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PAPER

Triboelectric generator for wearable devices fabricated using casting method

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In this study, we fabricate an efficient triboelectric generator (TEG) using inexpensive materials that are readily available in our surroundings. By casting polydimethylsiloxane (PDMS), we perform micropatterning on the surface of a sandpaper. We use aluminum foil as an electrode and electrified body. To improve the durability and resilience of the aluminum foil, we use a polyethylene terephthalate (PET) film. PET / Al electrodes may act on the bottom and top performing the role of an electrode, and at the same time as an electrified body. We applied an external force of 1 N using the pushing tester on the TEG created using the PDMS, and we then connected an external resistor to confirm the output power. Based on the patterning TEG, we confirmed that there was an increase in the output voltage by a factor of about 10 times compared to the flat TEG's output voltage of 15 V. We turned on 79 LEDS by hand pushing, and produced an output voltage of more than 250 V. In addition, we turned on 39 LEDs by performing a bending test with an average output voltage of more than 100 V.

Introduction

Energy harvesting involves the storage of energy that would otherwise be wasted, or the harnessing of energy that exists in its natural state. Energy types that exist in the natural state include solar energy, water, and wind[1-6].

Recently, there have been developments that enable us to harness discarded heat and potential energy from the surroundings, such as thermal energy[7-8], piezoelectric energy[9-10], and triboelectric energy[11-14]. In 2012, Zhong-Lin Wang, who is a part of the Georgia Institute of Technology Material Science Department, was the first to use the name triboelectric generator (TEG), which led to the start of active research in tribology[15].

The principle behind the generation of the voltage across the TEG is the same as the generation of heat when creating friction between two non-conducting materials. The active electrons move, based on the electron affinity of either material.[16] In the Triboelectric series, the substance that has a more positive charge loses electrons more easily, and the opposite is true for negatively charged substances. As the difference in the electron affinity between two materials increases, there will be a greater movement of electrons.

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The best way to increase the efficiency of a TEG is to increase the surface area by creating a more micro-sized patterning on the surface of the charged body. To accomplish this, some studies have been performed to incorporate micropatterning on the charged body. Youbin Zheng used the electrospinning method to turn polyvinylidene difluoride (PVDF) and nylon materials into 790-nm and 550-nm electrospun fiber, respectively, and he incorporated them into a nanofiber structure[17]. Finally, with the use of inductively coupled plasma (ICP) reactive-ion etching (RIE), Sihong Wang, generated a uniform microscale pattern on his TEG[18].

Many studies are being performed to incorporate TEGs into everyday applications. By adding the TEG to the soles of shoes[19-21], a voltage is generated purely by walking[22]. Creating a fiber-like TEG to be worn on body parts such as elbows and knees also generated voltage successfully[23-24].

Recently, there have been active studies to develop hybrid generators that simultaneously use more than two energy harvesters to generate electricity, e.g., the piezo/triboelectric generator[25], which involves electromagnetic/triboelectric energy[26].

However, using the above methods requires expensive equipment and is a complicated process. In this paper, we propose a simple method to produce an inexpensive TEG generator using easily accessible materials without the use of high vacuum or high-pressure equipment.

In this study, we used commercial sandpaper to generate micropatterning on a polydimethylsiloxane (PDMS) layer to create a simplified version of TEG, and we used scanning electron microscopy (SEM) to analyze the surface of the PDMS in order to check for the existence of micropatterning. We also analyzed the voltage generated based on the sandpaper's

