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Master's Degree Thesis

Fiber-based Triboelectric Nanogenerator for Self-powered System

Graduate School of Chosun University

Department of IT Fusion Technology

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Fiber-based Triboelectric Nanogenerator for Self-powered System

자가 발전 시스템을 위한 파이버 기반
마찰전기 나노제너레이터

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Fiber-based Triboelectric Nanogenerator for Self-powered System

Advisor: Prof. Youn Tae Kim

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Table of Contents

List of Figures

Acronyms

TENG	Triboelectric Nanogenerator
FTENG	Fiber-based Triboelectric Nanogenerator
FSTENG	Fiber-based Single-electrode Triboelectric Nanogenerator
FESEM	Field Emission Scanning Electron Microscope
AC	Alternating Current
DC	Direct Current
LEDs	Light Emitting Diodes

ABSTRACT

Fiber-based Triboelectric Nanogenerator for Self-powered system

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Fiber- or thread-based triboelectric nanogenerators are suitable for wearable application such as clothes embedded with communication devices or other electronic textiles. Unfortunately, previously reported fiber-based triboelectric nanogenerators had poor stretchability, because of which they were not suitable for weaving applications. In this paper, we propose a new structure of a fiber-based single-electrode triboelectric nanogenerator (FSTNEG). The proposed FSTENG uses silicone rubber as the negative part and a conductive thread as the electrode of the TENG. The electrical output of the FSTENG is generated by the continuous contact and separation between human skin and silicone rubber. A prototype of the proposed FSTENG showed an electrical output of 28 V and 0.56 μA, when in contact with human skin, and exhibited a high strain of up to 100 %. In addition, we fabricated a woven structure with dimensions of 45 mm × 45 mm, incorporating the FSTENG, and confirmed its power generation capabilities using LEDs and an electronic watch. The proposed FSTENG can be applied to various products ranging from wearable and stretchable energy harvesters to smart clothing, by facilitating the manufacture of large textiles.

요 약

자가발전 시스템을 위한 파이버 기반 마찰전기 나노제너레이터

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파이버 또는 섬유 기반의 마찰전기 나노제너레이터는 섬유 통신 디바이스, 전자 텍스타일 등 웨어러블 응용분야에 활용 가능하다. 그러나 기존의 파이버 기반 마찰전기 나노제너레이터는 신축성 있는 특성을 갖기 어려웠으며 제직 응용에 제한적이었다. 본 연구에서는 새로운 구조의 파이버 기반 단일전극 마찰전기 나노제너레이터(FSTENG)를 제안한다. FSTENG는 음의 대전체 역할을 하는 실리콘 고무와 전극 역할을 하는 전도성 실로 구성된다. FSTENG는 피부와 실리콘 고무 사이의 연속적인 접촉 분리 과정을 통해 전기적 출력을 생성한다. 피부와 접촉 시 각각 28 V, 0.56 uA의 전기적 출력을 나타냈고, 100 %의 높은 신축률을 보여주었다. 또한 본 FSTENG만을 가지고 45 mm × 45 mm의 크기로 직물을 제작하여, LED 및 전자시계 동작을 확인하였다. 이와 같이, FSTENG는 대면적 텍스타일 형성이 가능하여 웨어러블 및 신축성 있는 에너지 하베스터에서 스마트 의복 제품에 이르기까지 다양한 분야에 응용이 가능할 것이다.

I. Introduction

Environmental pollution problems such as shortage of energy due to the gradual depletion of fossil fuels and global warming caused by greenhouse gas emissions are faced globally. In order to overcome these issues, several studies on green energy have been conducted. Among them, energy harvesting using eco-friendly energy sources has received considerable attention. Energy harvesting involves converting abandoned energy sources in the surrounding environment into electric energy that can be used as a substitute for conventional fossil fuels to provide sustainable energy and address the cost and environmental problems.

Recently, various electronic devices have been developed in forms capable of miniaturization, which are lightweight and wireless. Therefore, the interest in small-scale power generation is increasing. Electronic devices are generally operated by batteries. Currently, the energy density and performance of the batteries are improving steadily; however, there exists an issue in that the battery needs to be charged or replaced when it has discharged completely [1,2]. Energy harvesting technologies have been proposed as a fundamental method to solve the power supply problems of such small electronic devices [3,4]. As shown in Figure 1, small-scale energy harvesting technologies include piezoelectric generation using mechanical energy [5,6], triboelectric generation using electrostatic induction [7-9], thermoelectric generation using waste heat [10,11], and generation using electromagnetic phenomena [12,13]. Each method has its advantages and disadvantages, and the different methods are applied according to the target environment. For example, the thermoelectric energy harvesting technology utilizes the electromotive force generated by the temperature difference between materials. The larger the temperature difference, the more the electric energy that can be harvested. However, the ambient temperature difference of the device is practically not sufficiently large for effective utilization.

