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Master's Degree Thesis

Triboelectric Generator for Wearable Devices Fabricated by Casting Method

Graduate School of Chosun University

Department of IT Fusion Technology

Chang Jun Lee

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웨어러블 디바이스를 위한 주조법 기반 마찰전기 발전소자

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Chang Jun Lee

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Advisor: Prof. Youn Tae Kim

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Department of IT Fusion Technology

Chang Jun Lee

This is to certify that the Master's Thesis
of Chang Jun Lee

has been approved by the Examining Committee for the thesis requirement for the Master's degree in IT Fusion Technology.

Committee Chairperson
Prof. Keun Chang Kwak ______________________ (Sign)

Committee Member
Prof. Sung Bum Pan ______________________ (Sign)

Committee Member
Prof. Youn Tae Kim ______________________ (Sign)

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Graduate School of Chosun University

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Acronyms

PVDF	Polyvinylidene difluoride
TEG	Triboelectric Generator
PDMS	Polydimethylsiloxane
SEM	Scanning Electron Microscopy
PET	Polyethylene Terephthalate
ICP	Inductively Coupled Plasma
RIE	Reactive Ion Etching
LEDs	Light Emitting Diodes

ABSTRACT

Triboelectric Generator for Wearable Devices Fabricated by Casting Method

Chang Jun Lee
Advisor: Prof. Youn Tae Kim, Ph.D.
Department of IT Fusion Technology,
Graduate School of Chosun University

In this study, fabricated an efficient triboelectric generator (TEG) using inexpensive materials that are readily available in our surroundings. By casting polydimethylsiloxane (PDMS), perform micropatterning on the surface of a sandpaper. Use aluminum foil as an electrode and electrified body. To improve the durability and resilience of the aluminum foil, 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. Applied an external force of 1 N using the pushing tester on the TEG created using the PDMS, and then connected an external resistor to confirm the output power. Based on the patterning TEG, 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. Turned on 79 LEDs by hand pushing, and produced an output voltage of more than 250 V. In addition, turned on 39 LEDs by performing a bending test with an average output voltage of more than 100 V.

요 약

웨어러블 디바이스를 위한 주조법 기반 마찰전기 발전소자

이창준
지도교수: 김윤태 교수, Ph. D.
조선대학교 대학원 IT융합학과

본 논문에서는 주변에서 쉽게 구할 수 있는 재료들을 이용해 저렴하고 효율적인 마찰전기 발생장치를 제작하였다. PDMS를 사포표면에 주조(casting)하여 마이크로패터닝 하였고, 알루미늄 호일을 대전체와 전극으로 사용하였다. 알루미늄 호일의 내구성과 복원력을 향상시키기 위해 PET film을 사용하였다. PET/Al은 바닥(bottom)에서 전극역할을 하고 있고, 천장(top)에서는 전극 및 대전체 역할을 동시에 수행하고 있다. 마이크로패터닝된 PDMS를 이용하여 제작한 마찰전기 발생장치(TEG)를 푸싱테스터(pushing tester)의 지금 1 cm의 팁(tip)을 이용하여 1N의 힘으로 외부압력을 가하였고, 외부 저항을 연결하여 출력 전력을 확인하였다. 마이크로패터닝된 마찰전기 발생장치(TEG)의 출력 전압은 평평(flat)한 것에 비해 약 10배 증가하는 것을 확인하였다. 손바닥을 이용하여 위에서 아래로 힘을 가했을 경우 250 V 이상의 출력 전압을 얻어 내어 79개의 LED를 작동하였다. 또한, 구부리는(bending) 실험을 통해 평균 100 V 이상의 출력 전압을 얻어 내어 39개의 LED를 작동시켰다.

I. 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, 2, 3, 4, 5, 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], piezoelectricenergy [9, 10], and triboelectricenergy [11, 12, 13, 14]. In 2012, Zhong-LinWang who is a part of the Georgia Institute of Technology Material Science Department, was the first to use the name triboelectricgenerator(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.

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-ionetching(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, 20, 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/triboelectricenergy [26].