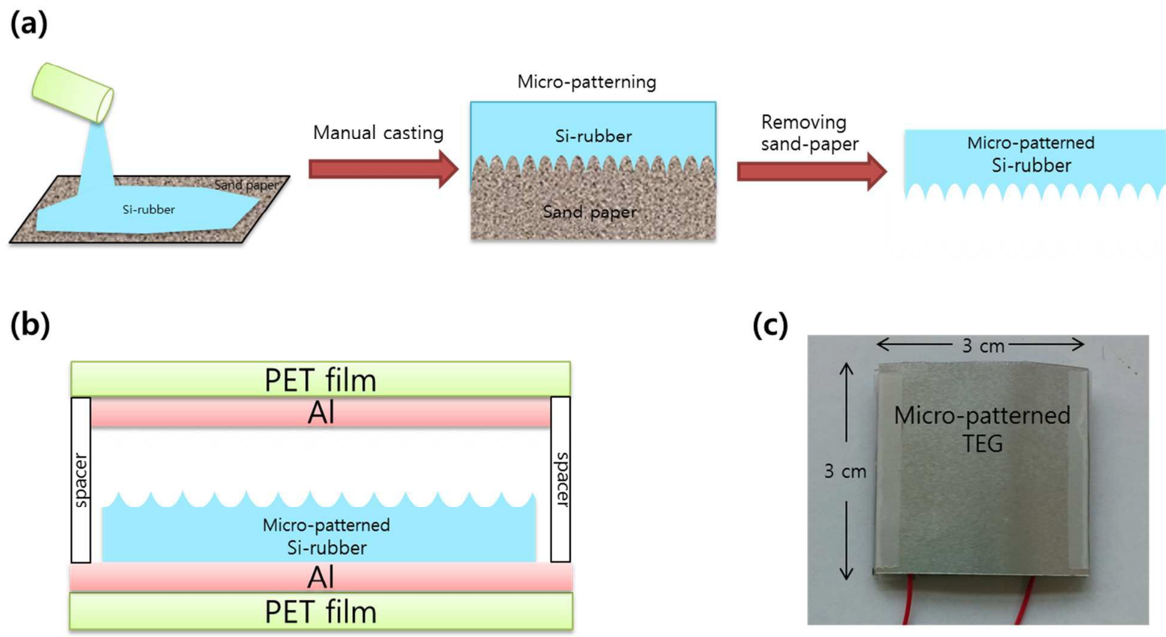

Figure 1. (a) schematic illustration of the structure and manufacture process of micropatterning PDMS (b) structure of flexible sand-patterned triboelectric generator (c) photograph of the micropatterned TEG.

grain size, and verified whether the device was operable by utilizing 79, 37 commercial light-emitting diodes (LEDs) under pushing and bending tests.

The proposed TEG does not require the use of expensive procedures such as lithography or etching, and it uses simple casting procedures that are much easier compared to conventional TEG-production methods. This results in a significant cost savings. In addition, we can easily modify the size and shape, which can enable the development of various forms of TEG.

Experimental details

The TEG consists of components such as PDMS and Al/PET, which are produced using the following methods. First, the production of PDMS involves mixing EcoFlex0050 solution in a one-to-one ratio for 5 min using a glass stick. We cast the well-mixed PDMS solution on top of sandpaper, and using the surface tension of the solution, we spread the solution evenly on top of the sandpaper. We dry the thinly spread PDMS solution at room temperature for 6 h, resulting in a micropatterned PDMS that has a thickness of 250~300 µm.

For the electrodes, we used commercial-off-the-shelf (COTS) aluminum foil. However, while foil is flexible, it lacks the ability to restore itself, so we compensate for this by attaching it on a film of polyethylene terephthalate (PET) prior to use. In the Triboelectric series, the aluminum possesses a positive property. We used the more adhesive flat part of the PDMS by applying it on top of the Al-foil/PET layer, and we realized additional space above those two by using the PET film.

We completed the TEG by adding another layer of Al-foil/PET, and tightly sealed the exterior. The total thickness of the sample was 1.3 mm, with Al/PET being 0.1 mm, PDMS 0.25 mm, and the spacer width 0.8 mm. Using the pushing tester, we found the voltage output generated from the pressure. The size of the TEG was 3 cm × 3 cm.

Results and discussion

Figure 1(a) illustrates the process of transferring a micropattern to the surface of the PDMS by casting sandpaper. The triboelectric effect is influenced by factors such as the used substances, coarseness, temperature, and humidity. Moreover, it is very important for the surface to have a micro-sized structural pattern in order to make a high-quality TEG [27-29]. In order to create a micro-sized structural pattern, we propose a design that uses sandpaper as a template. Sandpaper is mass produced according to standardized particle sizes, and the use of sandpaper is less costly (e.g., it costs $0.60 for a 28 cm × 23 cm-sized sheet). Therefore, there is good potential for the surface structure of sandpaper to serve as a template for micropatterning on PDMS. In order to form a micropattern structure on the surface, the liquidized PDMS is poured onto the sandpaper and "cured." The liquidized PDMS permeates through the sand particles on the sandpaper and solidifies while forming the micropattern. In addition, the PDMS is a substance that exhibits a strong triboelectric effect/phenomenon. Because PDMS is placed on the very lower side of the triboelectric effect spectrum/series, it has a very strong tendency to attract electrons when rubbed against another substance[30].

