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Master's Degree Thesis

A study of Flexible Material-based Triboelectric Nanogenerators for Self-powered Systems

Graduate School of Chosun University
Department of IT Fusion Technology
Da Eun Kim

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자가 발전 시스템을 위한 유연성 소재 기반 마찰전기 나노제너레이터에 관한 연구

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This thesis is submitted to The Graduate School of Chosun University in partial fulfillment of the requirements for the Master's degree.

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This is to certify that the Master's Thesis of Da Eun Kim

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

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May 2022

Graduate School of Chosun University

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Acronyms

TENG	Triblelectric Nanogenerator
FP-TENG	Foldable Paper based Triboelectric Nanognerator
STENG	Sandwich structured textile based Triboelectric Nanognerator
PTFE	Polytetrafluoroethylene
DC	Direct Current
AC	Alternating Current
LEDs	Light Emitting Diodes

요 약

자가 발전 시스템을 위한 유연성 소재 기반 마찰전기 나노제너레이터에 관한 연구

김다은
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최근 웨어러블 디바이스의 사용과 친환경 에너지의 수요가 증가하면서 경제적으로 에너지를 수확할 수 있는 triboelectric nanogenerator (TENG)에 대한 연구가 많이 진행되고 있다. 본 논문에서는 주변에서 쉽게 구할 수 있는 재료를 사용하여 간단하게 제작할 수 있고 이를 다양한 분야에서 응용 가능한 flexible material 기반 나노발전기를 제안하였다. 특히 반복적인 외력 및 비틀거나 구부리는 변형에도 효율적으로 에너지를 생성할 수 있는 내구성 향상을 위한 방법을 제시하였다. 이를 위해, 본 논문에서는 flexible material 중 paper와 textile을 기반으로 한 TENG를 제작하고 물리적, 전기적 특성을 측정하여 각 parameter의 영향을 분석하였다. 제작된 소자는 상단과 하단의 마찰전기 대전체의 접촉-분리 과정에 의해 최대 572 mW/m^2의 전력을 생성하고, 접을수록 마찰 단면적이 넓어져 전기적 출력이 증가한다. 또한, 5000 사이클의 반복적인 푸싱 모션에도 출력 저하 없이 뛰어난 내구성을 나타내었고, 외부 전원 없이 제작된 소자의 출력만으로 전자시계판과 발광 다이오드의 작동을 성공적으로 시연하였다. 따라서 개발된 나노발전기는 소형 전자기기의 지속 가능하고 유망한 친환경 에너지원으로 활용될 것으로 기대되며, 향후 e-textile 및 self-powered electronics에서 실질적으로 적용 가능한 textile 기반 전원을 제공할 수 있을 것으로 기대된다.

I. Introduction

1.1. Research Background

1.1.1. Triboelectric nanogenerator

With the depletion of finite energy resources, such as coal and natural gas, and an increase in environmental issues, the market for eco-friendly electronic products is continuously growing. Therefore, energy-harvesting technology, which can harvest energy generated from natural energy sources, is in the spotlight.

Energy-harvesting technology produces electrical output from various mechanical energies, such as piezoelectric, electromagnetic, and triboelectric effects. Among them, the triboelectric nanogenerator (TENG), which is based on the combined effects of electrostatic induction and contact triboelectric charging, is a power source that can efficiently harvest energy by friction between two materials with different electron affinities **[1,2]**.

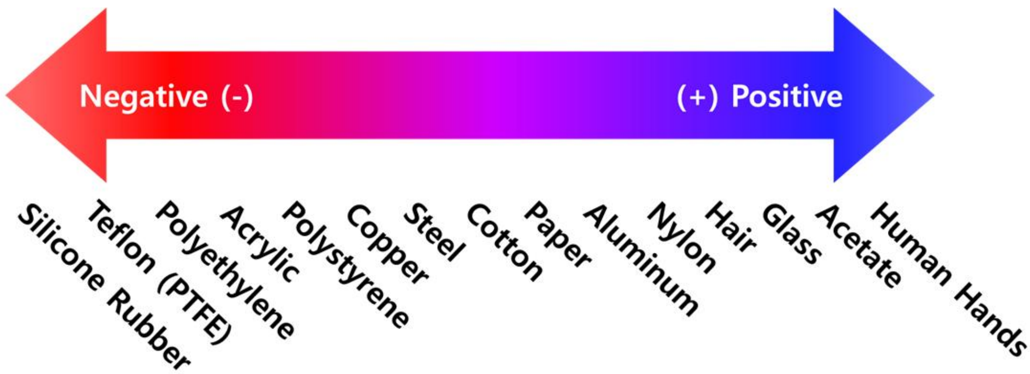

Figure 1.1. Triboelectric Series

Triboelectric charging refers to a phenomenon in which two different materials are charged positively and negatively, respectively, when they are separated by contact with each other by an external force. As shown in Figure 1.1, when different materials with relative positions in the triboelectric series come into contact with each other, a potential difference occurs and electric charges flow between the electrodes.

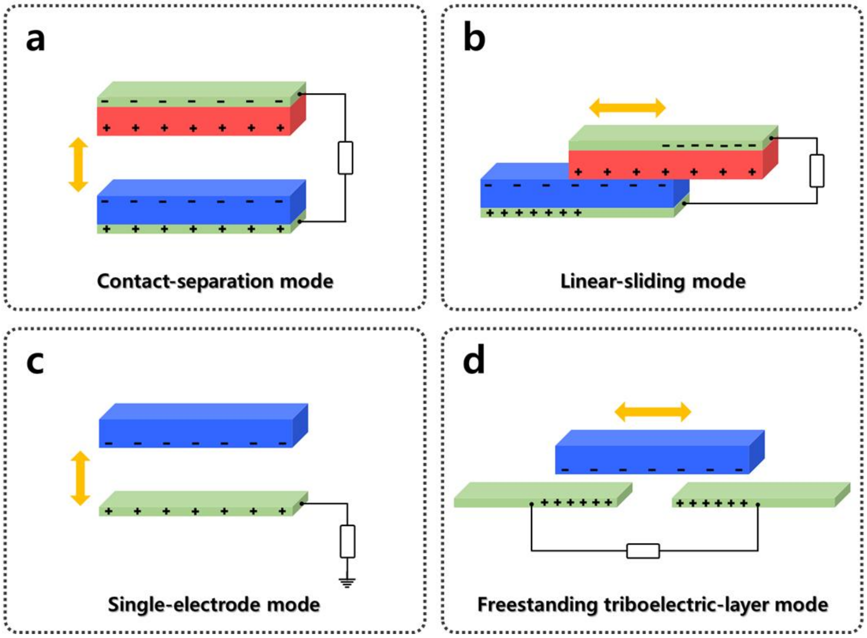

Figure 1.2. Four fundamental modes of TENG: (a) vertical contact- separation mode; (b) lateral sliding mode; (c) single-electrode mode; (d) freestanding triboelectric-layer mode