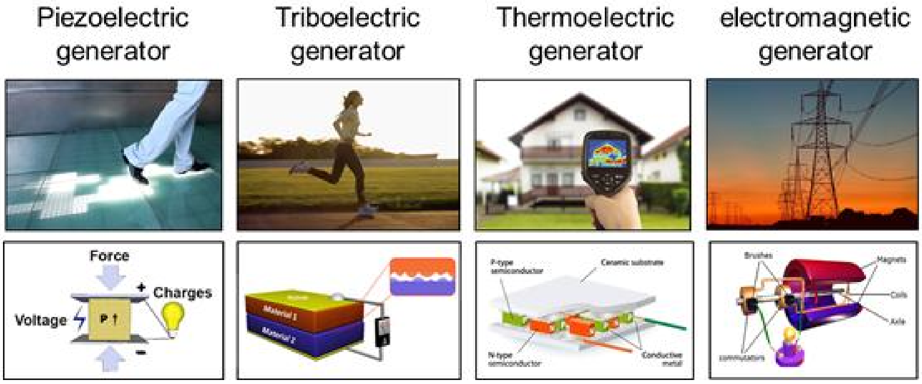

Figure 1. Energy sources and generators for energy harvesting.

However, triboelectric energy harvesting is a phenomenon in which energy is generated by triboelectrification and electrostatic induction when different materials are brought in contact with each other. Therefore, it can be applied to various small electronic devices easily, with high efficiency and low costs [14-17]. Most materials can be implemented in various ways for generating triboelectricity.

A triboelectric nanogenerator (TENG) consists of two materials, which are oppositely charged, and an electrode that generates external current. TENG has a simple structure and can be developed in various forms using a simple manufacturing process.

A TENG has various modes depending on the contact method of the device and the position of the electrode [18]. As shown in Fig. 2(a), the initial model of the TENG consists of a vertical contact-separation mode in which two different materials include an electrode and generate a continuous electrical output by friction with external pressure at regular intervals. However, the disadvantage is that the two surfaces do not efficiently make contact unless a certain amount of force is applied. The lateral sliding mode of Fig. 2(b) has the same structure as the vertical contact-separation mode but generates electrical output by sliding the contact surface of the two materials. A disk-type and cylindrical-type rotating structure rather than a simple planar structure have been developed for effective friction. However, the use of organic-based polymers has the disadvantage of being easily damaged because of the low abrasion resistance. The freestanding triboelectric-layer mode in Fig. 2(c) connects the two electrodes with symmetrical structures and generates current between the two electrodes by using the electrostatic induction effect that occurs when the friction surface approaches one electrode. Compared with the two modes described earlier, this mode does not have to maintain contact, greatly improving the abrasion resistance. As shown in Fig. 2(d), the single-electrode mode only uses electrodes on one material out of the two different materials that are in contact. This mode has a structure that changes free-moving motion into electric current and generates current while maintaining the balance of electric charges through the movement of electrons from the electrodes according to the contact or separation of the charged substances. As the single electrode mode is not limited in the movement of other materials, it can be applied to various applications such as wearable devices.

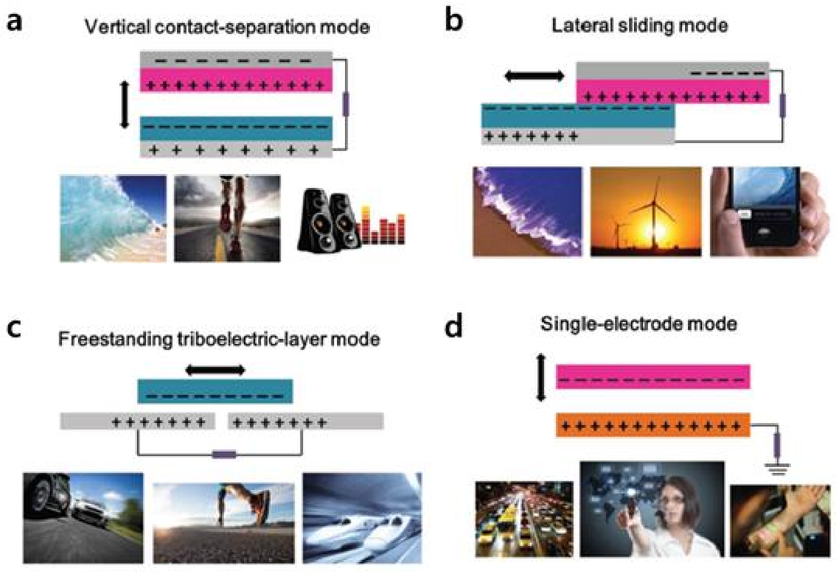

Figure 2. Four fundamental modes of TENG: (a) vertical contact-separation mode; (b) lateral sliding mode; (c) freestanding triboelectric-layer mode; (d) single-electrode mode.