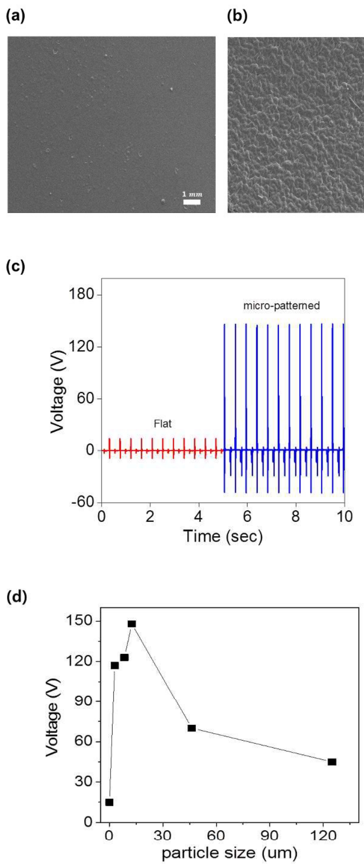

Figure 2. SEM image of (a) flat PDMS surface and (b) micropatterned PDMS surface. (c) output voltage of flat PDMS TEG and micropatterned PDMS TEG, (d) electrical performance of TEG output voltage for various particle sizes (roughness).

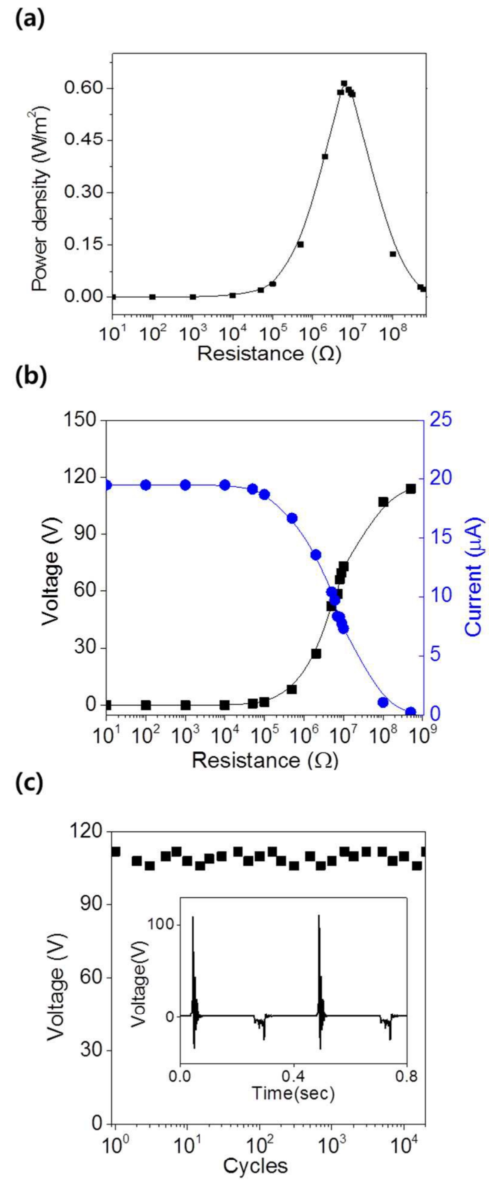

Figure 3. Electric output of a patterned triboelectric generator obtained using sandpaper (a) power density obtained for difference resistances (b) connected to the loads with different resistances, the current density and the voltage on the loads, (c) the output stability of the TEG.

Therefore, when rubbed against another substance, a large number of electrons build up on the PDMS surface, and we expect a high generating power when using the TEG. Furthermore, PDMS is highly elastic. Internal cracks and breakdowns may occur through metamorphosis and twisting because of the high pressure on the TEG resulting from the applied friction. However, PDMS by itself has a highly elastic nature, and has been known to return to its original form even after having been morphed by a factor of 1000%. The micropatterned PDMS used in this paper can tolerate increase in tension of up to approximately 650% at a very small thickness of 250 µm.