According to the contact of the friction material and the position of the electrode, the TENG is divided into four basic operating modes. As shown in Fig. 1.2(a), the TENG operating in the vertical contact separation mode is usually composed of two different friction materials, and generates an electrical output through the contact and separation of the friction materials. In this mode, TENG is attached to the sole of most shoes to generate electricity through the movement of people in daily life, walking or running, and it can be easily manufactured at low cost with a simple structure. However, if the external force applied to the TENG is irregular, it may affect the electrical output. The operation of the lateral sliding mode is similar to that of the vertical contact separation mode as shown in Fig. 1.2(b), but generates an electrical output based on the translational motion in the state where two different friction materials are not separated. This mode can improve the output performance due to the higher contact area than the vertical contact mode. As shown in Fig. 1.3(c), the single-electrode mode is the simplest mode requiring only one electrode, and the friction material can move freely without being constrained by movement. The single-electrode mode is suitable for portable and self-powered systems due to the disadvantage of lower output performance compared to other modes. Unlike other modes, the free-standing mode, in which two electrodes and friction materials are configured vertically/horizontally, does not need to maintain contact, so high electrical output and efficiency can be obtained. Fig. 1.3(d) shows the operating principle of the free-standing mode, which has the advantage that the friction material can move freely.

TENG can be used for various applications and has advantages including versatility in material selection and conversion efficiency. However, complex processes and expensive equipment are generally required to manufacture TENG. In addition, most of the existing TENGs generate energy only in the intentional vertical-contact mode, and have poor durability against twisting or bending deformation using metal materials. To compensate for this, a flexible material-based TENG should be developed that can be folded several times without deterioration in durability even under an external force.

1.1.2. Paper based triboelectric nanogenerator

Paper has distinct advantages, such as biocompatibility, flexibility, low cost, and easy disposal; therefore, it was used as a substrate for TENG [3,4]. Because paper is insulating, a conductive layer coating is required on the surface of the paper when it is used as the substrate for TENG. For this purpose, the paper surface was coated using metals such as Au or Ag, ink, and an airbrush [5-10]. In addition, acrylic, graphite, and PET were used as triboelectric materials for paper-based TENG [11-15].

Paper is foldable; thus, it can be manufactured in various shapes. Further, the more folded it is, the larger is the area to which the external force is applied; thus, the frictional surface area increases. However, folding was impossible because of the hard physical properties of the materials constituting most of the existing paper-based TENGs, or the method was to form electrodes and electrification layers on each frictional layer after folding the paper [16-23]. This structure was weak in durability to repeated external forces, and thus, the TENG could be easily damaged, and energy generation was temporary. To compensate for this, a paper-based TENG should be developed that can be folded several times without deterioration in durability even under an external force.

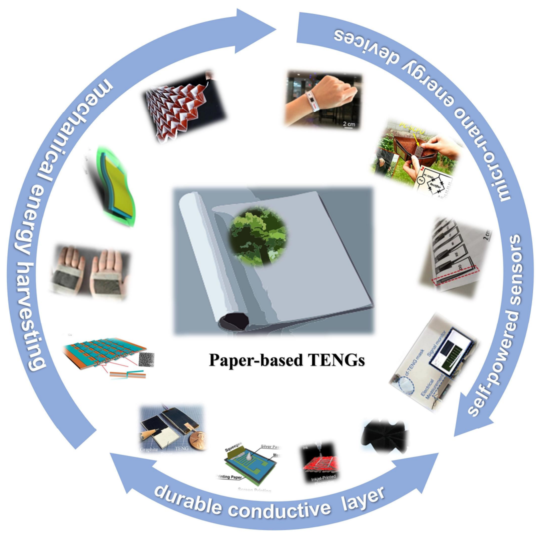

Figure 1.3. Typical preparation methods of Paper-based TENG [3]

1.1.3. Textile based triboelectric nanogenerator

A textile-based triboelectric nanogenerator (T-TENG) is a promising energy harvester for realizing wearable devices and self-powered smart clothing **[24,25]**. Textiles have distinct advantages, such as a wide selection of materials, flexibility, stretch, durability, permeability, lightness, and biocompatibility; therefore, they have been used as triboelectric materials for TENGs **[26]**. Textiles can efficiently harvest energy by friction with materials with different electron affinities and generate high power as the relative difference in electron affinity increases. T-TENGs can harvest large amounts of energy by moving the human body in daily life, such as shaking arms, walking, and bending arms and knees **[27]**. A T-TENG was coated with polyvinylidene fluoride (PVDF), PTFE, and polydimethylsiloxane (PDMS) for the increase in the frictional surface area **[28-30]**. In addition, the power generation performance of the T-TENG was improved by transforming the surface of the friction material into a line, cubic, or pyramid pattern structure by physical/chemical transformation. As the surface charge density increased according to the nanoscale patterned application, the electrical output of the TENG also increased. To improve the output of a textile-based TENG, metals with hard physical properties, such as Au, Ag, and Cu, have been used as relative triboelectric materials **[31]**.

However, most existing T-TENGs generate energy only in the intentional vertical contact mode and have poor durability against twisting or bending deformations when using metal materials **[32-33]**. In addition, disadvantages exist in the complicated manufacturing process and limited size of the manufactured TENG. Therefore, a T-TENG that can efficiently harvest energy in various modes, including the vertical contact mode, and whose durability does not deteriorate even with repeated shape deformation and the external force of the TENG, should be developed.