TENG has been developed in various types to suit different applications or necessities, and can be manufactured as a self-powered device that can be used directly on the human body [19-22]. Among TENGs, fiber-based triboelectric nanogenerators (FTENG) can convert mechanical energy generated from body motion into electrical energy and can be easily integrated with clothing [23,24]. In the previous studies, most FTENGs generated electrical output from the contact between two or more strands of thread. However, it was difficult to form contact and separation between threads, and thus, they exhibited slightly low electrical outputs [25]. Moreover, the previous FTENGs had trouble in bending and it was hard to make stretchable structures for obtaining an effective electrical output, using metal as the electrode material. Additionally, there was limited scope for weaving [26].

In this paper, we present the development of a new type of fiber-based single-electrode triboelectric nanogenerator (FSTENG) that is composed of stretchable silicone rubber and conductive thread. We also confirm its electrical efficiency, stability, and durability. FSTENG uses silicone rubber as the negative part and a conductive thread as the electrode. The FSTENG can obtain electrical energy through skin contact. To evaluate the performance of the FSTENG, several strands of FSTENG were fabricated into a woven structure (45 mm × 45 mm), and were used to charge commercial capacitors and drive LEDs and electronic watches. It was found that, because the FSTENG is stretchable, it is convenient to wear, and it can be fabricated in large sizes. The FSTENG proposed in this letter is expected to be applicable in various products such as wearable and portable devices, owing to its simple manufacturing process and flexibility.

II. Experimental details

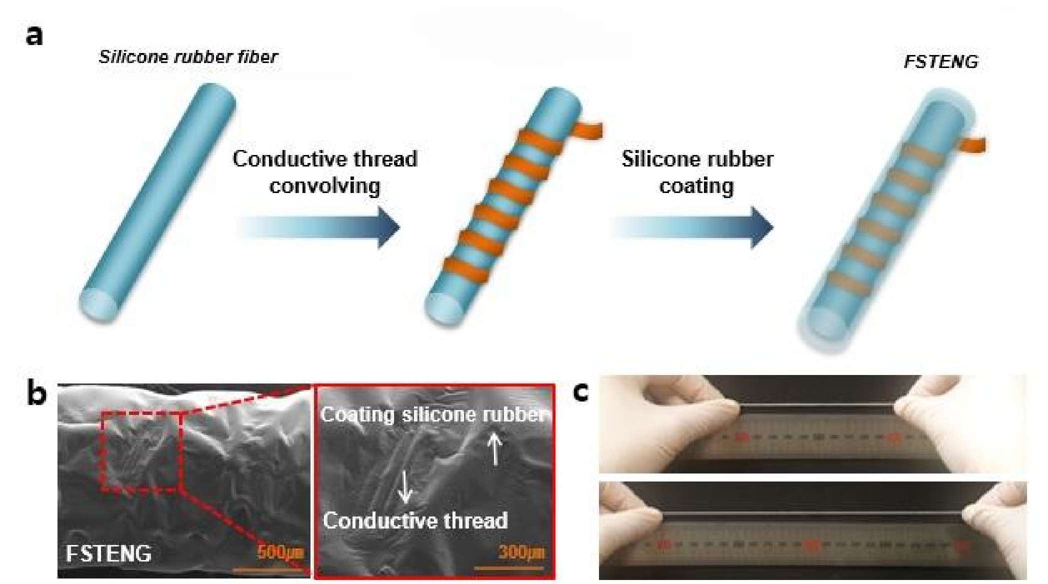

Figure 3. (a) Schematic of the structure and manufacturing process of FSTENG. (b) Field emission scanning electron microscope (FESEM) image of FSTENG surface. (c) Photograph of the FSTENG in the released state and stretched state with 100 % strain.