For this reason, it can return to its original form securely without any structural change of the substance, even after having been morphed by applied pressure. In addition, it requires a smaller applied force for morphing compared to other ceramic or metal substances. It can therefore be used to make an efficient generator as it induces the generator's morphing and friction with a relatively lower force. Using a micropatterned PDMS, we developed a TEG, as shown in Figure 1(b). We formed a flexible electrode by attaching a PET film to the Al foil. According to the triboelectric spectrum, Al foil has a higher tendency to transmit an electric charge compared to PDMS, so it can be used as a triboelectric material as well as an electrode.

We also placed on the edge a spacer made using PET film, which enabled us to build a package-type TEG that allows for

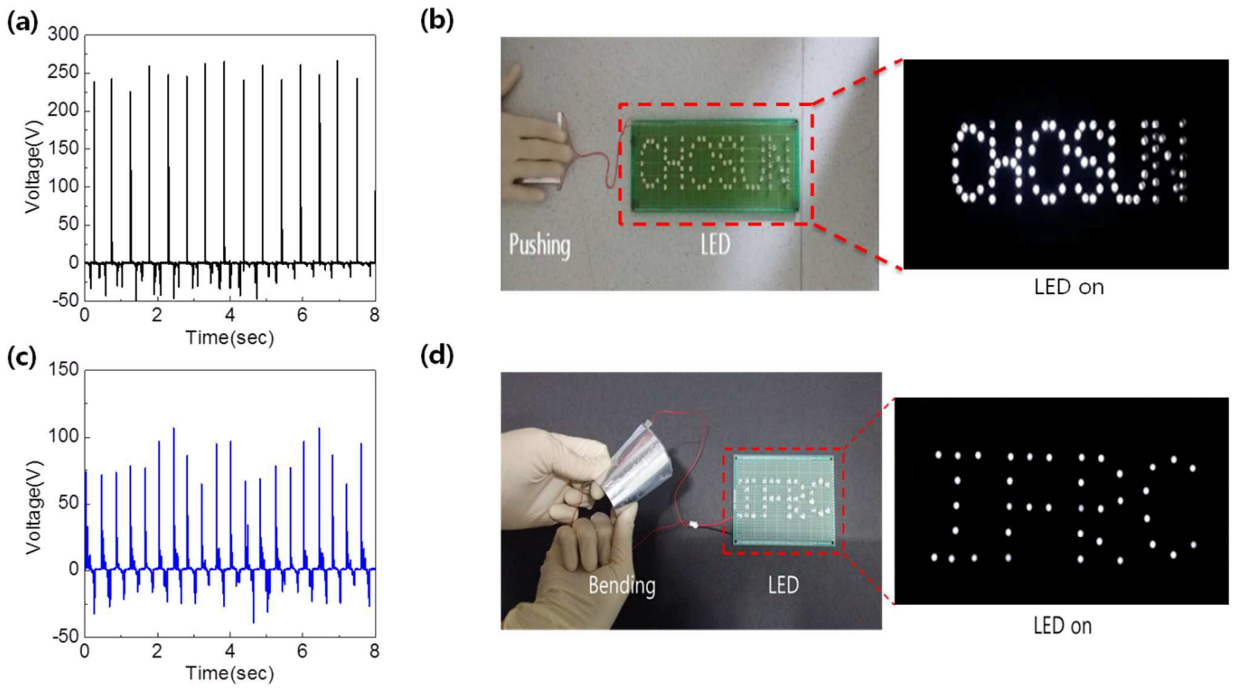

Figure 4. Performance of TEG (a) output voltage of TEG obtained by hand pushing, (b) photograph of 79 LED lamps lit using the pushing test by hand with no external circuit components, (c) output voltage of TEG obtained by hand bending, and (d) photograph of 37 LED lamps lit using the bending test by hand with no external circuit components

bending, and that also outputs a larger generating power. Figure 1(c) shows the final form of the TEG.

Figure 2(a) shows the SEM image of the PDMS film surface that we cast on a sheet of glass. The roughness of the cast PDMS surface is near zero because the glass surface is even. Figure 2(b) shows a contrasting SEM image of the PDMS film surface that we cast on a sheet of sandpaper. The size of the sand particles for the sandpaper surface averaged about 12.6 µm, and the casted PDMS film surface is formed by micro-sized holes. In addition, as shown on the SEM, all sections show a consistently formed micropatterned structure. Figure 2(c) shows the performance of the TEG that was produced using the micropatterned PDMS film. We measured the open-circuit voltage by performing repeated trials using the pushing tester on the 3 × 3 × 0.14 cm TEG with a force of 1 N. TEGs produced using the PDMS with a flat surface had an average open-circuit voltage of ~ 15 V. In contrast, TEGs produced using the PDMS surface micropatterned to 12.6 µm produced an average generating power of 148 V. We performed the experiments more than 20 times, and we obtained an average open-circuit voltage signal of 148 V. Therefore, the voltage signal generated by the TEG has good reproducibility.