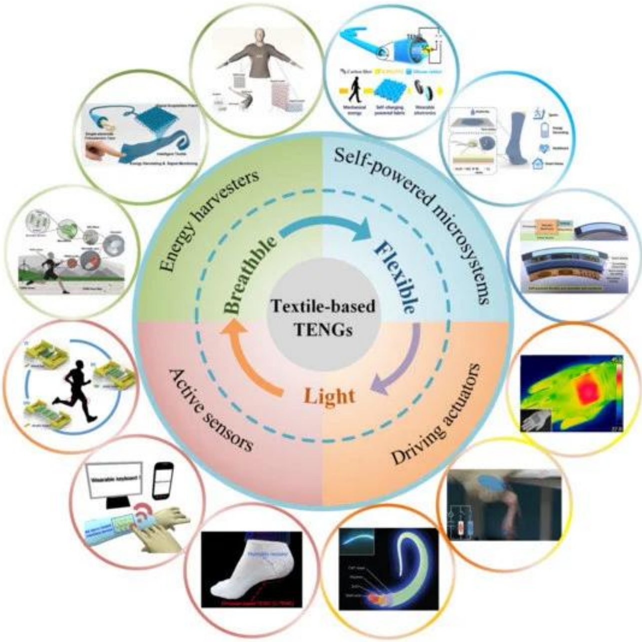

Figure 1.4. Typical preparation methods of Textile-based TENG **[26]**

1.1.4. Outline of this dissertation

As environmental issues arise, the market of eco-friendly electronic products is steadily growing, and many research on energy harvesting technology that can supply power efficiently are being conducted. In particular, as the demand for low-carbon and eco-friendly energy is increasing and the use of wearable devices is soaring, the triboelectric nanogenerator (TENG), which can economically harvest energy, is in the spotlight. TENG is attracting more attention than other generators due to its distinct characteristics such as simple structure and simple fabrication, variety of material choices, and high power generation efficiency.

TENG has a variety of cost-effective, flexible, lightweight, and environmentally friendly properties that can be used in a wide range of applications. However, most of them require complicated processes and expensive equipment, and their biodegradability and recyclability are limited. In addition, energy was generated only in the intentional vertical-contact mode, and the durability against repeated deformation was weak by using a metallic material for connecting the external electrode. To overcome this, materials can be easily obtained in daily life and flexible material-based TENGs that can be manufactured simply, are being studied.

In this study, TENG of sandwich structure using paper and textile among flexible materials was fabricated for eco-friendly and wearable energy harvesting. It can be utilized as a power source for wearable and self-powered portable devices. The proposed TENG uses Si-rubber/EcoFlex as a friction material to supplement elasticity and flexibility, and to secure durability against repeated external forces and deformations. In addition, by patterning the micro-structure of the crepe paper surface on the EcoFlex surface to increase the surface charge density, the power generation performance of TENG was improved. It can be transformed into various shapes and can be applied as a wearable device. This study is expected to be utilized as a promising power source for self-powered wearables/portable devices, and it can be applied as an educational tool to learn the principle of triboelectric generation.

In the first chapter, we will discuss the foldable paper based TENG that allow free deformation. However, folding was impossible because of the hard physical properties of the materials constituting most of the existing paper-based TENGs, or the durability was weak by forming electrodes and electrification layers on each frictional layer after folding the paper. The FP-TENG proposed in this study was fabricated a sandwich structure that improves durability and allows free deformation by combining flexible aluminum tape, polytetrafluoroethylene (PTFE), and Si-rubber with paper. The FP-TENG generates up to 572 mW/m^2 of power via contact-separation of the triboelectric electrified body at the top and bottom. The more the FP-TENG is folded, the triboelectric cross-sectional area increases, and thus, the electrical output increases. In addition, it shows excellent durability without signal degradation under 5,000 cycles of repeated pushing motions. Finally, the electrical characteristics and durability of the origami were analyzed, and the possibility of driving electronic devices for practical applications was confirmed. This study can be utilized as a sustainable and promising eco-friendly energy source for small electronic devices, and is expected to be applied as an educational tool to learn the power generation principle of triboelectric devices.

In the second chapter, We discuss a sandwich-structured textile-based TENG (STENG) with stretchability and full flexibility for wearable energy harvesting. To address the problems of the existing T-TENG, one side of the stretchable textile was coated with micropatterned Ecoflex, and the power generation performance was improved by patterning the Ecoflex surface based on the microstructure of the crepe paper surface. On the other side, an acetate cloth tape was attached to the stretchable textile as a serpentine structure; this serpentine structure enabled up to 50% expansion and contraction in the lateral direction. Through friction between the micropatterned Ecoflex and acetate, an STENG could harvest mechanical energy in the contact-separate, stretching, and rubbing modes. The STENG generated power of up to 361.4 V and 58.2 μA in the contact-separate mode, which is the result of 250% improvement in the output performance compared to that of a flat Ecoflex-based STENG without nanopatterns. In addition, we successfully demonstrated the operation of 135 LEDs using the STENG output without an external power source and presented excellent durability and potential applications. These findings could provide a textile-based power source with practical applications in future e-textiles and self-powered electronics.

II. Flexible sandwich-structured foldable triboelectric nanogenerator

2.1. Experimental details

2.1.1. Fabrication of the foldable paper based TENG

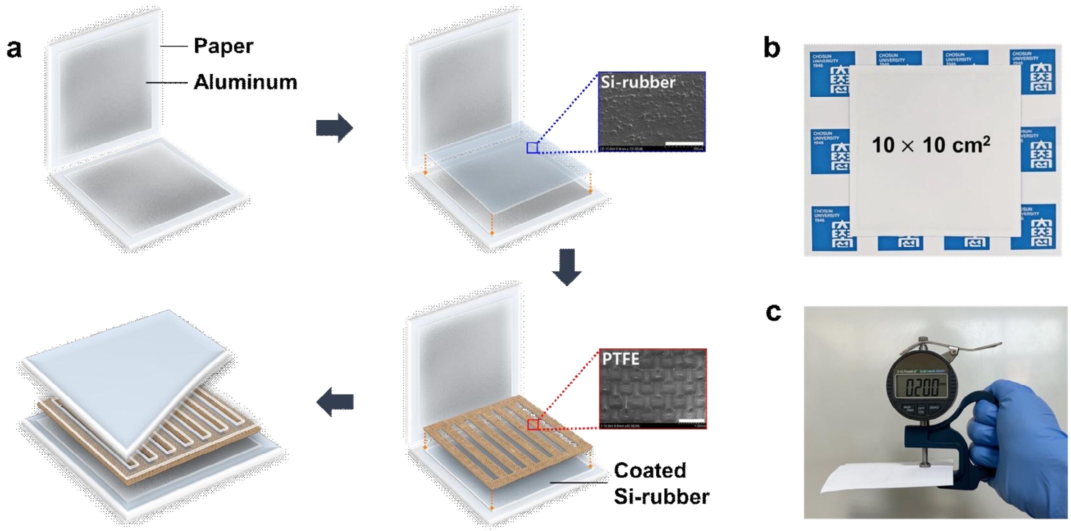

Figure 2.1. (a) Schematic of FP-TENG fabrication process. The inset shows FESEM images of the coated Si-rubber surface PTFE at a scale bar of 300 μm. (b) Photograph of FP-TENG with a surface area of 10 ~ 10 cm^2. (c) The thickness of FP-TENG