However, using the above methods requires expensive equipment and is a complicated process. In this paper, 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, used commercial sandpaper to generate micropatterning on a polydimethylsiloxane (PDMS) layer to create a simplified version of TEG, and used scanning electron microscopy (SEM) to analyze the surface of the PDMS in order to check for the existence of micropatterning. Also analyzed the voltage generated based on the sandpaper’s grain size, and verified whether the device was operable by utilizing 79 and 37 commercial light-emitting diodes (LEDs) under pushing and bending tests, respectively.

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, can easily modify the size and shape, which can enable the development of various forms of TEG.

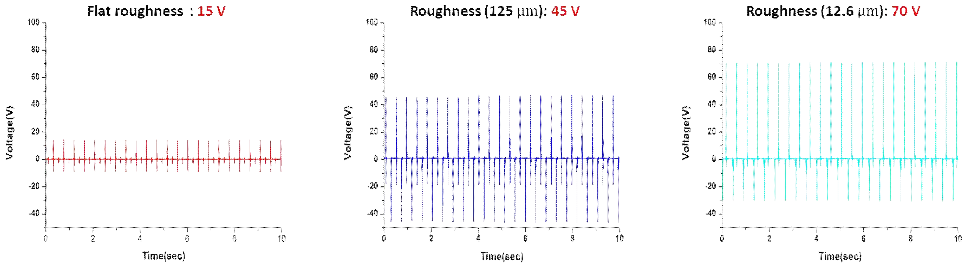
II. Experimental details

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. Cast the solution and spread the solution evenly on top of the sandpaper. Drying the thinly spread PDMS solution at room temperature for 6 h, resulting in a micropatterned PDMS has a thickness of 250 ~ 300 μm.

ISO/FEPA Grit designation	CAMI Grit designation	Average particle diameter (μm)	ISO/FEPA Grit designation	CAMI Grit designation	Average particle diameter (μm)
P12		1815	P180	180	82
P16		1324	P220	220	68
P20		1000	P240		58.5
P24		764		240	53.0
	24	708	P280		52.2
P30		642	P320		46.2
	30	632	P360		40.5
	36	530		320	36.0
P36		538	P400		35.0
P40	40	425	P500		30.2
	50	348		360	28.0
P50		336	P600		25.8
	60	265		400	23.0
P60		269	P800		21.8
P80		201		500	20.0
	80	190	P1000		18.3
P100		162		600	16.0
	100	140	P1200		15.3
P120		125	P1500	800	12.6
	120	115	P2000	1000	10.3
P150		100	P2500		8.4
	150	92			

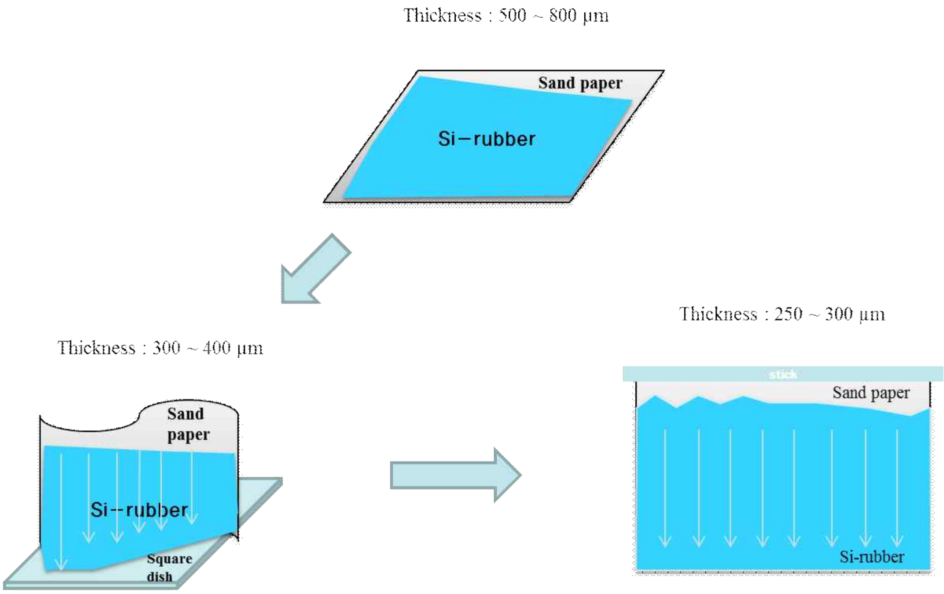
< Figure 1 Grit size of sandpaper >

Figure 1 illustrates Grit size of commercial-off-the-shelf sandpaper. P12 ~ 50 is used to quickly remove the rigid portion. It has a very rough surface, even look into the eye. P40 ~ 220 is a common sandpaper that has been marketed as sandpaper used to process the wood. After P1500 sandpaper used to gloss processing. Hardly felt roughness in the case of hand touch, it has a very smooth surface.



