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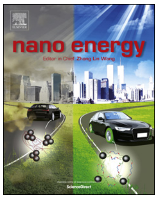

Full paper

Triboelectric electronic-skin based on graphene quantum dots for application in self-powered, smart, artificial fingers

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ABSTRACT

The development of electronic-skin (e-skin) with artificial tactile-perception is crucial for emerging artificial-intelligence systems. However, considering the relatively simple function of existing e-skins, their performances still have much room for improvement. Here, a cuttable, transparent, stretchable, and lightweight e-skin that functions on the basis of the triboelectric effect is demonstrated. Well-designed micro-gaps are introduced to make the e-skin respond sensitively to various mechanical stimulations, including pressing, stretching, folding, and twisting. Ag nanowires coated with graphene quantum dots are employed as the electrode, as well as the friction layer, to increase the sensitivity to external mechanical stimulations. Self-powered, smart, artificial fingers with tactile sensation to monitor the actions of the fingers were fabricated to demonstrate the potential application of our newly developed e-skin. The architecture and the material system of the device demonstrated in this work will promote the development of human-machine interfaces and intelligent machines.

1. Introduction

Promoted by the potential market value of emerging artificial intelligence, smart robots, artificial prostheses, and wearable electronics, the development of electronic-skin (e-skin) mimicking the many functions of human skin has attracted unprecedented attention because human skin is a key interface with the external environment [1–6]. As an important somatosensory system, human skin is extremely sensitive to the environment and can possess tactile perceptions for distinguishing external mechanical stimulations, such as pressing, touching, straining, and bending, and for generating bioelectric signals to nerve centers. Until now, various approaches for sensing touch/pressure stimulations have been utilized to develop e-skin. Especially, resistive sensors utilizing the resistance change and capacitive sensors utilizing the capacitance change have met great commercial success [7–10]. Worth noting is that the resistive sensors and the capacitive seniors are not self-powered electronics; rather, they need an external electrical supply to continuously detect the changes in resistance/capacitance. As a result, integration of a battery into the e-skin system is necessary. However, the presence of batteries makes the overall system bulkier, shortens its life-span, and limits applications in wearable electronics. The high dependence of e-skins on an external electrical supply is one of its essential differences from human skin, which can self-generate bioelectric signals according to changes in the external environment.

One of the key characteristics of e-skin, if it is to mimic human skin, is the ability to self-generate feedback electric signals according to changes in external mechanical stimulations. Thus, the concept of self-powered electronic devices becomes the key issue in the development of e-skin systems. A zinc-oxide nanostructure combined with a piezoelectric polymer has been used to realize flexible, self-powered e-skin [11]. Recently, triboelectric nanogenerators (TENGs) and related self-powered technology, which are based on triboelectrification and electrostatic induction, have been proven to be a promising approach to realizing self-powered mechanical sensors due to their high efficiency for converting vibration energy to electrical energy [12–15]. Especially, flexible triboelectric devices that hold promising in e-skin applications have been realized using graphene [16], electronic textiles [17], conductive paper [18], and conductive polymer composites [19]. Several kinds of e-skin have been successfully demonstrated to perceive external mechanical stimulations. For example, a TENG-based e-skin was developed to detect static finger gestures and dynamic motion [20]. A fully self-sufficient and body-conformable e-skin system that could generate electricity from external touch was realized by utilizing a skin-like triboelectric nanogenerator [21]. Graphene tribotronics for interfacing electronics to environmental touch stimuli have been developed and have been shown to exhibit excellent touch-sensing performance

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[22]. Even though the development of TENG-based e-skins has made great progress, the performances of e-skins still have much room for improvement. Worth noting is that human skin can distinguish various mechanical stimulations, such as pressing, touching, straining, and bending. However, most reported e-skins based on a planar structure can only produce electrical outputs in response to external presses and touches. The realization of strain and bending sensing is of importance for the development of a fully functional e-skin. On the other hand, astonishingly, human skin can judge the stimulation strength, which capability has never been reported for e-skins. These considerations show that the development of e-skin that can establish a highly sensitive interaction with diverse external mechanical stimulations, as a multi-mechanical mode sensor system, is necessary to ensure continuous progress in the emerging field of artificial smart electronics.

In this work, two approaches are employed to solving the problems of the existing plane-structure-based e-skins and to enhance the performance of e-skins: (1) Well-designed micro-gaps are introduced into the membrane structure to make the e-skin respond sensitively in real time to changes in pressure. (2) Graphene quantum dot-coated Ag nanowires (G-Ag NWs) are employed as the electrode, as well as the friction layer, which helps to generate a much stronger output and increase the sensitivity to the mechanical stimulations. Based on these designs, a transparent, stretchable, and lightweight TENG-based self-powered e-skin that can generate electricity from not only touch but also pressing, twisting, stretching, and folding were demonstrated in this work. Furthermore, the electrical outputs of our e-skin are highly sensitive to the magnitude of the pressure and the degree of deformation. The simple structure of our e-skin allows its size and shape to be modified without adversely affecting its ability to function properly. Finally, we show that the e-skin, with its excellent flexibility, can fully conform to a finger and can act as a self-powered mechanical sensor with tactile sensation, which holds promise for potential applications in smart artificial fingers and smart robots.