As shown in Figure 2.1(a), the FP-TENG is a sandwich-type structure constructed using top and bottom papers as substrates. The insulating coating of the paper was used by attaching a flexible aluminum tape. The aluminum (charge affinity of +10–30 nC/J) tape of the upper paper was regarded as an insulating material and a positive triboelectric material. A copper wire was used as the electrode of the positive triboelectric layer. Si-rubber and

PTFE (charge affinity of -72 nC/J and -190 nC/J, respectively) of the lower paper were considered as negative triboelectric materials. To coat the Si-rubber, an aluminum tape was attached to the paper and coated with the Si-rubber solution. The electrode of the negative triboelectric layer was the aluminum tape attached to the paper. When the Si-rubber hardens to a certain thickness, PTFE is attached to a striped pattern with uniform spacing. Because Si-rubber and PTFE have a high negative charge affinity according to the triboelectric series, they can generate a large amount of triboelectric charge in the material, thereby improving the power generation performance of the TENG. Figures 2.1(b) and (c) show the FP-TENG fabricated with dimensions of 10 × 10 cm^2 and constant thickness in the range of 20 ± 5 mm, respectively. Because the FP-TENG comprises flexible materials including paper, it can be deformed and folded freely.

2.2. Results and discussion

2.2.1. Working mechanism

Figure 2.2 shows the working mechanism of FP-TENG when it is operated in the vertical contact-separation mode. Initially, no charge is present between the electrode and contact surface. When an external force is applied to FP-TENG, the aluminum at the top and PTFE/Si-rubber at the bottom come into contact and are charged positively and negatively, respectively (Fig. 2.2 (i)). When the force is released, the two triboelectric materials separate and return to their original shapes, and the opposite charges in each material are rapidly separated by voids that form a dipole moment. Electrons flow from the bottom to the top electrode until a potential difference occurs between the top and bottom electrodes, and the charges accumulate (Fig. 2.2 (ii)). When they are completely separated and reach an equilibrium state, there is no movement of electrons between the two substances (Fig. 2.2 (iii)). When an external force is applied again, the dipole moment and potential difference decrease, causing electrons to flow from the top to the bottom electrode in the reverse direction (Fig. 2.2 (iv)). In other words, the contact-separation process between aluminum and PTFE/Si-rubber generates an instantaneous alternating current through an external load.

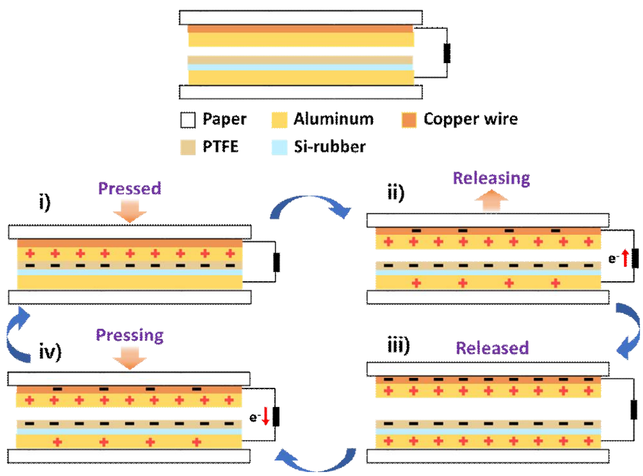

Figure 2.2. Working mechanism of FP-TENG in the vertical contact-separation mode

2.2.2. Output performance and stability

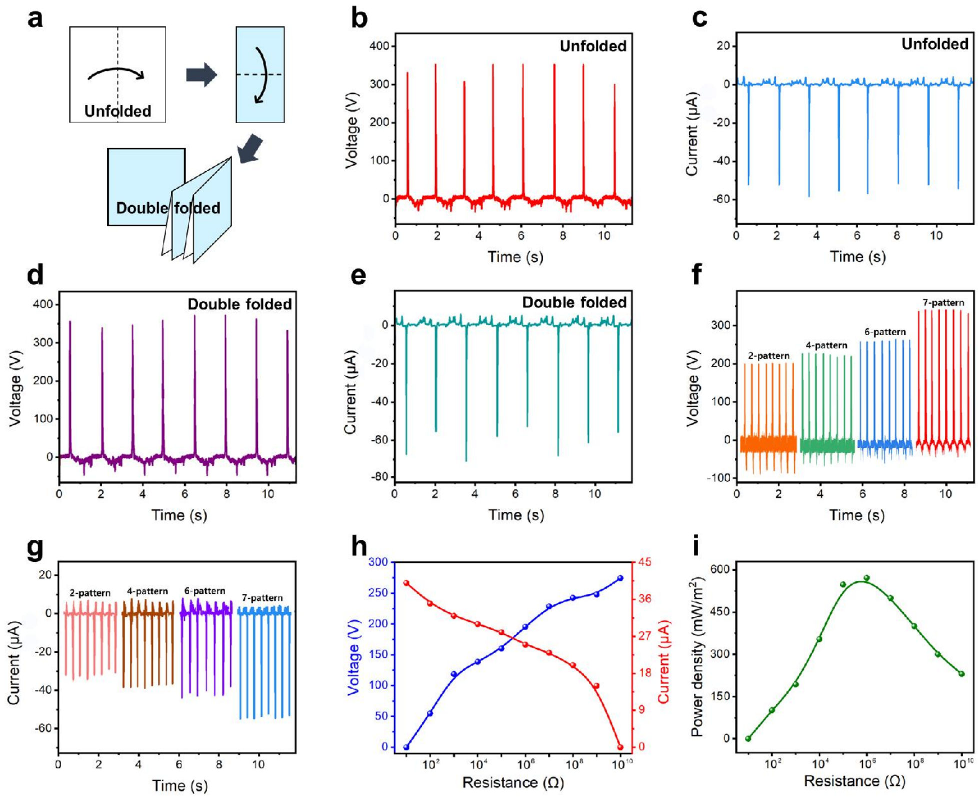

Figure 2.3. (a) Schematic of the unfolded and double-folded FP-TENG. Comparison of output voltage and current for: (b and c) unfolded and (d and e) double-folded FP-TENG, (f and g) output voltages and currents for different PTFE patterns, (h) Measured voltage and current, and (i) power density across various loading resistors