< Figure 2 Output voltage of various roughness >

Figure 2 shows the performance of the TEG that was produced using the glass and two types of sandpaper. TEGs produced using the PDMS with a flat surface had an average open-circuit voltage of 15 V, using the PDMS surface micropatterned to 125 μm produced an average generating power of 45 V and using the 12.6 μm produced an average generating power of 70 V. TEG consisting of micropatterned PDMS tended to increase gradually until the grains of 12.6 μm. however, the smaller grain size than the 12.6 μm, showed a tendency to PDMS solution can not be firmly penetration between grain, but rather efficiency is lowered.



< Figure 3 Drying method for patterning >

The efficiency of TEG is depended on the thickness of the electrified body. To find a best condition of PDMS thickness, try various drying method by casting 10 cm x 10 cm sandpaper (Figure 3).

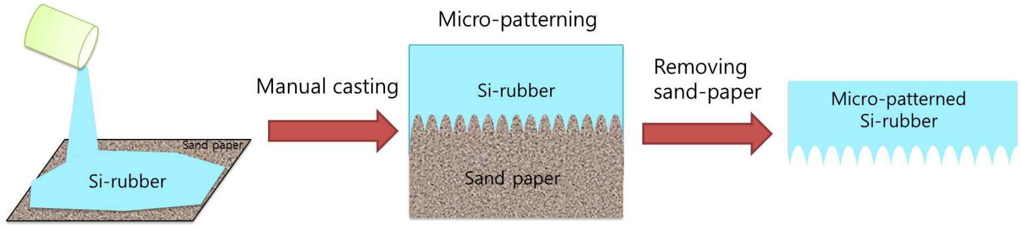
First, dried casting a PDMS solution in attached sandpaper on square dish, while maintaining the horizontal. The viscosity is high PDMS solution showed a tendency of being concentrated in certain parts that were not spread evenly, which is micropatterned with an average thickness of 500 ~ 800 μm.

Second, dried casting a PDMS solution in vertically attached sandpaper on square dish. The flow was spread evenly over the sandpaper down while the top can be obtained thin thickness of the micropatterned PDMS. However, deposition on the bottom PDMS solution is designed evenly in 300 ~ 600 μm.

Finally, the stick was vertically attached to the casting sandpaper to fall on the ground without being deposited at the bottom of the hung in the air. As a result, obtain a micropatterned PDMS evenly distributed to 250 ~ 300 μm.

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, found the voltage output generated from the pressure. The size of the TEG was 3 cm × 3 cm.

III. Results and discussion



< Figure 4 Process of micropatterning PDMS >

Figure 4 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, 28, 29].

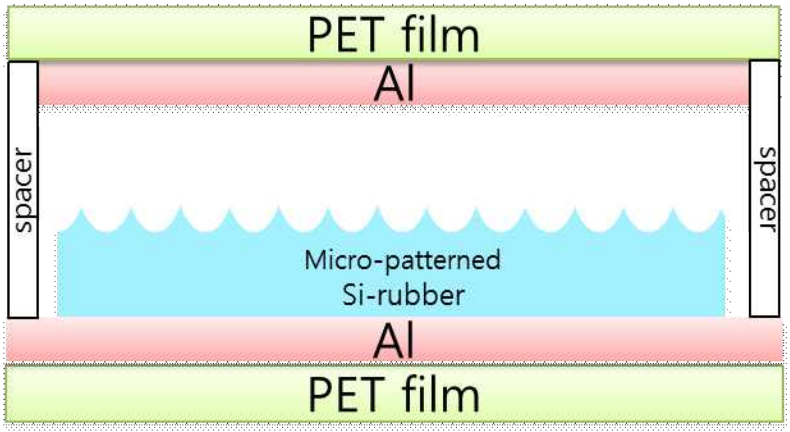
In order to create a micro-sized structural pattern, propose a design that uses sandpaper as a template. Sandpaper is mass produced according to standardized particle sizes and the use of sandpaper is less costly (e.g., it costs $0.60 for a 28 cm × 23 cm-sized sheet).

