Sand-polished Kapton film and aluminum as source of electron transfer triboelectric nanogenerator through vertical contact separation mode

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ABSTRACT

Contact electrification is a direct triboelectrification method for producing current through charge transfer when two different differentiated materials have brought into contact. For the first time, we developed a simple triboelectric nanogenerator (TENG) where the electronic charges were realized through contact separation mode between sand-polished Kapton (SPK) and Al surface. Here, we demonstrated the energetic interfacial contact between these surfaces and observed satisfactory output performance. The novel SPK-TENG produced 40 V and 2.8 µA, of open-circuit voltages ($V_{oc}$) and short-circuit currents ($I_{sc}$) at 4 Hz, respectively. Mainly, the SPK-TENG was dramatically increased up the performance of TENG, up to 40% of $V_{oc}$ and 42% of $I_{sc}$ with respect to the Kapton film because the mobility of electrons is very high on the device surface compared to the other pristine Kapton film. The fabricated SPK-TENGs were good candidates for satisfying the need for alternative contact separation mode TENGs.

1. Introduction

With the growing hazard of energy calamity and ecological degradation by global roasting, scientist were seeking potential alternative energy technologies that can replace the conventional sources such as solar, wind, tidal energies, etc. [1–4]. Until now, various types of energy-harvesting systems were developed to collect energy from ambient resources, such as piezoelectric, photoelectric, thermoelectric, electrostatic, and electromagnetic strategies [5,6]. However, more robust, eco-friendly, cost-effective, and reliable energy-harvesting...
systems with modern technologies are desirable to satisfy the manufacturing demand. Mechanical energy is one of the natural renewable energy sources in the existing environment that can be taken care from human motion, including the body’s vibration, rotation, etc. [7,8]. Recently, triboelectric nanogenerators (TENGs) have received worldwide attention for the harvesting of sustainable green energy from ambient resources. TENGs are developed based on a combination of contact separation mode electrification and electrostatic induction to scavenge reduced mechanical energy using triboelectric materials [9,10]. The proper selection of triboelectric pair materials, and their rational design can upsurge the rate of energy harvesting and energy conversion efficiency [11,12]. At regular intervals of materials with oppositely charged surfaces, ions or electrons can be driven to flow through the external load, and generate a continuous voltage and currents [13]. The proposed sand-polished Kapton (SPK)-Al TENG shows vital chemical solidity, and high strength to enhance the triboelectric current against to simple Kapton film and Al (K-Al) TENG [14,15]. The movement of electrons from the SPK-Al TENG is novel and simple system to generate the power from the contact separation mode process. The electric output was observed by contact separation mode TENG to generate maximum of $V_{oc}$ and $I_{sc}$ up to 75 V and 1 µA at 4 Hz, Figure 1 [15,16,17].

2. Experimental section

2.1. Preparation of SPK film

A total of 2.0 cm × 2.0 cm = 4.0 cm$^2$ of Kapton (K) commercial film was sand polished by free hand for 5 min. After completion of polish, the film was washed with acetone, DI water, and dried at 50°C until evaporation of DI water.
2.2 Characterization

The surface morphologies of Kapton before and after sand-polished samples were determined by FE-SEM using a Hitachi cold FE-SEM at 10 kV. The output signal of the all K-Al TENG and SPK-Al TENGs was performed by periodically pressed and released by means of an oscillator. The electrical outputs were measured by a Keithley Digital Multi Meter (KDMM). Next, we performed some experiments to determine the impact force using load cell YC33-5K (SETECH) at different frequencies of 1, 2, 3, and 4 Hz, respectively.

2.3. Fabrication of the contact separation K-AL TENG and SPK-AL TENGs

The fabrication, the working principle, and methodical understanding of the contact separation mode K-Al TENG and SPK-Al TENGs are examined [17 18, 19]. Here, the construction of the typical model is depicted in Figure 2. First, the K-Al TENG and SPK-Al TENG were developed by attaching the Kapton and SPK films with the dimensions of 2.0 cm × 2.0 cm = 4.0 cm² on an Al electrode. Then, the K-Al TENG and SPK-Al TENG electrodes were attached to commercial foam to reduce the reflecting force while contact and separation were progressed. Then, a load cell was connected to the top of the Al electrode.