As shown in Figure 2.3, the electrical performance of the FP-TENG (area: 10 × 10 cm^2) was evaluated. The output voltage was measured using an oscilloscope (MSO9104A) with an internal impedance of 1 MΩ, and the output current was measured using a precision source/measurement device (B2911A). Because the FP-TENG comprises a flexible material, it can be folded, as shown in Figure 2.3(a). The more it is folded, the wider the cross-sectional area to which the force is applied. As shown in Figs. 2.3(b) and (c), when a force of approximately 1 kgf was applied to the unfolded FP-TENG, a voltage of 386 V and a current of 60 μA were measured. As shown in Figs. 2.3(d) and e, in the same experimental environment, the double-folded FP-TENG had a voltage of 456 V and a current of 75.8 μA. As shown in table 2.1, the output voltage and current values of our proposed FP-TENG are higher than those of previously reported paper-based TENG. As the frictional surface area increased when the paper was folded, the double-folded FP-TENG exhibited more than 1.5 times the output performance. Because PTFE and Si-rubber are negative triboelectric materials, the output was compared according to the number of PTFE patterns to obtain the optimal output performance.

Table 2.1. Compared with the existing triboelectric nanogenerator using paper

Ref	Paper as a substrate	Materials		Typical performance	
		Electrode	Triboelectric	Isc	Voc
[8]	Paper based TENG	Conductive ink	PTFE tape	72μA	218V
[9]	Milk-based paper TENG	Conductive ink	Cardboard, PTFE	43.6μA	292.5V
[11]	Crepe cellulose paper/ NCM based TENG	Copper	Crepe cellulose paper, NCM	45μA	103.2V
[13]	Simple/low cost TENG	Copper wire	Graphite, PET	75.6μA	69.8V
[15]	Teflon/vitamin B1 powder based TENG	Copper foil	Vitamin B1 powder, teflon tape	46.3μA	340V
[21]	Paper based TENG (Kirigami pattern)	Copper	FEP	2.64nA	7.32V
[34]	Penciling a TENG on paper	Copper	Graphite, teflon tape	3.75μA	85V
This work	Foldable paper based TENG	Copper, Aluminum	Aluminum, PTFE/Si-rubber	75.8μA	456V

Figures 2.3(f) and (g) show the output voltage and current values of the FP-TENG fabricated by varying the number of PTFE stripe patterns, respectively. The output voltage and current for two, four, six, and seven patterns of PTFE were measured, and we see that the output increased as the number of patterns increased. Therefore, FP-TENG was

fabricated with 7 patterns of PTFE. To measure the power density of FP-TENG, load resistance values of 10–10^{10} Ω were connected to the electrode, and the output was measured for each case. As shown in Figure 2.3(h), when the load resistance increased, the output voltage increased initially and then became saturated. On the contrary, the output voltage is reduced by Ohm's law. The output power density was calculated by the formula $P = I^2R$. The maximum output power density can be obtained when the load resistance is equal to the internal impedance of FP-TENG. As shown in Fig. 2.3(i), a maximum power density of 572 mW/m^2 was observed at a load resistance of 10^6 Ω.

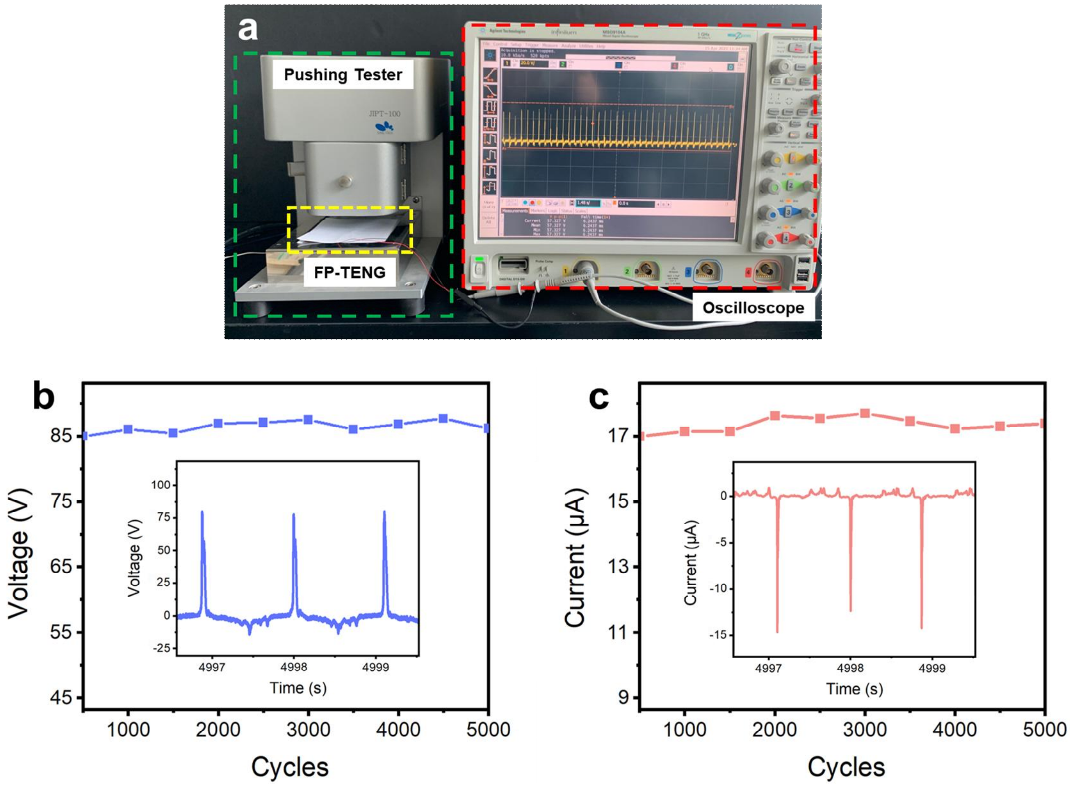

Figure. 2.4. (a) Photograph of the test setup using a pushing tester. (b and c) Durability and stability tests under 5000 cycles of contact-separation motions