Figure 3(a) shows the schematic and manufacturing process of the FSTENG. An FSTENG is a single-electrode triboelectric nanogenerator with a core–shell structure consisting of silicone rubber and conductive thread. The conductive thread, which provides high conductivity and electrical stability, is composed of silver-coated copper and polyester and has an average resistance of 0.049 Ω/cm for a diameter of 300 μm. It exhibits higher mechanical durability, flexibility, and electrical conductivity, compared to other threads coated with metal. In addition, it demonstrates 980 % elongation and has outstanding electrical properties, and hence, is used as a triboelectric material, i.e., the negative part.

In order to fabricate a silicone rubber frame, an elastomer and a curing agent are mixed in a ratio of 1:1. The conductive thread is coiled around the silicone rubber frame and it serves as a flexible single electrode. Next, the entire surface is coated with silicone rubber by the dip-coating method, followed by drying at room temperature for approximately three hours, to use it as a material with electric charge. The thickness of the silicone rubber layer on the surface is 100 μm. In this process, the silicone rubber is cured in vacuum to prevent the electrical resistance from increasing because of the formation of bubbles. Figure 3(b) shows a field emission scanning electron microscope (FESEM) photograph of an FSTENG with a diameter of 1.2 mm, and its enlarged side image. This image shows the structure of the silicone rubber frame with the conductive thread coiled around it and a silicone rubber coating on the surface of the fiber. Figure 3(c) shows the initial state of the FSTENG and its stretched state under 100 % strain. Even when the length of the FSTENG is increased, the electrical pathway along the conductive thread of the electrode remains constant.

III. Results and discussion

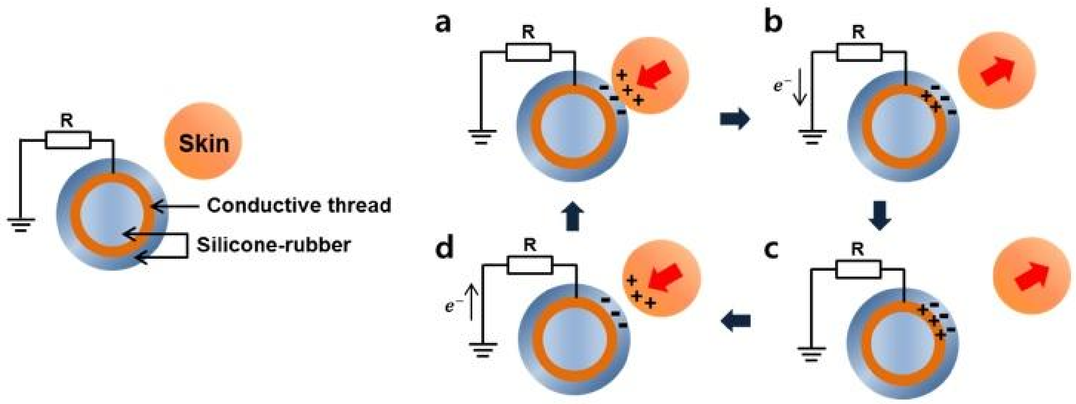

Figure 4. Schematic of the charge distribution in the FSTENG in the case of contact with human skin, (a-d) show the four statuses of one current generation cycle.

The power generation process in the FSTENG is illustrated in Figure 4. The FSTENG generates electrical output using a combination of triboelectric and electrostatic induction in different materials during regular contact and noncontact. As human skin and silicone rubber have different features, they cause the movement of surface charges when they are in contact with each other. According to the triboelectric series (Figure 5), the electrons move from human skin to silicone rubber during contact because silicone rubber has a higher electron affinity than human skin (Figure 4(a)). When the two surfaces are separated, the negative charge on the silicone rubber surface induces a positive charge in the conductive thread, causing current to flow from human skin to the conductive thread (Figure 4(b)). This electrostatic induction provides electrical current flow, through the electron mobility. When the negative triboelectric charge on silicone rubber is balanced by the induced charge, no electrical output is observed (Figure 4(c)). When human skin and silicone rubber come in contact again, the induced positive electric charge of the conductive thread decreases and a reverse current is generated (Figure 4(d)). As a result, an electrical output is generated by the continuous contact and separation of human skin and silicone rubber.

