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Application of Highly flexible self-powered sensors via sequentially deposited piezoelectric fibers on printed circuit board for wearable electronics devices

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ABSTRACT

Consistently, sequentially and spatially controlled stacking of piezoelectric polyvinylidene fluoride (PVDF) fibers in three-dimensional (3D) configurations is successfully demonstrated via Near-field electrospinning (NFES) technique. In application, a highly flexible and PVDF fibers based sensor is integrated with printed circuit board (PCB) substrates. The proposed self-powered sensor exhibits lightweight, low cost, easily scale-up production and high stability. By using a sequentially deposited the three-dimensional structures for the enhancement of power generating capability, the PCB-based self-powered sensor (PSS) can be directly applied to make smart gloves for human–machine interfaces (HMI) of wirelessly controlled machines.

1. Introduction

Ubiquitously wearable electronic is the highly pursuit development in the microelectronic technology which inevitably brings insatiable demands on power supply. One application is in the field of electronic textiles (e-textiles), which multiple electronic elements are concurrently integrated into fabrics to achieve smart and pervasive computing capability [1]. Wearable electronics represents a paradigm shift in consumer electronics assemblages with human motion monitoring and integration with surgical tools as well as body sensor networks (BSN) [2]. However, a sustainable energy source for continuously powering the wearable electronics with minimal obstruction is still at its nascent stage [3]. One of the recently demanding trends for self-powered nanosystems is called nanogenerators (NGs), which has become more technologically and economically feasible such that ubiquitous computing, human–machine interfacing and implantable biomedical devices are demonstrated previously [4–6]. Further integration with biomechanical motions as the smart garment can quantitatively monitoring and recognizing human activities in-situ [7–9].

On the other hand, triboelectric based self-powered sensors had been recently demonstrated applications to be used ubiquitously. In particular, triboelectric nanogenerators (TENGs) with various working modes that can be universally self-charged by random body motion were exceedingly explored for energy harvesting from human biomechanical movement as a mean to sustainable operation of mobile and wearable electronics [10–13]. Moreover, self-powered motion sensor system for HMI showed a great potential toward the many practical applications [14].

Concerning the first demonstration of the power generating devices based on nanomaterials, piezoelectric zinc oxide (ZnO) nanowires (NWs) arrays were successfully demonstrated in converting nanoscale mechanical energy into electrical energy [15]. In the following development, a fully packaged, vertically aligned ZnO NWs array integrated with a zigzag metal electrode was ultrasonically driven in a fashion of direct-current output of 20–30 mV, and 1.2 nA from a total of 1000 NWs [16]. Piezoelectric NGs based on lead zirconate titanate (PZT) NWs was also investigated such that the measured output voltage and power under periodic stress application was 1.63 V and 0.03 μW, respectively [17]. Another interesting nanomaterials under development is the polyvinylidene fluoride (PVDF) with diameters of electrospun nanofibers (NFs) ranging from 70 to 400 nm can be produced by traditional electrospinning direct-write near field electrospinning (NFES) [18–21] technique with high energy conversion efficiency. In order to amplify the harvested energy, PVDF electrospun NFs were massively deposited in a series and/or in parallel with patterned electrodes [22,23]. The NFES direct-write capability is very promising due to the highly controllable and patterning precision to