Because paper can be relatively easily wrinkled or torn, it is important to secure durability and stability when used as a frictional material or substrate for TENG. As shown in Fig. 2.4(a), the output voltage and current values from repetitive contact-separation motions in the FP-TENG were measured using a pushing tester. As shown in Figure 2.4(b), by applying a force of approximately 0.1 kgf for 5000 cycles, the output voltage showed an error range of up to 1.6 V. In addition, as shown in Figure 2.4(c), the output current showed a low error range of up to 0.7 μA in the same experimental environment. Thus, the FP-TENG exhibited excellent mechanical durability and stability since it had a constant signal output without significant degradation of the electrical output.

2.2.3. Practical applications

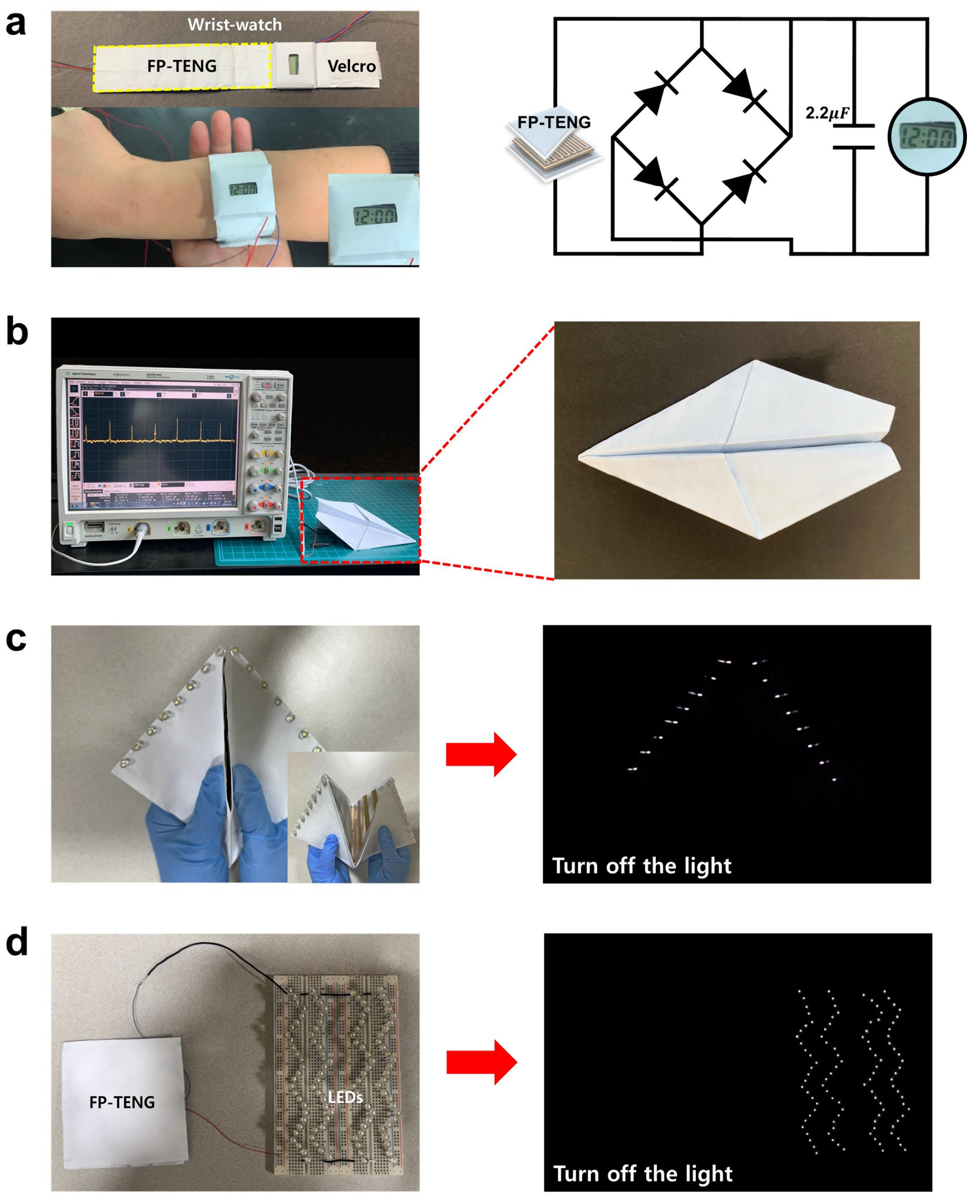

Figure. 2.5. (a) Demonstration of continuously driving a wristwatch using FP-TENG and schematic of a full-wave rectifier circuit, (b) Output voltage of FP-TENG folding under pushing motion, (c) LEDs powered by FP-TENG folding under folded and unfolded motions, and (d) Lighting of 96 LEDs by hand tapping and visible in a dark environment

As shown in Figure 2.5, the applications of FP-TENG were demonstrated by operating a wristwatch and turning on LEDs. As shown in Figure 2.5(a), the FP-TENG was manufactured as a watch band and connected to an electronic watch panel such that it could be worn on the wrist. The FP-TENG watchband could continuously drive the watch when an external force was applied. It supplied power to the electronic watch face by hand tapping. The watch was operated by connecting a 2.2 μF capacitor and bridge circuit. The alternating current output by hand tapping was rectified into direct current (DC) by the bridge circuit. In addition, as shown in Figure 2.5(b), the origami was made into a pear shape owing to the foldable characteristics of FP-TENG, and voltage was generated by an external force. Furthermore, the origami was made as shown in Figure 2.5(c) and LEDs were connected in series to turn on the LED light by folding and unfolding motions. Finally, as shown in Figure. 2.5(d), the FP-TENG operated up to 96 LEDs under an external force. Thus, we observe that the FP-TENG generates sufficient power from external forces to drive electronic clocks and LEDs, and its flexible characteristics make origami possible. Therefore, it can be used as a promising power source for eco-friendly wearables and portable devices and can be applied as an educational tool to learn the power generation principle of triboelectric devices **[35]**.