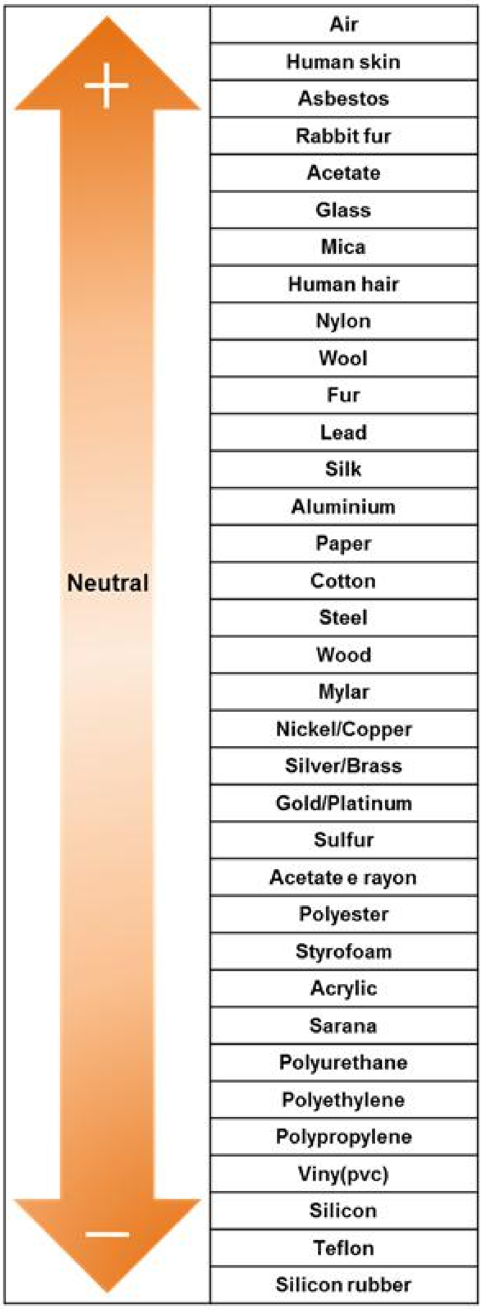

Figure 5. Triboelectric series

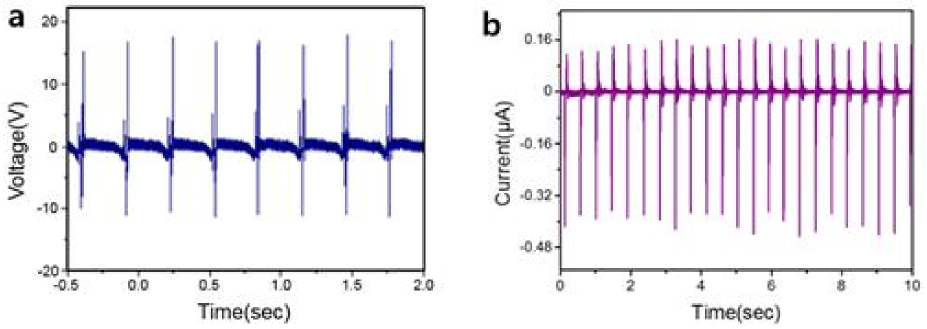

Figure 6. Electrical characteristics of the FSTENG. (a) Electrical output voltage and (b) current of the FSTENG under a force of 1 kgf.

In FSTENG, silicone rubber is a triboelectric layer that generates electrical output through friction with human skin. The electrical characteristics are analyzed by bringing an FSTENG 8.5 cm in length and 1.2 mm in diameter in contact with human skin. The output voltage is measured by connecting an electrode to the output of an oscilloscope (MSO9104A), and the short-circuit current is measured using a precision source/measure device (B2911A). When the skin and FSTENG are in contact with a force of 1 kgf, the instantaneous voltage and current signals can be measured. The maximum output voltage and current are 28 V and 0.56 μA, as shown in Figures 6(a) and 6(b), respectively.

In order to supply energy to wearable devices, it is necessary for the FSTENG to generate energy and be flexible, durable, and stable. As shown in Figure 7(a-b), the durability is analyzed by the repeated application of pressure using a pushing tester (JIPT-100). A constant output of 90% of the electrical output generated under normal operating conditions, when compared to the initial output voltage, is obtained from the FSTENG when a force of 0.6 kgf is applied for 3,000 pushing cycles. Figure 7(c-d), which shows the comparisons of the FSTENG before and after the stretching tests wherein it was stretched by 50% 3,000 times using a tensile tester, shows that a stable triboelectric performance is obtained. Thus, it can be concluded that the FSTENG shows outstanding durability without degrading the electrical output.