2. Experimental section

2.1. Fabrication of patterned PDMS films

The flow of the process used to fabricate the e-skin is depicted in Fig. S1. The fabrication process starts with the preparation of patterned polydimethylsiloxane (PDMS) films. Firstly, a photoresist film with a thickness of 5 μm is spin-coated on a clean glass substrate. Then, a uniform line array with a linewidth of 100 μm and a gap of 100 μm is fabricated by using the traditional photolithography method. The patterned photoresist acts as the mold for fabricating the patterned PDMS films. In the preparation of the patterned PDMS films, a PDMS elastomer and a cross-linker (SYLGARD 184, Dow Corning) are mixed in a weight ratio of 10:1. After a degassing process under vacuum, the elastomer mixture is spin-coated on the patterned photoresist-coated glass at 300 rpm, followed by annealing at 120 °C for 1 h. Finally, the free-standing PDMS film with the groove pattern is peeled off the glass substrate.

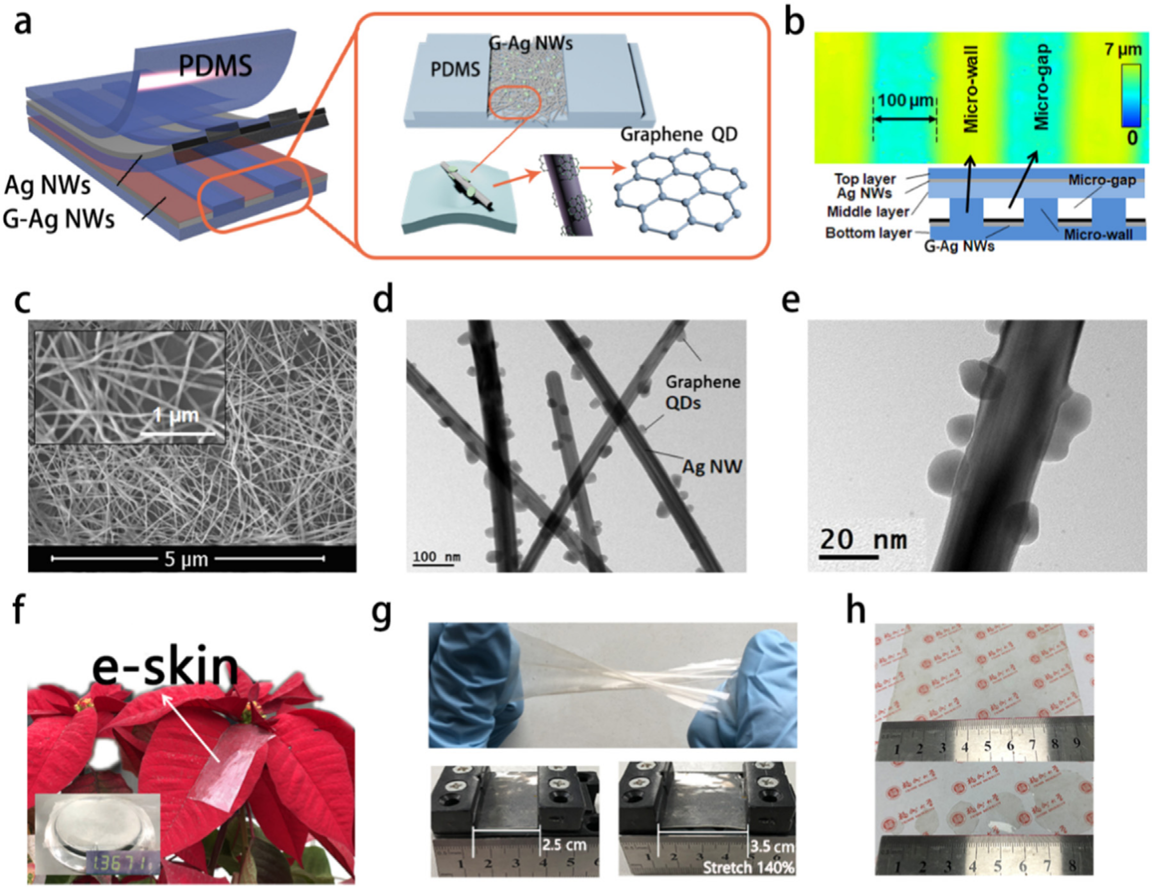

Fig. 1. Basic structure and design of the e-skin. (a) Schematic of the e-skin and the graphene quantum dot-coated Ag NW (G-Ag NW) network. (b) 3D optical image of the patterned PDMS layer. The bottom panel presents the schematic cross section of the device. (c) SEM image of the Ag NWs. The inset is a high-magnification SEM image. (d) Low-magnification TEM image of G-Ag NWs. (e) High-magnification TEM image of G-Ag NWs. (f) Photograph of the transparent and lightweight e-skin. (g) Photographs of the e-skin with demonstrations of it undergoing different mechanical deformations, including twisting and stretching. (h) Photographs demonstrating that the as-fabricated e-skin is cuttable and that a big e-skin can be cut into smaller pieces.