III. Fully Stretchable Sandwich Structured Textile-based Triboelectric Nanogenerator

3.1. Experimental details

3.1.1. Fabrication of the sandwich-structured textile based TENG

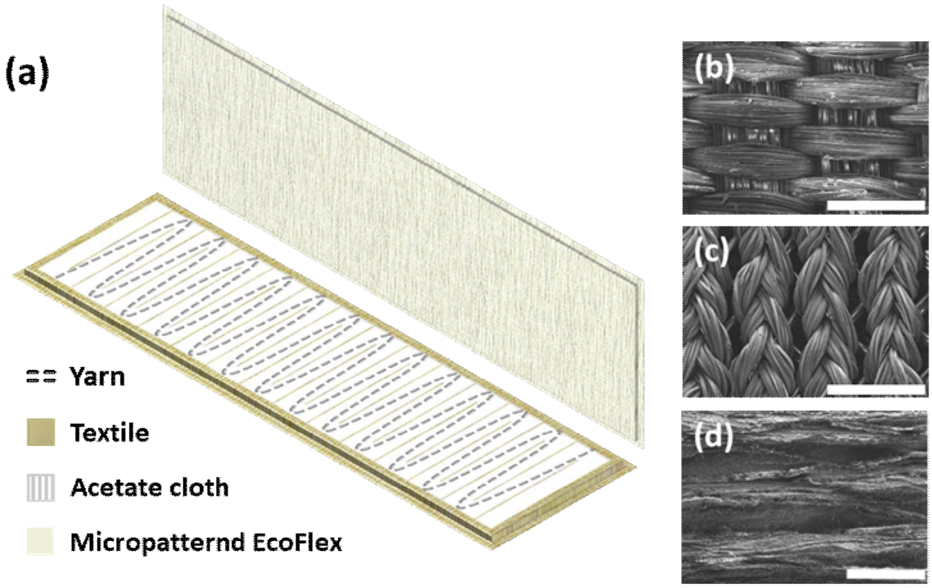

Figure 3.1. (a) Schematic of a sandwich-structured textile-based TENG (STENG). (b) Field emission scanning electron microscopy (FESEM) images of the acetate cloth and (c) textile at a scale bar of 500 μm. (d) FESEM image of the micropatterned Ecoflex at a scale bar of 1 mm

As shown in Figure 3.1, the STENG had a sandwich-type structure made of two stretchable textiles, and all flexible materials were used. One side of the stretchable textile was coated with a micropatterned Ecoflex and used as the negative triboelectric material.

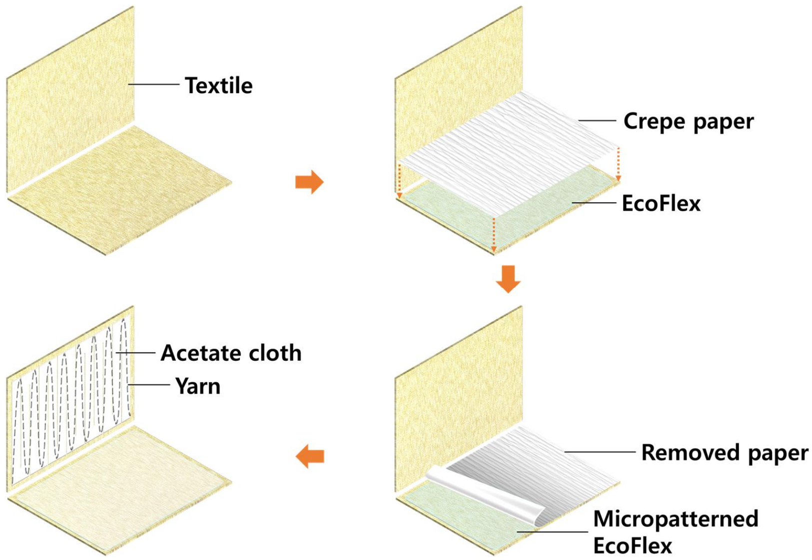

Figure 3.2. Schematic of the STENG fabrication process. STENG, with a surface area of 5 × 10 cm^2

The power generation performance was improved by patterning the Ecoflex surface based on the microstructure of the crepe paper surface (Figure 3.2). To increase the surface charge density during contact charging, a nanoscale microstructure was patterned on the Ecoflex surface. The micropatterned Ecoflex was cured to a constant thickness of 60 ± 5 mm. A copper wire was used as the electrode of the triboelectric layer. On the other side, an acetate cloth tape was attached to the stretchable textile as a serpentine structure and was used as the positive triboelectric material. The serpentine structure enabled up to 50% expansion and contraction in the lateral direction. The top of the acetate cloth was sewn with yarn to generate an air gap, which can generate energy even in the stretching mode. That is, through friction between the micropatterned Ecoflex and acetate, the STENG harvested mechanical energy in contact-separate, stretching, and rubbing modes. In addition, because all the materials used were flexible, the structure was free from deformation. The total area of the STENG was 5 × 10 cm^2 and thickness was 135 ± 5mm. Because the STENG used only flexible and stretchable materials, electrical outputs could be generated in various modes.