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].

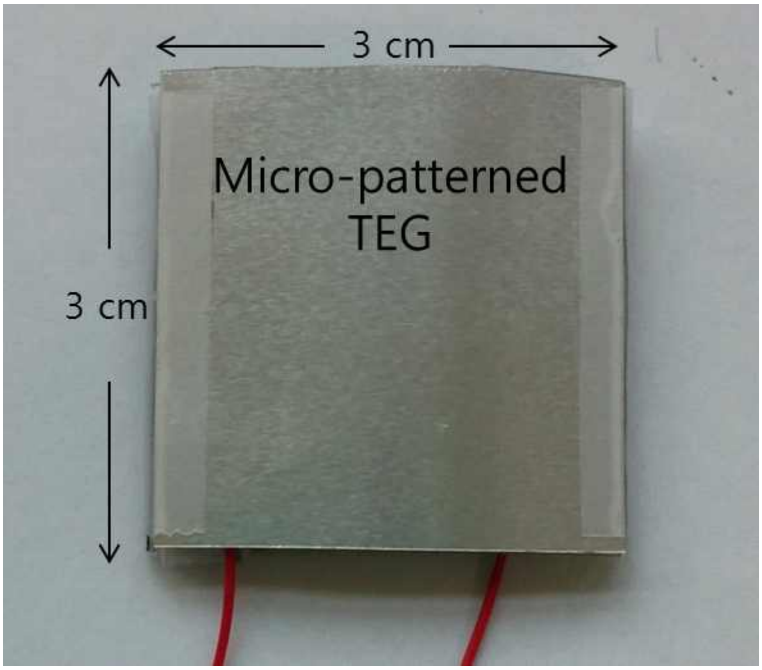
Therefore, when rubbed against another substance, a large number of electrons build up on the PDMS surface, and expect a high generating power when using the TEG. Furthermore, PDMS is highly elastic. Internal cracks and breakdowns may occur through metamorphosis and twisting because of the high pressure 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%.
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.



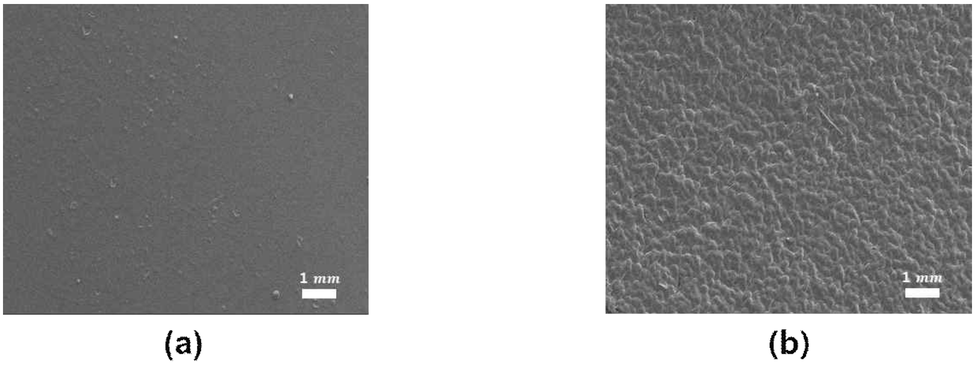
< Figure 5 Structure of flexible sand-patterned triboelectric generator >

Using a micropatterned PDMS, developed a TEG, as shown in Figure 5. 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.



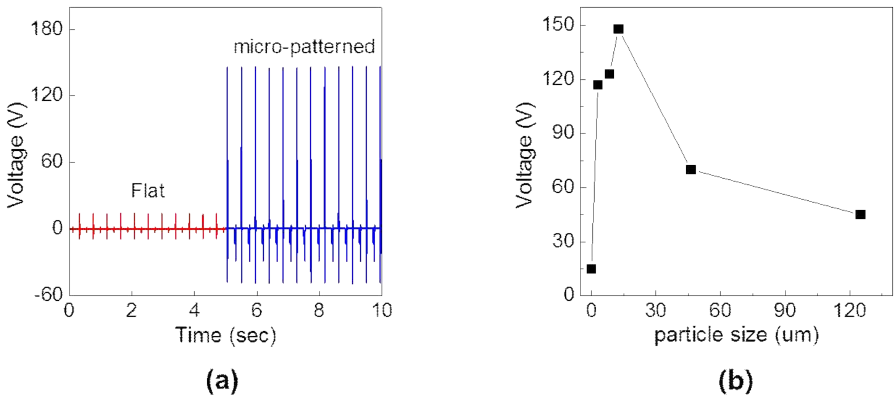
< Figure 6 Photograph of the micropatterned TEG >

