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Soft triboelectric generators by use of cost-effective elastomers and simple casting process

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ABSTRACT

We are reporting a new approach of developing of soft triboelectric devices with improved conformability and scalability. Here, elastomers, namely, polydimethylsiloxane (PDMS), polyurethane (PU), were used as triboelectric layers, and their carbon based conductive elastomeric composites were implemented as electrodes since they offer greater softness and flexibility. Elastomers can also be coupled with the textile. Simple film casting technique, that provides fast and readily scalable route, was used to prepare low-cost multilayer structures. The technology was tested by preparing vertical-contact separation based triboelectric shoe-insole and stretchable triboelectric band. These examples were tested at low frequencies and at different load resistors for different gestures. The shoe-insole generated optimum rms power (P_{rms}) of 0.28 mW for load resistance (R_L) of 150 MΩ for walking and 1.79 mW for the R_L of 110 MΩ for running, respectively. Stretchable band, which can be applied on different body joints, was tested for the arm stretching motion that delivers the optimum P_{rms} of 9 μW for the R_L of 400 MΩ.

1. Introduction

The fast development of the internet of things (IoT) and different types of consumer low power electronics and sensors, prompted the requirement of portable power source. The conventional power supply, such as, batteries, has limited lifespan that requires frequent monitoring and replacements, and hazardous for the environment due to use of various chemicals. Therefore, with the ultimate aim of developing fully autonomous electronic systems, over the past years, growing demand for environment friendly, maintenance-free, sustainable, light weight and cost-effective renewable power sources are observed.

Like other renewable sources, different types of mechanical and kinetic energies can be a potential prospect to power energy-efficient electronic devices [1,2]. Generally, electromagnetic, electrostatic and piezoelectric techniques are used to convert mechanical energy to electrical signal [2–4]. In recent time, triboelectric effect, which is mainly known for its negative effects in electronic industries for years [5], was reported to be utilized for harnessing and sensing of mechanical energies [6].

Triboelectric nanogenerator (TENG) basically uses contact electrification and electrostatic induction methods. The physical contact or friction between two materials, having opposite charge affinity [7], is required for this mechanism to be functional. Since its discovery in 2012 [6], TENGs have shown exciting prospects for energy harvesting at large and small scale from surrounding kinetics energies, and for pressure/motion sensing applications [8–17]. In addition, triboelectric effect allows energy scavenging from and/or sensing of low frequency motions, such as, human body movements [10,18]. Wide variety of materials can be used to fabricated such devices [7]. Although, polytetrafluoroethylene (PTFE) is generally preferred as triboelectric materials due to its highest affinity toward negative charges, but this material is expensive, it is not standard in the field of microfabrication, adhesion of other materials on PTFE foil, such as the charge collector electrodes, is problematic. Furthermore, for wearable systems, materials need to be soft and flexible, which make them adaptive to various complex surface topologies and enable them to withstand high mechanical deformations.

To date, various triboelectric nanogenerators have been prepared and reported, with the ultimate goal of developing fully autonomous wearable electronic systems [10,19–29]. As an example, fabrication of triboelectric shoe insoles [19,20] have been reported to harvest energy for walking and with the capability of charging consumer electronics. The stretchable rubber based tri-

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boelectric device with the signal electrode has been reported [21], where the in-plane charge distribution due to the stretching of the rubber led to the charge flow between electrode and ground. Such system can be used to detect moving direction. In addition, a conductive fabric based stretchable single electrode TENG was demonstrated [22]. The friction between the dielectric layer and carbon nanotubes based custom made conductive fabric generated the electrical signal. Furthermore, stretchable fibre based triboelectric nanogenerators have been described [23], where copper wire convolved the silicone fibre structures with stretchable electrode. Kim et al. [24] have reported vertical contact separation mode based highly stretchable wearable TENG, where a metallic wire was placed inside the PDMS tube. However, there are still lack of simple technological approach that combines cost-effective processing technique and use of economical materials to fabricate low-cost soft triboelectric devices, which is compatible with large area applications and can be readily industrialized.

This work presents, the fabrication of soft triboelectric devices with improved conformability, scalable, and cost-effective process. Soft elastomeric materials were used, during this work, because of their higher softness and flexibility. In addition, the elastomers used are biocompatible, which make them more preferable for developing wearable devices, and ultimately implantable devices. Here, soft dielectric elastomers, namely, PDMS and PU, were employed as triboelectric layer, and their carbon based conductive composites were utilized as electrodes. Moreover, we demonstrated that the elastomeric technology can be incorporated with textile layers. The simple film casting technique was adapted to pattern multilayer structures of various materials, which is fast and applicable for large area applications. Finally, to manifest the potential of this technology, evaluation of two different soft triboelectric configurations, such as, vertical-contact separation and stretchable triboelectric devices, in the forms of shoe insole and stretchable band are presented as examples. Both the generators have simple designs and were characterized at low frequencies for different gestures.