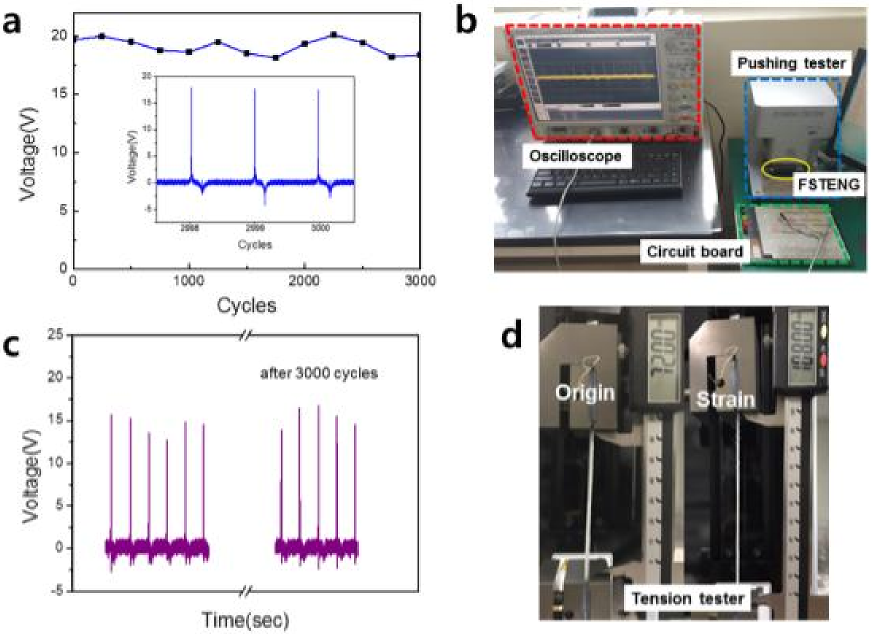

Figure 7. Electrical stability and durability of the FSTENG. (a) Performance during pushing 3,000 cycles (b) using pushing tester under a force of 0.6kgf. (c) Performance before and after stretching by 50 % 3,000 cycles (d) using tension tester.

In wearable energy harvesting, the most easily available energy source is used with clothing. Thus, energy can be harvested most efficiently from the human motion in daily life. Therefore, we fabricated a 45 mm × 45 mm woven structure by weaving several strands of the FSTENG proposed in our work, and analyzed its electrical characteristics (Figure 8(a)). As shown in Figures 8(b) and 8(c), maximum voltage and current values of 170 V and 6 μA are obtained, and these are six and ten times the voltage and current from one strand of the FSTENG. Thus, the charging performance can be improved by increasing the tribo-surface and efficiency. It is possible to manufacture various products such as smart clothes using the FSTENG, because FSTENG can be fabricated easily and it is possible to use it to supply energy easily to wearable devices.

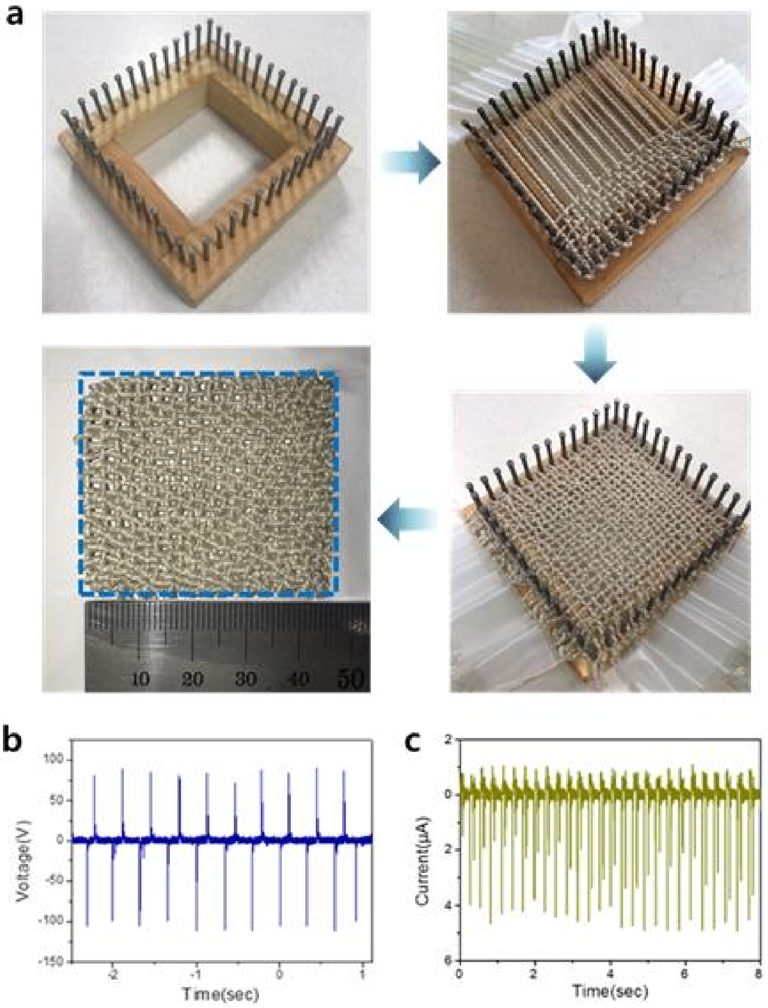

Figure 8. (a) Photograph of the FSTENG based woven structure (45 mm × 45 mm) and manufacture process. (b) Electrical output voltage and (c) current of the FSTENG.