Placed on the edge a spacer made using PET film, which enabled us to build a package-type TEG that allows for bending, and that also outputs a larger generating power. Figure 6 shows the final form of the TEG.



< Figure 7 SEM image of (a) flat PDMS surface and (b) micropatterned PDMS surface>

Figure 7(a) shows the SEM image of the PDMS film surface that cast on a sheet of glass. The roughness of the cast PDMS surface is near zero because the glass surface is even. Figure 7(b) shows a contrasting SEM image of the PDMS film surface that 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.



< Figure 8 (a) Output voltage of flat PDMS TEG and micropatterned PDMS TEG, (b) Electrical performance of TEG output voltage for various particle sizes (roughness) >

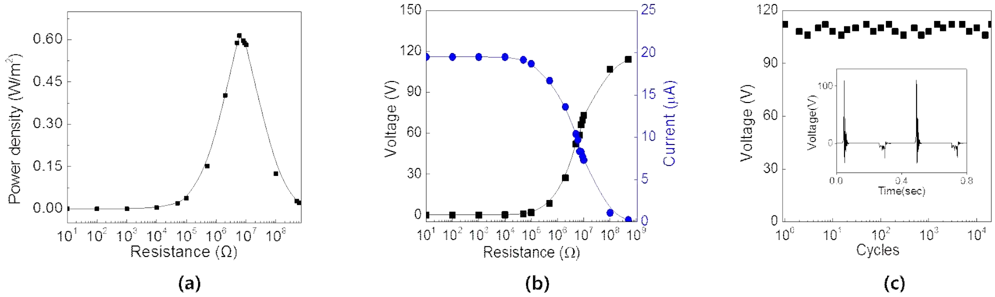
In addition, as shown on the SEM, all sections show a consistently formed micropatterned structure. Figure 8(a) shows the performance of the TEG that was produced using the micropatterned PDMS film.

Measured the open-circuit voltage by performing repeated trials using the pushing tester on the 3 cm × 3 cm × 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. 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 8(b). 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.



< Figure 9 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 >

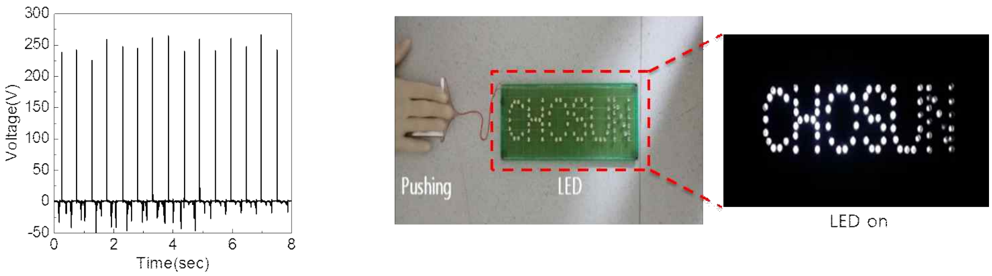
In fact, it is important to determine the maximum operating force that is required in order to use the TEG. Figure 9(a) shows the variation in the voltage and electric current with an external resistance/force. Using a pushing tester, applied a force of 1 N to a 3 cm × 3 cm × 0.14 cm TEG with a PDMS 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 9(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. It is important to realize consistency in the repeated experimental trials in order to practically apply TEGs in applications.

Figure 9(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.