Secondly, the Al electrode was placed on the foam with 2.0 cm × 2.0 cm. Meanwhile, a linear oscillator composed of a DC motor with an eccentric system consistently oscillated a linear slider. The maximum oscillation amplitude is 40 mm. The upper portion of the K-Al and SPK-Al films (load cell and Al) was then suspended by a cantilever-

Figure 2. Mechanical manipulation of SPK-Al TENGs at (a) separation state, (b) full contact (pressed), (c) releasing, (d) full separation (released), and (e) contacting again (pressing).
3. Results and discussion
3.1. Set-up of SPK-AL TENG

Figure 2 showed the mechanical setup of the SPI-TENGs in full departure, and contact state, respectively, for generating high triboelectric voltage and currents. Harvesting of energy by contact electrification method by the contact and separation of SPK and Al under various frequencies of 1, 2, 3, and 4 Hz, respectively [13].

The working mechanism of the developed SPK-TENGs is elucidated by the SPI polymeric surface and the aluminum (Al) electrodes were initially free of charge, as shown in Figure 2(a). However, after the oscillation was started by a DC motor, the triboelectrically negative Al material barely touched the surface of the SPK. The Al surface thus became negatively charged and the SPK surface became positively charged due to the contact electrification, Figure 2(b).

In the contact electrification procedure, the active charges were remain for a longer period of time due to the insulating properties of the material. Because of the superior hydrophobic properties of the Al surface (contact angle, CA ~ 120°), its dry nature was maintained and an effective charge separation occurs when it was detached from the SPI surface. In the course of this separation process, the charges were traveled through an external load and the current movement occurred, as shown in Figure 2(c). The current was remained stationary as two surfaces completely separated and new equilibrium state was reached, Figure 2(d). When the SPK and Al were both in a closing situation, the electrostatic induction became progressively stronger such that it broke the equilibrium, resulting in charge redistribution of Al electrodes through the acceptance, and release of electrons, as shown in Figure 2(e). As a consequence, the current flow in the opposite direction. Until the two layers have been completely sealed, the charge-transfer process vanished and there was no current at all [11,12].

To investigate the influence of the ion movement on the electric output of a SPK-Al TENG, we fabricated two types of devices for comparison: SPK-Al TENG and K-Al TENG with similar thickness (~110 µm). The two Al electrodes arranged at both sides for the electric measurements, including the open-circuit voltage (Voc) and short-circuit current (Isc) [13].

3.2 FE-SEM

FE-SEM images are shown in Figure 3, which disclose the surface morphologies and cross-sectional images before and after sand polishing of Kapton films. Mainly, plain surface was found without any abnormal changes on the surface, as shown in Figure 3(a), and the cross-sectional image was attributed longitudinal layers as layer-on-layer network due to several mono layers were packed by π-π stacking’s, as shown in Figure 3(b). Besides that several irregular submicron to micron-sized wholes, and channels were found on the surface which are coming from the sand polishing of the rough surface, Figure 3(c). Apart from, in the cross-sectional view, the sand-polished film contained inclined micro-patterned layers with uniform distance as shown in Figure 3(d). The distance of layers which were uniform and they can significantly contact over the surfaces when they press and
released each other for generating of high output voltage and output currents while contact separation mode TENG process. Mainly, the loan pairs of electrons on the nitrogen atoms which carried by amidic links in the backbone of the oligomer chains of SPK polymer were contributed to generate power when they touch with the opposite charged surface. The loan pair of electrons were freely move with in/on the surface as source of negative charges. In addition, they can \( \pi-\pi \) stacking’s on the surface along with conjugated benzene sextets. The positive charges on Al metal surface that carry’s free positive charges while close interaction through contact separation mode phenomena. Obviously, the FE-SEM images suggested that the surface when it touches with oppositely charged Al metal surface, the power output was low. The power output was very important in the case of surface morphologies [10, 14].