Because the FSTENG based woven structure generates power from alternating current (AC), it is confirmed that a 2.2 μF capacitor is charged up to 1.2 V in 25 s using a bridge rectifier circuit that converts AC to direct current (DC) (Figure 9(a)). The capacitors can accumulate the charges until the positive and negative charges are parallel to the externally applied voltage. According to the formula $Q = CV$, the amount of charge stored in the 2.2 μF capacitor over 25 s is approximately 2.64 μC. The voltages measured at both ends of capacitors of various capacitances increase with time, and it is confirmed that the device successfully outputs the electric energy (Figure 9(b)).

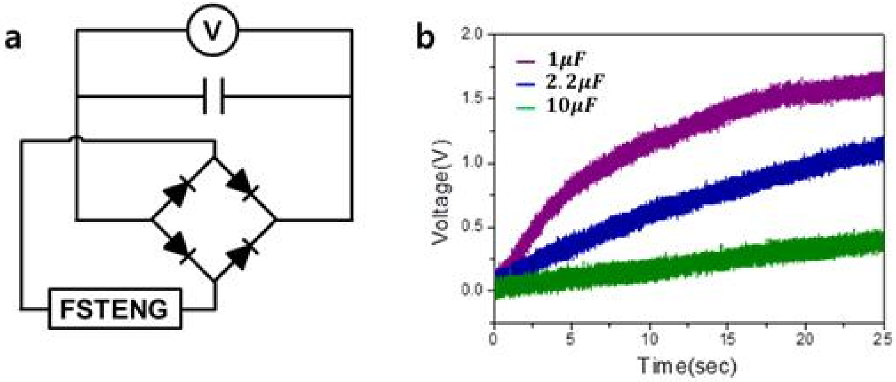

Figure 9. (a) Circuit diagram of a full-wave bridge rectifier and (b) charging curve of different capacitors.

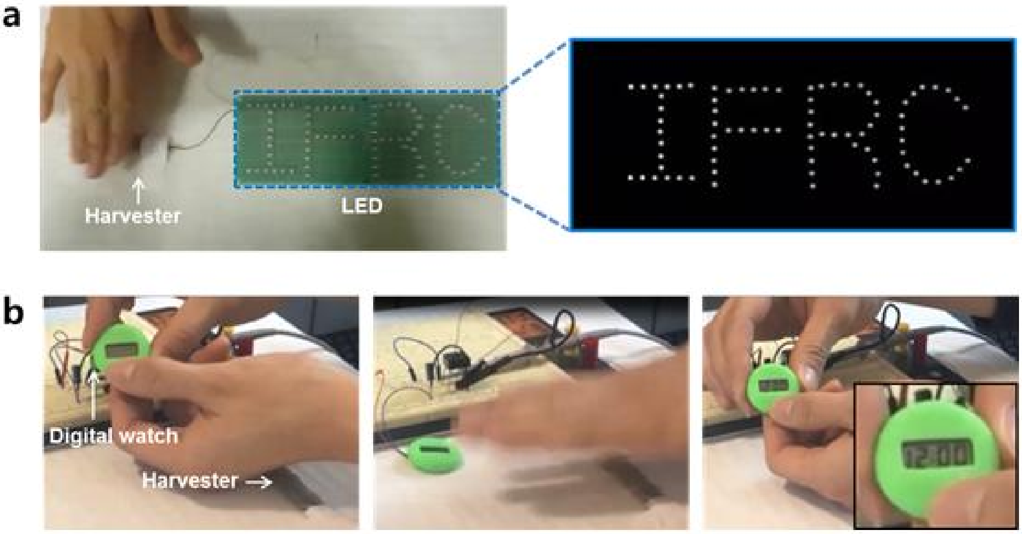

Figure 10. (a) Light of 82 white LEDs, visible in dark environment. (b) Digital watch lit up by the FSTENG based woven structure.