The micropatterned TEG produced using the sandpaper generated a significantly higher open-circuit voltage that is 10 times the voltage obtained using the flat PDMS. Furthermore, the value of the open-circuit voltage of the TEG varies with the size of the patterning, as shown in Figure 2(d). This indicates that as the particle size of the sandpaper varies from 0 µm to 120 µm, the open-circuit voltage value also changes from 15 V to 148 V, and the open-circuit voltage values decreases as the particle size increases above 15 µm. TEGs are known to generate greater output with smaller-sized patterns as a larger surface area is exposed to the triboelectric effect. However, as the size of the patterning decreases below a certain level, the roughness of the area cannot generate a sufficient amount of friction to the point that it increasingly resembles the result obtained using the flat/even surface.

In fact, it is important to determine the maximum operating force that is required in order to use the TEG. Figure 3(a) shows the variation in the voltage and electric current with an external resistance/force. Using a pushing tester, we applied a force of 1 N to a 3 cm × 3 cm × 0.14 cm TEG with a PDMS patterned to 12.6 µm. The resulting voltage has a generating power of near 0 for an externally applied resistance of 10 Ω ~ 0.1 MΩ. However, the electric current generates 20 µA of power for an externally applied resistance of 10 Ω ~ 0.1 MΩ, and shows a tendency to decrease sharply with a resistance of more than 1 MΩ. The generating power of the TEG can be found using the following formula. Figure 3(b) shows the power that was obtained with the external resistance using the above formula. As shown in the figure, the power measurement is near 0 until the external resistance reaches 1 MΩ, but as it increases above 1 MΩ, the measurement increases exponentially, and from 6 MΩ and above, it has a generating power of 0.6 W/m^2. It is important to realize consistency in the repeated experimental trials in order to practically apply TEGs in applications. Figure 3(c) shows the variation in the generating power over the course of 20000 repeated trials. According to the figure, the first measurement obtained was 120 V, and the 20000th measurement was 119 V, showing no apparent decline in the performance as a TEG. Furthermore, as shown in the inset of Figure 3(c), the shape of the peak value after 10000 repeated trials is very similar to that observed at the very beginning of the experiment. This suggests that there is potential for its application in future. In addition, from a safety perspective, the generator showed no structural changes after having gone through continuous morphing due to repeated exposure to pressure.

TEGs that are produced as in the above figures can produce a large amount of generating power by performing various movements of the human body. Figure 4(a) shows the open-circuit voltage of a 5 cm × 5 cm TEG when pressed by hand. Pressing the generator by hand produced a maximum electric pressure of 250 V or higher, and we were able to light up 79 LED lights with it, as shown in Figure 4(b). In order to efficiently transform the human body movement into electric energy, it is desired that we are able to extract power, not only through pressure, but also from the bending of the body, namely joints. Figure 4(c) shows the TEG's ability to produce electric pressure using bending exercises. It generated more than 100 V of electric pressure through bending, and we were able to light up 39 LED lights, as shown in Figure 4(d).

Conclusion

In this study, we confirmed that the affordable TEG made from easily accessible parts was capable of operating simple devices. We used sandpaper to produce micropatterning on the surface of the PDMS, and after producing a TEG with such patterning, we compared it to a flat-surface PDMS TEG. Using the pushing tester, we performed a test that provides a constant external pressure of 1 N, and while the TEG with a flat-surface PDMS produced an average of 15 V, the TEG with the micropatterned PDMS produced an average of 148 V, which amounts to almost 10 times that with a flat surface. We also tested the power produced from an external resistance. When 1 N was applied, we realized an output power ranging from 6 MΩ to 564 µW, and when pressing it by hand, all 79 LEDs were working. From this, we can deduce that the voltage is not noise, but triboelectricity, and that the micro-pattern on the surface of the PDMS was well-formed using only sandpaper. Our results show that a device can become operable using TEG made from cheap materials.

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