3.3. Results of SPI-TENGs

Figure 4 showed the confirmation of our idea, we first examined the electric output of the K-Al and SPK-Al TENGs through the contact separation mode protocol. Figure 4(a) shows that the open-circuit \( V_{oc} \) of the K-Al TENG at 1 Hz surged from 1.3 to \(-1.2\) V upon separated. By gradually increasing the speed of the linear motor from 1, 2, 3, and 4 Hz, the \( V_{oc} \) values of K-Al TENG were increased from \(-1.2\) to 1.3, \(-15.2\) to 5.9, \(-7.6\) to 8.7, and \(-10.8\) to 12.3 V, respectively. And the output current (\( I_{sc} \)) was also increased while increasing of the liner motor. Here, the \( I_{sc} \) was attained from \(-0.03\) to 0.026 \( \mu \)A at 1 Hz, \(-0.17\) to 0.16 \( \mu \)A at 2 Hz, \(-0.42\) to 0.47 \( \mu \)A at 3 Hz, and \(-0.9\) to 0.9 \( \mu \)A at 4 Hz, as shown in Figure 4(b), respectively. On the other hand, the SPK-Al TENG was showed superior \( V_{oc} \).
and $I_{sc}$ at various applied speeds of contact separation TENG. Mainly, the $V_{oc}$ and $I_{sc}$ observed from SPK-Al TENG were from $-2.1$ to $2.6$, $-9.6$ to $10.6$, $-12.7$ to $14.5$ V, as shown in Figure 4(c), and $-18.5$ to $21.2$ V and from $-0.086$ to $0.086$, $-0.49$ to $0.49$, $-0.72$ to $0.72$, and $-1.4$ to $1.4$ µA, as shown in Figure 4(d), respectively. Also, the charge transferred between the Al electrodes promptly produced both $V_{oc}$ and $I_{sc}$ and the peak values were reached maximum from the TENG systems. The quantitative characterization of the output performance was showed due to induced surface charge density with respect to the $V_{oc}$ and $J_{sc}$ of K-Al TENG is lower than that of SPK-Al TENG because the loan pair electrons were effectively participated during transferring of electrons. The tendency clearly shows that the triboelectric charge density in the SPK-Al TENG is strongly influenced by electrons moment when the contact separation process was occurred [15].

Next, we conducted some experiments to determine the impact force at various frequencies. The load cell YC33-5K (SETECH) was utilized to measure the contact force and the result is shown in Figure 5(a). Based on the experimental results, the change of impact force gradually increases with respect to the contact frequencies. The more impact force is applied, the more effective area is induced, which means the higher output current generated [15,16]. The examination of electric output of SPK-Al TENG upon connecting directly to an external load at different resistors. Based on the experimental results, the change in impact force was gradually increased with respect to the applied contact frequencies. When more impact force was applied, the more effective area was
induced, which means that the higher output current generated according to the applied frequencies [17,19–21].

The power and currents of K-Al TENGs are 0.625, 12.32, 26.56, and 53.3 μW; and 0.25, 1.1, 1.63, and 2.3 μA at 1, 2, 3, and 4 Hz, respectively [22–24]. Similarly, the power and currents of SPK-Al TENGs were produced 2.2 μW and 0.47 μA at 1 Hz, 44.9 μW and 2.1 μA at 2 Hz, 73.9 μW and 2.72 μA at 3 Hz, and 157.6 μW and 3.97 μA at 4 Hz, respectively. The power densities (PD) of K-Al TENGs are 0.312, 6.1, 13.13, and 26.68 μW/cm² at 1, 2, 3, and 4 Hz due to smooth surface and the releasing electrons were poor. Whereas in the case of SPK-Al TENGs, the PD values were obtained from 1.10, 22.47, 36.9, 78.8 μW/cm² at 1, 2, 3, and 4 Hz, respectively at 20 MΩ. These PD values of SPK-Al TENG were increased up to 71.6% at 1 Hz, 72.7% at 2 Hz, 64.4% at 3 Hz, and 66% at 4 Hz. Also, the mechanistic clarification strongly recommends that sand-polished surface was played a key role to generate more power output [25].

4. Conclusion

We fabricated the commercial Kapton film for TENG application with the help of Al sheet as source of positive electrode. Next, we used sand-polished Kapton (SPK) film as negative electrode for the generation of the TENG applications. The contact separation modes SPK-Al TENG and K-Al TENG were developed which have been transferred electrons by electron transfer mechanism when they contacted each other. The K-Al and SPK-Al TENGs shown the \( V_{oc} \) and \( I_{sc} \) are 23.1 V and 1.8 μA, 39.7 V and 2.8 μA at 4 Hz, respectively. The \( V_{oc} \) and \( I_{sc} \) of SPK-Al TENG shown 40% and 42% with respect to K-Al TENG because the mobility of electrons is very high on the device surface. Consequently, the maximum
instantaneous power, current and power density of SPK-Al TENG were reached up to 157.6 μW, 3.97 μA, 78.8 μW/cm² (0.788 W/m²) at 4 Hz and 20 MΩ, respectively. These values are superior compared to the bare K-Al TENG.

**Acknowledgments**

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korean government (MSIP No. 2017R1A2B2011730, No. 2018R1A6A1A03024509 and No. 2019R1A2C1011113).

**Disclosure statement**

No potential conflict of interest was reported by the authors.

**Funding**

This work was supported by the NRF Korea [NRF Korea].

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