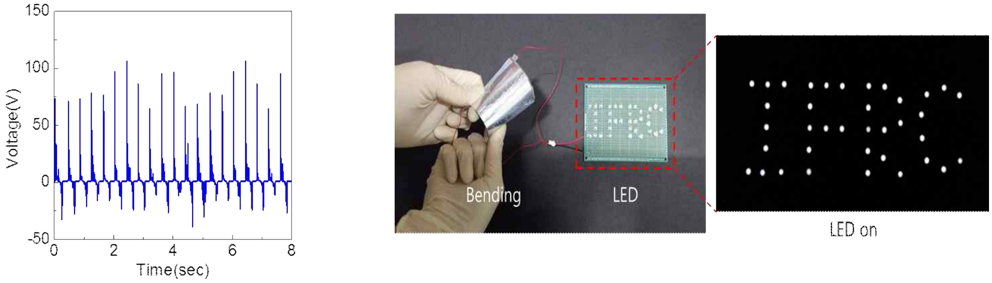
Furthermore, as shown in the inset of Figure 9(c), the shape of the peak value after 10000 repeated trials is very similar to that observed at the very beginning of the experiment. This suggests that there is potential for its application in future. In addition, from a safety perspective, the generator showed no structural changes after having gone through continuous morphing due to repeated exposure to pressure.



(a) (b)

< Figure 10 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 >

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 10(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 it was able to light up 79 LED lights, as shown in Figure 10(b).



(a) (b)

< Figure 11 Performance of TEG (a) output voltage of TEG obtained by hand bending, and (b) photograph of 37 LED lamps lit using the bending test by hand with no external circuit components >

In order to efficiently transform the human body movement into electric energy, it is desired that it is able to extract power, not only through pressure, but also from the bending of the body, namely joints. Figure 11(a) shows the TEG's ability to produce electric pressure using bending exercises. It generated more than 100 V of electric pressure through bending, and it was able to light up 39 LED lights, as shown in Figure 11(b).

IV. Conclusion

In this study, confirmed that the affordable TEG made from easily accessible parts was capable of operating simple devices. Used sandpaper to produce micropatterning on the surface of the PDMS, and after producing a TEG with such patterning, compared it to a flat-surface PDMS TEG.

Using the pushing tester, 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. Tested the power produced from an external resistance. When 1 N was applied, realized an output power ranging 564 μW at 6 MΩ, and when pressing it by hand, all 79 LEDs were working. From this, 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. These results show that a device can become operable using TEG made from cheap materials.

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Paper

1) **Chang Jun Lee**, A Y. Choi, Y. T. Kim, "Triboelectric Generator for Wearable Devices Fabricated by Casting Method", submitted to *RSC advances*, Oct. 2015.

2) H. J. Sim, C. S. Choi, **Chang Jun Lee**, Y. T. Kim and S. J. Kim, "Flexible two-ply piezoelectric yarn energy harvester", *Current Nanoscience*, Vol. 11, Issue 4, pp. 539-544, Aug. 2015.

3) H. J. Sim, C. S. Choi, **Chang Jun Lee**, Y. T. Kim, G. M. Spinks, M. D. Lima, R. H. Baughman and S. J. Kim, "Flexible, stretchable and weavable piezoelectric fiber", *Advanced engineering materials*, Vol. 17, Issue 9, pp. 1270-1275, Sep. 2015.

List of Publications

Conference

1) J. W. Park, **Chang Jun Lee**, Y. T. Kim, “Flexible two-ply tarn based generator for energy harvesting”, *Materials Research Society Fall meeting*, Nov. 2015.

2) **Chang Jun Lee**, A Y. Choi, H. J. Sim, S. J. Kim, Y. T. Kim, “Effects of additional poling process for the electrospun based PVDF-TrFE nanofibers on metal electrode”, *EMRS Fall Meeting*, Sep. 2013.

3) **Chang Jun Lee**, A Y. Choi, H. J. Sim, S. J. Kim, Y. T. Kim, “Piezoelectric ceramic/polymer nanofibers mat for mechanical energy harvesters”, *EMRS Fall Meeting*, Sep. 2013.

4) A Y. Choi, **Chang Jun Lee**, H. J. Sim, M. K. Shin, S. H. Kim, S. J. Kim and Y. T. Kim, “Enhanced β phase content and piezoelectric properties of electrospun PVDF nanofibers”, *Materials Research Society Fall Meeting*, Nov. 2012.

List of Publications

patent

1) "Human Activity based Integrated Triboelectric Generator" will be submitted, Dec. 2015.

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