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Research paper

Comb-shaped electrode-based triboelectric nanogenerators for bi-directional mechanical energy harvesting

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ABSTRACT

Triboelectric nanogenerators (TENGs), which utilize coupling of contact electrification and electric induction to effectively harvest the mechanical energy around us, have attracted much attention due to their advantages such as simple design and high accessibility. Herein, we report new types of TENGs containing comb-shaped electrode, which are fabricated with a simple thermal nanoimprinting process where a commercially-available metal mesh was used as a stamp to simply impart microtopography on the TENGs to increase electrical output performance. The fabricated TENG with the comb-shaped electrode enables to harvest bi-directional mechanical energy (including both lateral and vertical contact/separation), which can be a new strategy to efficiently harvest the energy from complex real mechanical motions. The TENG with the comb-shaped electrode generates a short circuit current (I_{sc}) of 85 nA and an open circuit voltage (V_{oc}) of 6.4 V under the lateral contact/separation, which are increased up to 850% and 1600%, respectively, compared to the TENGs with the conventional rectangular electrode. The TENG with comb-shaped electrode is also found to harvest energy of I_{sc} of 339 nA and V_{oc} of 31 V at a pressing frequency of 0.5 Hz and force of 58.8 N under the vertical contact/separation without significant loss of electrical output performance compared with the TENG with the conventional rectangular electrode. The results indicate that the comb-shaped electrode would be a powerful (potential) candidate of electrode shape of the TENG to harvest the energy from real mechanical motions.

1. Introduction

Recently, the triboelectric nanogenerators (TENGs) have been verified as a promising energy harvesting system that converts mechanical energy to electrical energy with the help of triboelectric effect (or contact electrification) [1,2]. Given that the triboelectric effect is ubiquitous in our daily life, the unique advantage of the TENGs compared to the other energy harvesting systems can be a high accessibility. In addition, due to its simple design, components and the operation principle, TENGs have another advantage of situational easy modification and tailoring [3,4]. The main components of TENGs are a counter layer, a contact layer and an electrode layer which is attached to the contact layer and/or the counter layer. When the frictional contact occurs between the counter layer and the contact layer, each becomes electrically charged with opposite sign by the triboelectric effect. After that, the relative motion between two layers can generate electrical energy with the help of the electric induction in the electrode layer. Along with it, the practical application of TENGs is close at hand due to the countless effort to enhance electrical output performance. According to the previous literatures, the roughness of the contact surface of TENGs plays a critical role to enhance electrical output performance, since the operation mechanism of the TENGs is highly related to the surface contact area followed by separation as abovementioned; the rougher the contact surface area of the TENG has, the higher the electrical output performance of the TENG generates [5–7]. Among several methods, fabrication of surface micro/nanotopography on the contact and/or counter surface is a well-known and easiest way to increase the roughness [8–11].

Effective harvesting of the surrounding energy is one of the main issues of research regarding TENGs. To meet this concern, a proper design of the TENG should be carefully selected according to its circumstance, which is highly related to the type of surrounding mechanical energy [12–19]. However, many of the previously reported TENGs exclude the consideration of a complex real motion composed of mixed vertical and lateral contact/separation-based mechanical motions. For example, in the case of the human walking-related circumstance, previous reports only have focused on vertical contact/separation between the human foot and the insole [20–22]. In other words, TENGs cannot harvest energy from lateral contact/separation, which is also one of walking motions. Following the concern, a new type of TENG system, which can

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harvest bi-directional mechanical energy (including both vertical and lateral contact/separation) is expected as a new strategy to effectively harvest the energy from a real circumstance in our daily life.

Herein, we report a microtopographical-pattern assisted triboelectric replicable nanogenerator with a comb-shaped electrode, named a micro-PATERN-comb. The micro-PATERN-comb is fabricated according to our previously reported methodology, which is based on the thermal nanoimprinting process [23]. The present micro-PATERN-comb shows a bi-directional mechanical energy harvesting ability, which is essential for efficiently harvest the energy from complex real mechanical motions, compared to the TENGs with the conventional rectangular electrode. The study about the effect of the comb-shaped electrode area on the electrical output performance is systematically performed and as a result, it is shown that the introduction of the comb-shaped electrode can enhance the amount of the energy generated from the lateral motion without significant loss of the energy generated from the vertical motion compared with the energies from TENGs with the conventional rectangular electrode. Considering the fact, the micro-PATERN-comb suggests a new guideline of TENG design to overcome the limited energy harvesting way of preceding TENGs.