2. Soft elastomers and casting approach

Materials explored herein, during this development process, were elastomers, as they are low-cost, and provide, thanks to their stretchability, conformability and softness, and they can be biocompatible as well. Elastomeric materials can be patterned for variable area and geometries, and can easily be adapted and optimized for large area manufacturing and nowadays for 3D-printing. Furthermore, elastomeric materials can be combined with various electrically conductive particles to develop elastomeric electrode materials, which can be casted directly on various material layers and provide better adhesion between dielectric and conductive layers without compromising much of their mechanical properties. Finally, these functional materials can be solution processed and patterned using the simple film casting technique. The latter allows to deposit materials having wide range of viscosities with different thickness. Therefore, the use of elastomeric materials along with the casting approach provides cost-effective and simple technological platform, which can be applied for the fabrication of conformable devices with different geometries and areas.

In this work, soft dielectric elastomers widely available, namely, polydimethylsiloxane (PDMS) and polyurethane (PU), were exploited as functional materials. These materials have opposite charge affinities that promoted contact electrification and thus can be used to prepare triboelectric devices. Moreover, by adding to them cost effective carbon black particles elastomeric carbon-based PDMS (CPDMS) and carbon-based PU composites (CPU) conductive composites were prepared for the electrodes of the generators. Furthermore, these elastomers can also be directly casted

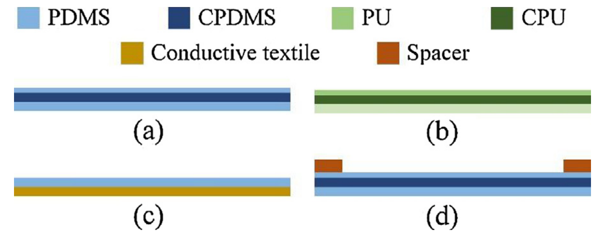

Fig. 1. Schematic diagram of the layer structures (a) PDMS-CPDMS-PMDMS, (b) PU-CPU-PU, (c) PDMS-textile and (d) PDMS-CPDMS-PDMS layer with spacer.

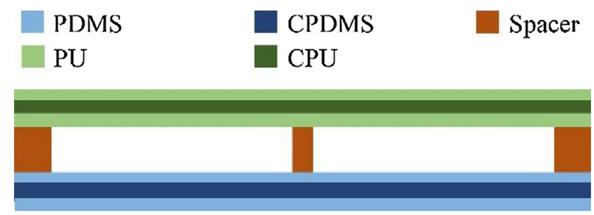

Fig. 2. Schematic diagram of the design of vertical mode triboelectric generator implemented as shoe insole.

on or integrated with the electronic textile (e-textile), which enable easy incorporation of soft triboelectric generators with clothing.

The technological realization processes began with the development of elastomeric PDMS, PU and their composites materials preparation and optimization of the casting processes. The triboelectric structures were made of three casted layers. The initial PDMS layer acts as protective/ support layer, followed by the casting CPDMS layer as electrode and final layer of PDMS as active triboelectric layer. As result, we obtained PDMS-CPDMS-PDMS layer structure (Fig. 1(a)). Similarly, triboelectric PU structure was developed by casting PU, CPU and PU layers to obtained PU-CPU-PU structure, as shown in Fig. 1(b).

The integration of the PDMS elastomer with an electrically conductive stretchable textile materials was also examined. This can be performed either by casting the PDMS layer directly on the textile or by laminating approach. It has been observed that the direct casting of PDMS could reduce the stretchability of the layer due to materials absorption by the fabric. Therefore, lamination process was optimized during this work. In this regard, ultra-thin layer of PDMS elastomer, acting as adhesive, was casted on the previously prepared PDMS layer, and then electrically conductive textile was laminate with the PDMS layer by applying pressure. The resulting structure provides PDMS-textile layer (Fig. 1(c)).

Moreover, in case of requirement, elastomers can either be casted or molded directly on the active PDMS layer to create spacer, as presented in Fig. 1(d). In this case, stencil is used to cast the spacer shape on active PDMS layer. The potential of the developed technological platform was tested by preparing triboelectric devices applying vertical-contact separation and vertical-contact separation/sliding mechanisms. As examples, we realized triboelectric generator based shoe insole and stretchable band. Their designs, operation principles and the results obtained on these devices are discussed in the later sections.

3. Experimental procedures

3.1. Designs & materials

The vertical contact mode based soft triboelectric device was tested by preparing the form of shoe insole. Fig. 2 presents the cross-sectional view of the design of the triboelectric insole. The fully elastomeric vertical contact mode generator was composed of two active layers separated by a spacer and assembled facing