Through this outstanding power generation performance, we can confirm the practical applications. To verify the LED operation, we use a white commercial LED that requires a minimum voltage of 1.8 V and a current of 100 μA. Since the FSTENG based woven structure can generate enough electrical output voltage above 100 V, 82 LEDs are connected in series and driven. Figure 10(a) shows the letters “IFRC” formed by LED lights that are lit by contacting the human skin with an FSTENG based woven structure. In addition, the possibility of running an electronic watch through continuous skin contact is shown in Figure 10(b). Therefore, it is shown that it is easy to fabricate the proposed FSTENG as a woven structure and that energy can be generated by the triboelectric effect with human skin. The FSTENGs, as self-powered devices, can be used to supply energy to small electronic devices such as wearable devices, by efficiently converting the mechanical energy generated by human motion into electrical energy.

IV. Conclusion

A highly stretchable FSTENG was fabricated using silicone rubber and conductive thread. The advantages of the FSTENG proposed in this paper, when compared to the previously studied FTENGs, are: 1) 100 % high stretchability and flexibility; 2) demonstration of durability and stability without deterioration of output, even with repetitive external force; 3) suitability of being fabricated in two-dimensional large areas, which indicates that the power generation performance can be improved by widening the tribo-surface. In the proposed FSTENG, energy was generated from the contact between human skin and silicone rubber. The output voltage and current were 28 V and 0.56 μA, respectively. A woven structured (45 mm × 45 mm) energy harvester was fabricated using several strands of the FSTENG, and voltage and current of 170 V and 6 μA, respectively, were obtained through the contact with human skin. The fabricated FSTENG based woven structure proved that it could be used in self-powered systems, by driving 82 white commercial LEDs and an electronic watch. The proposed FSTENG is expected to provide a new solution for supplying power to wearable devices through human motion based on stretchable textiles of large dimensions.

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List of Publications

Paper

1) **Jiwon Park**, A Young Choi, Chang Jun Lee, Dogyun Kim and Youn Tae Kim, "Highly stretchable fiber-based single-electrode triboelectric nanogenerator for wearable devices", accepted to *RSC Advances* (2017)

2) A Young Choi, Chang Jun Lee, **Jiwon Park**, Dogyun Kim and Youn Tae Kim, "Corrugated textile based triboelectric generator for wearable energy harvesting", *Scientific Reports*, 7, 1-6 (2017)

3) Chang Jun Lee, A Young Choi, **Jiwon Park**, Hyeon Jun Sim, Changsoon Choi, Seon Jeong Kim and Youn Tae Kim, **"**Triboelectric generator for wearable devices fabricated using casting method", *RSC Advances*, 6, 10094-10098 (2016)

List of Publications

Conference

1) “Highly stretchable fiber-based single-electrode triboelectric nanogenerator for wearable devices”, **J. Park**, A. Y. Choi, C. J. Lee, D. Kim and Y. T. Kim, *MRS Fall Meeting*, November 2017

2) "Stretchable and flexible cylindrical-fiber-based triboelectric nanogenerator", D. Kim, A. Y. Choi, **J. Park**, C. J. Lee and Y. T. Kim, *IEEE NANO*, July 2017

3) "Flexible fiber-based triboelectric generator for self-powered sensors", **J. Park**, A. Y. Choi, C. J. Lee and Y. T. Kim, *IEEE Sensors*, October 2016

4) "Flexible two-ply yarn based generator for energy harvesting", **J. Park**, Y. S. Kim, C. J. Lee and Y. T. Kim, *MRS Fall Meeting*, November 2015

5) "Triboelectric generator made with corrugated stretchable textile for energy harvesting", Y. S. Kim, **J. Park**, A. Y. Choi and Y. T. Kim, *MRS Fall Meeting*, November 2015

List of Publications

Patent

1) Youn Tae Kim A Young Choi, Chang Jun Lee, **Jiwon Park**, Dogyun Kim, “Fibrous energy harvesting device having corrugated textile and clothes comprising thereof”, (2017. 06. 15, 15/623,437)

2) Youn Tae Kim, Chang Jun Lee, A Young Choi, **Jiwon Park**, Dogyun Kim, “Wearable energy generating apparatus”, (2016. 12. 05, 15/368,807)

3) 김윤태, 최아영, 이창준, **박지원**, 김도균, “주름 구조를 가진 섬유형 에너지 하베스팅 및 이를 포함하는 의류” (2016. 10. 31, 10-2016-0143542)

4) 김윤태, 이창준, 최아영, **박지원**, 김도균, “웨어러블 에너지 발생장치” (2016. 04. 27, 10-2016-00051302)