2. Experiments

2.1. Fabrication of the micro-PATERN-comb

Fluorinated ethylene propylene (FEP) films with 25 μm thickness (DuPont) and Indium tin oxide (ITO) films with 200 μm thickness (SHINJIN Future Film) were utilized as the contact layer and the electrode layer, respectively, in the present TENG. The FEP film, which possesses high electron affinity, is one of the well-known thermoplastic fluoropolymers [24,25]. Due to its thermoplastic property, the replication of micro/nanotopography can be easily obtained at an increasing temperature above the specific glass transition temperature (T_g), at which the FEP films become moldable. Using a laser cutter (INNOSTA), the geometry of the comb-shaped electrode (the number, length and pitch of arms on comb) layer can be precisely realized by cutting the ITO film. After stacking the films in order of FEP/comb-shaped ITO/FEP, a commercially-available stainless-steel mesh was placed on the top FEP film as shown in Fig. 1a. The metal mesh possessing microtopography was utilized as a stamp for thermal nanoimprinting to increase the roughness of the contact layer surface and topography was replicated into the top FEP film by applying heat and pressure. The processing imprinting temperature was fixed as 210 °C according to our previous work [23]. After cooling both the stamp and the stacked films down to 30 °C, the stamp was mildly removed and the resultant micro-PATERN-comb was successfully fabricated. Fig. 1b shows that microtopography of the stamp was successfully replicated on the FEP film, and at the same time, the films were thermal bonded with each other, which is one of the main advantages of utilizing the thermal nanoimprinting process to fabricate the TENG. The final product had semi-transparent and flexible characteristics as shown in Fig. 1c.

2.2. Evaluation of microtopography replication

To evaluate the quality of replication, the PDMS oligomer (Sylgard 184, Dow Corning Toray) mixed with its curing agent (at a 10:1 ratio by weight) was poured onto the surface of the replicated micro-PATERN-comb. After curing at 65 °C for 6 h, the cured PDMS, which had an inverted pattern to the microtopography on top FEP surface of micro-PATERN-comb, was peeled off and the surface profile was investigated to indirectly evaluate the height of microtopography on the micro-PATERN-comb.

2.3. Evaluation of electrical output performance

To quantitatively evaluate the electrical output performance of the fabricated micro-PATERN-comb under the vertical contact/separation, a latex surface, which is used as the counter layer, connected with the electrodynamic shaker (Labworks) was utilized with a pressing frequency of 0.5 Hz and a pressing force of 58.5 N. In the case of the lateral

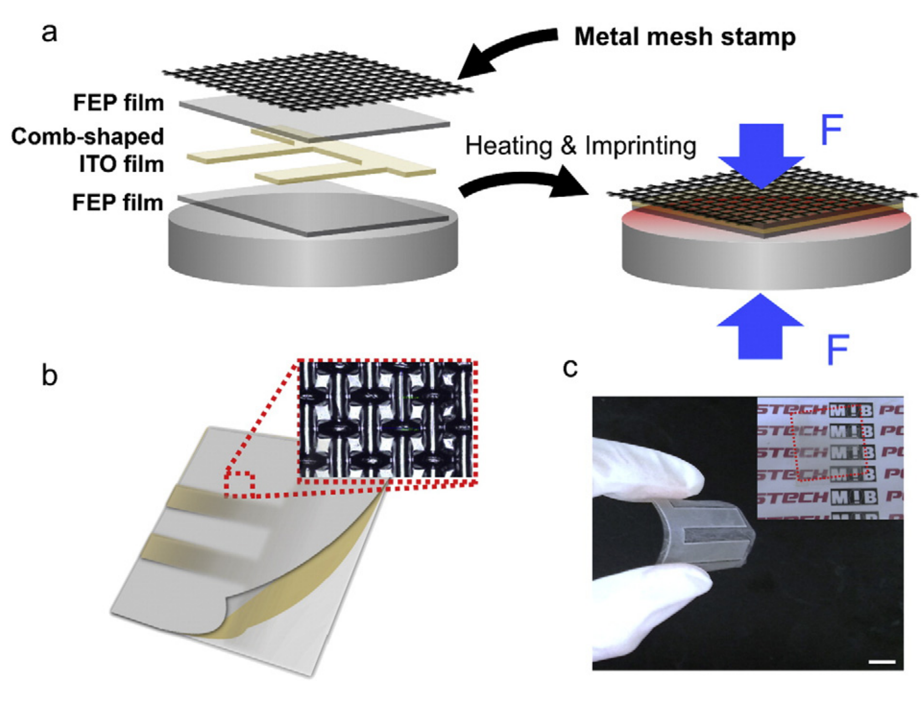

Fig. 1. Schematics of fabrication of the micro-PATERN-comb by the thermal nanoimprinting process and its characteristics (a) A fabrication process of the micro-PATERN-comb. Conventionally available FEP and ITO films are utilized as a contact layer and an electrode layer, respectively. A metal mesh is utilized as a stamp. (b) Schematic of the fabricated micro-PATERN-comb. The microscopic image shows microtophography on the stamp is successfully replicated to the micro-PATERN-comb. (c) The real image of the fabricated mico-PATERN-comb. Scale bar, 1 cm.