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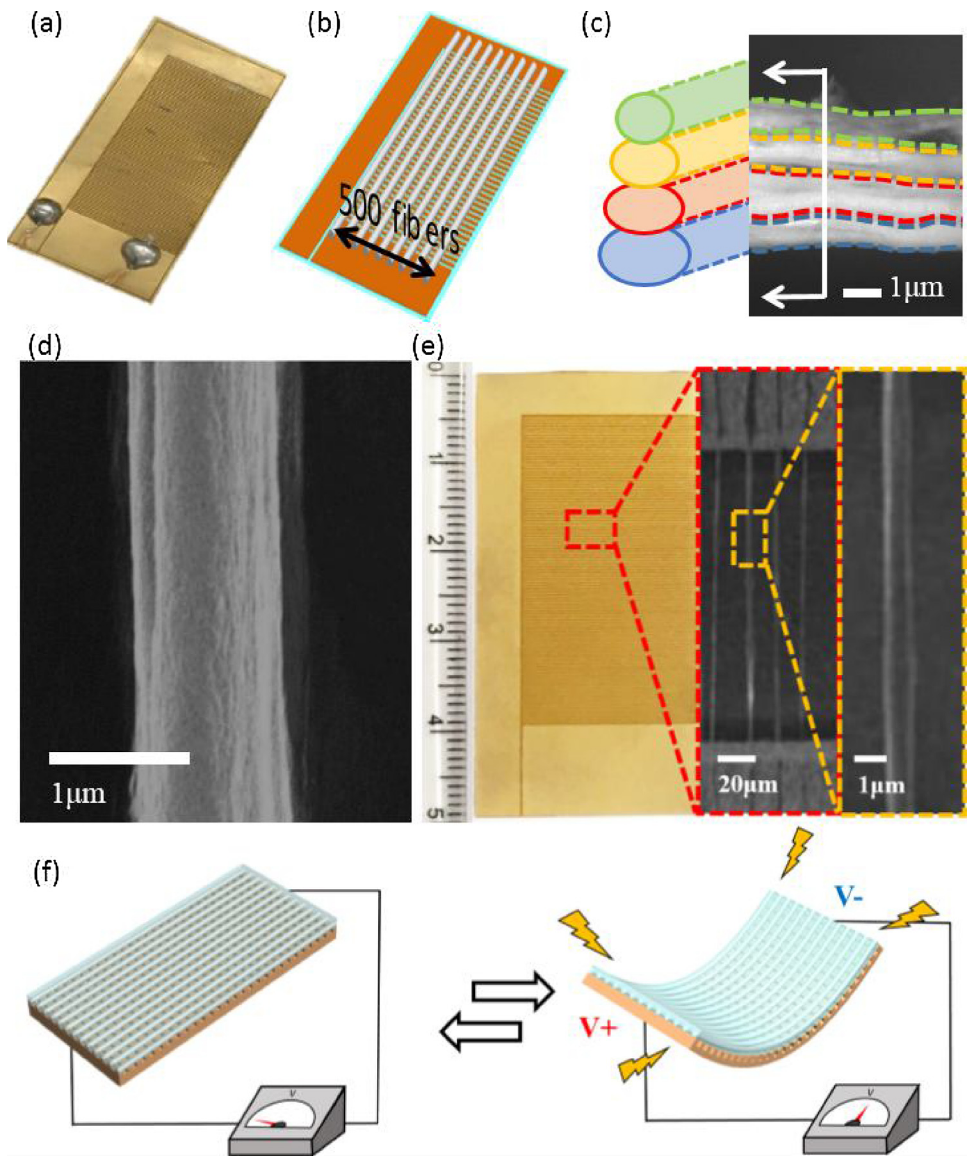

Fig. 1. (a) Photograph of the flexible PSS device. (b) Schematic structure of the PSS. Gray, orange and light blue layers correspond to the PVDF micro/nanofibers (MNFs), Au electrodes and PCB substrate, respectively. The effect of sequentially deposited layers of MNFs in 1–4 layers can be seen in the (c) Schematic diagram for sectional view and Scanning electron microscope (SEM) photograph of side view as well as top view in (d). (e) Photograph of the flexible PSS device with SEM photograph of massively parallel aligned MNFs. The fabricated PVDF MNFs has a diameter of about 600–800 nm. (f) Working principle of the voltage and current scaling-up superposition for the electrospun MNFs. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

deposit solid NFs in a direct, continuous, and controllable manner [24]. For example, the highly flexible and substrate-independent piezoelectric NMFs arrays had been demonstrated to functionally serve as a self-powered active deformation sensor. The distinctive advantage of this kind of device can be easily embedded as a part of human skin or clothing, smart concept of cyber garment/skin which can be ubiquitously used in the sustainable and self-powered monitoring sensors for the muscular movement [25,26]. Moreover, the integration of NFES piezoelectric PVDF NMFs and printed circuit board (PCB) technology offers the advantages of the scalable production and low cost [27]. The demonstrated PCB-based self-powered sensor (PSS) can play an important role in converting tiny mechanical strain into electricity for harvesting and self-powered sensing applications. In this paper, the controllable three-dimensional (3D) micro-/nano-scale fibers are NFES deposited [28]. with controlled stacking of sequentially deposited piezoelectric PVDF fibers and fully integrated with the PCB substrate. The presented highly flexible and wearable sensors are further transformed into the smart glove to detect and manipulate wirelessly the light emitting diode (LED) and remote controlled car, by incorporating the pervasively available biomechanical energy. Furthermore, the self-powered sensors can be vastly expanded to the gas sensing applications such as volatile organic compounds [29] and photocatalytic capabilities of T-ZnO nanostructures [30].

In this study, the integration of direct-write NFES piezoelectric PVDF MNFs and PCB technology is demonstrated. The fabricated self-powered sensors have the merits of scalable production and relatively low cost. The construction of PCB based devices is schematically shown in Fig. 1. Fig. 1(a) shows the optical photo of the fabricated device. Adopting PCB technology is highly beneficial and inherently suitable to affordable mass production, industrial compatibility and structural robustness. The narrowest electrode intervals can be systematically investigated is in the range of 0.15 mm to 0.40 mm [29] while the main focus of study adopts the 0.15 mm intervals for maximizing the output power. Fig. 1(b) shows that the physical construction of piezoelectric PSS,