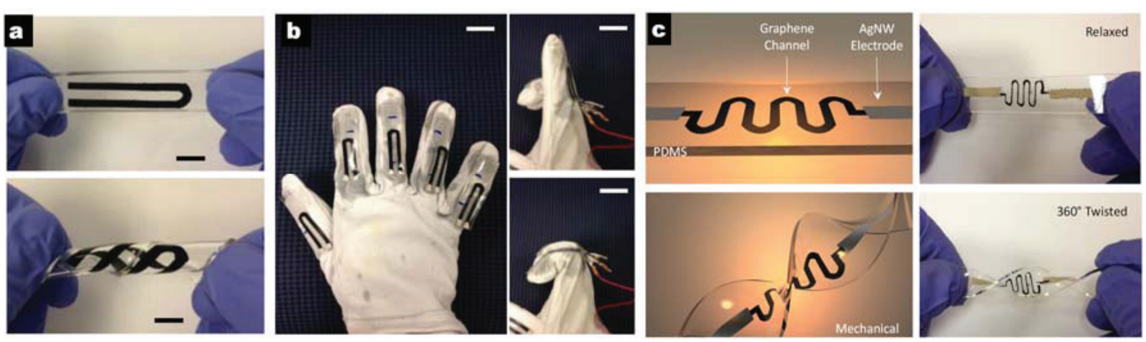

Figure 1. (a) Photographs of the stretchable graphene nanopaper embedded in PDMS. (b) Photographs of the wearable data glove based on the stretchable nanopaper sensors. Reproduced with permission from [19]. (c) Schematic images and photographs of the stretchable graphene thermistors. Reproduced with permission from [20]. Copyright (2015) American Chemical Society.

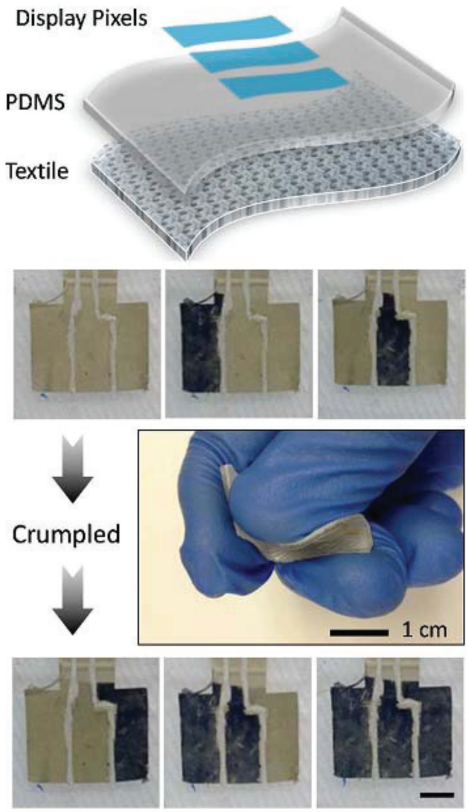

Figure 2. The electrochromic devices implanted onto wearable textiles which can confront large mechanical deformations. The individual display pixels can be independently controlled. Reproduced with permission from [21]. Copyright (2014) American Chemical Society.

the EC devices based on percolating silver nanowires (AgNWs).[21] The AgNWs with the length of 20-50 µm was embedded into the elastic substrate (such as PDMS) which will impart stretchability to the percolating AgNW electrodes. Utilizing the excellent electrochromic behavior of WO_3 film, an electrodeposition of WO_3 onto the AgNWs embedded in PDMS was carried out. The WO_3 film can change from the transparent state to blue color during the bleaching and coloration process. The WO_3 film was conformably coated on the stretchable AgNW surfaces, it can be repeatedly stretched and released without losing the functionality. The achieved EC devices demonstrate excellent stretchability which can be strained up to 50%. The reflective behavior of the EC device was characterized under relaxed and strained states. Only a small decrease in the contrast was observed in the device under strain testing. The contrast is 56% and 50% at 633 nm under the relaxed and strained states correspondingly. We also demonstrated that the stretchable electrochromic devices can be patterned into individual pixels and implanted onto textiles for wearable display applications, as shown in Figure 2.

2.4 Electroluminescent (EL) devices

Electroluminescent devices are the primary components in lighting and display applications. Stretchable electroluminescent devices will benefit a plethora of emerging applications such as soft display system, conformable visual readout, and biomedical imaging devices. We have developed a stretchable light-emitting layer (Zinc Sulfide particles embedded in elastomer) to achieve light-emitting devices which can be stretched up to 100% strain, as shown in Figure 3a.[22] Recently, great progress was also achieved in our group to significantly improve the stretchability of the light-emitting devices by using ionic conductors as the electrode. The super-elastic light-emitting device could be stretched to 700% strain, as shown in Figure 3b.[23]

We have also demonstrated an unprecedented self-deformable alternating-current electroluminescent (ACEL) device by integrating the stretchable light-emitting device with actuators, achieving dynamic shape changes on the light-emitting device. The emerging "smart materials" (dielectric elastomer) which can generate mechanical motions under electrical bias possesses the advantages of ease of miniaturization, high power density and low-cost fabrication. By using the dielectric elastomer, we have demonstrated the fabrication of transparent, thin and soft actuators. With the simply fabrication process we have developed in the stretchable ACEL device, it can be successfully integrated with the dielectric elastomer actuator, as shown in Figure 3c. The self-deformable light-emitting device will have great potentials for applications in volumetric and interactive display systems.

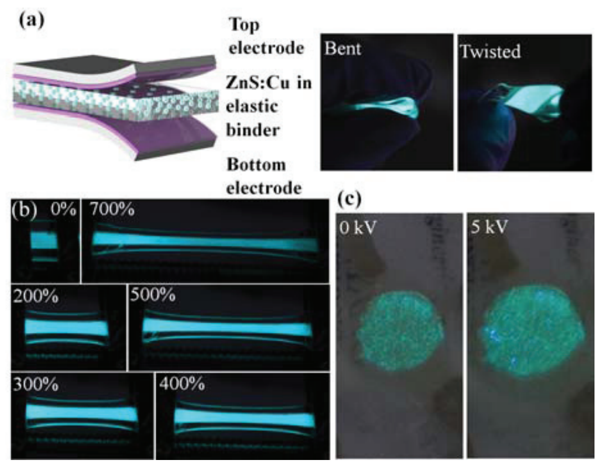

Figure 3. (a) A schematic image of the ACEL deices and photographs of the as-fabricated devices under bending and twisting. Reproduced with permission from [22]. (b) Photographs of the extremely stretchable ACEL device under stretching strains up to 700%. Reproduced with permission from [23]. (c) Photographes of the self-deformable ACEL devices. Reproduced with permission from [22].

3 SUMMARY

With extensive studies being carried out based on the material and structural strategies, we have successfully demonstrated stretchable photodetectors, strain sensors, thermistors, EC devices, and EL devices. These stretchable devices greatly exceed in their versatility compared to the preceding flexible electronics. They are promising electronic components for the next-generation soft and interactive electronic systems. However, great research endeavors are still required to improve the electrical performance, mechanical stability, and scalability in the stretchable devices. With the enabling and supporting technologies being developed, a revolution can be envisioned in the way information is delivered and communicated.

ACKNOWLEDGEMENT

The authors thank the funding support from the National Research Foundation Competitive Research Programme, Award No. NRF-CRP-13-2014-02 and NRF Investigatorship Award.

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