3.2. Results and discussion

3.2.1. Output performance

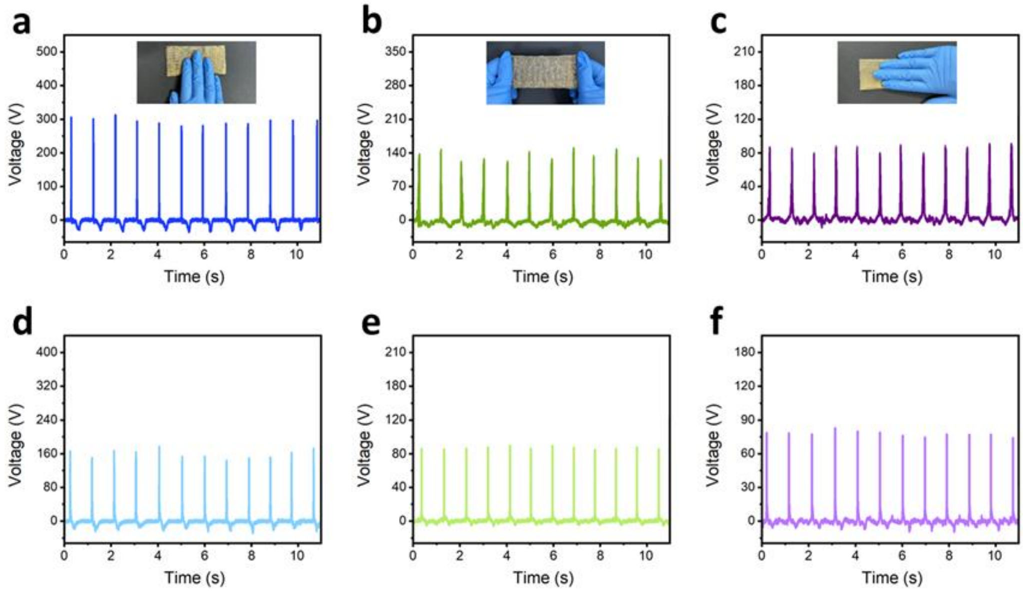

Figure 3.3. Comparison of the electrical output power performance of the three types of STENG; (a) contact-separation (361.4 V), (b) stretchable (166.1 V), and (c) rubbing (119.5 V) mode comparison of three-mode STENG; (d-f) the electrical output power performance of the three types of non-patterned STENG

As shown in Figure 3.3, the electrical performance of the STENG (area, 5 × 10 cm^2) was evaluated. A digital oscilloscope with an internal impedance of 1 MΩ was used to measure output power. An output of 361.4 V in the vertical contact mode, 166.1 V in the stretching mode, and 119.5 V in the rubbing mode were observed (Figures 3.3a-c) for the STENG. As shown in Figs. 3.3d-f, in the same experimental environment, an output of 214.7 V in the vertical contact mode, 94.4 V in the stretching mode, and 85.7 V in the rubbing mode were observed for the flat Ecoflex-based STENG without nanopatterns.

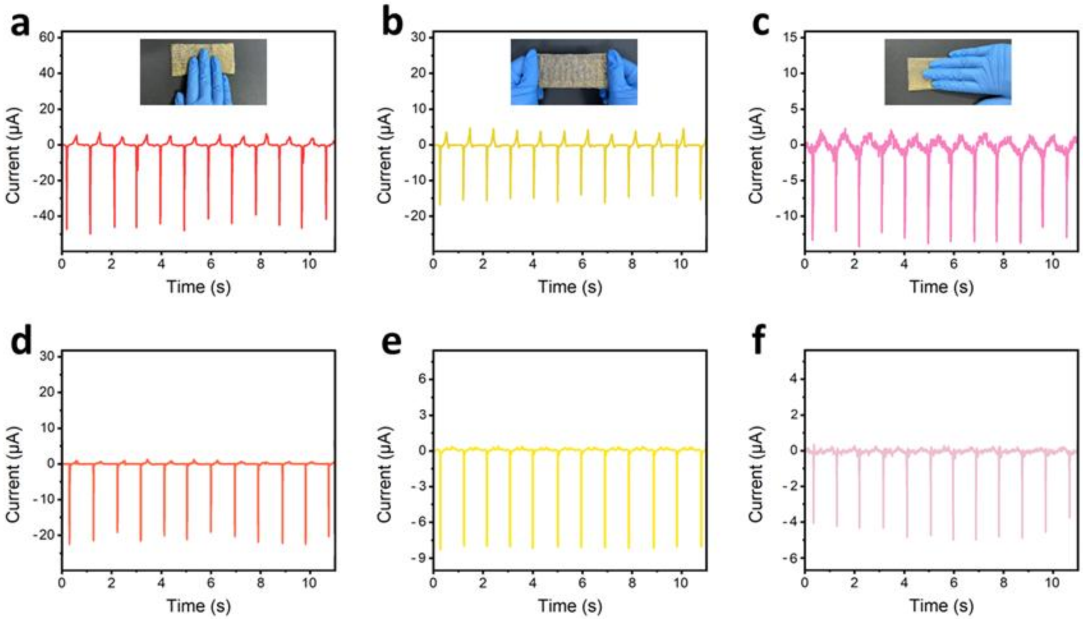

Figure 3.4. Comparison of the electrical current performance of the three types of STENG; (a) contact-separation (58.2 μA), (b) stretchable (23 μA), and (c) rubbing (17 μA) mode comparison of three-mode STENG; (d-f) the electrical output power performance of the three types of non-patterned STENG

The output current of STENG was measured using a precision source/measurement device. An output current of 58.2 μA in the vertical contact mode, 23 μA in the stretching mode, and 17 μA in the rubbing mode were measured (Figure 3.4a-c) for the STENG. As shown in Figs. 3.4d-f, in the same experimental environment, an output of 25 μA in the vertical contact mode, 8 μA in the stretching mode, and 4.2 μA in the rubbing mode were observed for the flat Ecoflex-based STENG without nanopatterns.

This was the result of a 250% improvement in the output performance compared to that of the flat Ecoflex-based STENG without nanopatterns. Because the STENG used flexible materials, including textiles, output power could be obtained in the vertical contact, stretching, and rubbing modes. In addition, as shown in Table 1, the proposed STENG exhibited a better output performance than the previously reported textile-based TENG.

Table 3.1. Compared with the existing triboelectric nanogenerator using textile

Number	Textile as a friction layer	Materials		Typical performance	
		Electrode	Triboelectric	Isc	Voc
[28]	Electronic-Textiles Based TENG	AgNFs	PTFE, embroidery	72μA	270V
[29]	Flexible woven TENG	Ag	PDMS, PVDF	5.39μA	105.5V
[30]	Nanopatterned Textile-Based TENG	Ag	PDMS, ZnO	65μA	120V
[31]	PVC/Nylon grating structure TENG	Ag	PVC HTV, Nylon	4.41μA	238V
[33]	Enhanced flexible TENG	AgNWs	PTFE/PDMS, Nanofibers	9.5μA	275V
[37]	Large-Area Textile-Based TENG	ACF	Ag, PDMS	16μA	160V
This work	Sandwich structured textile-based TENG	Copper	EcoFlex, acetate, yarn	58.2μA	361.4V

3.2.2. Stability

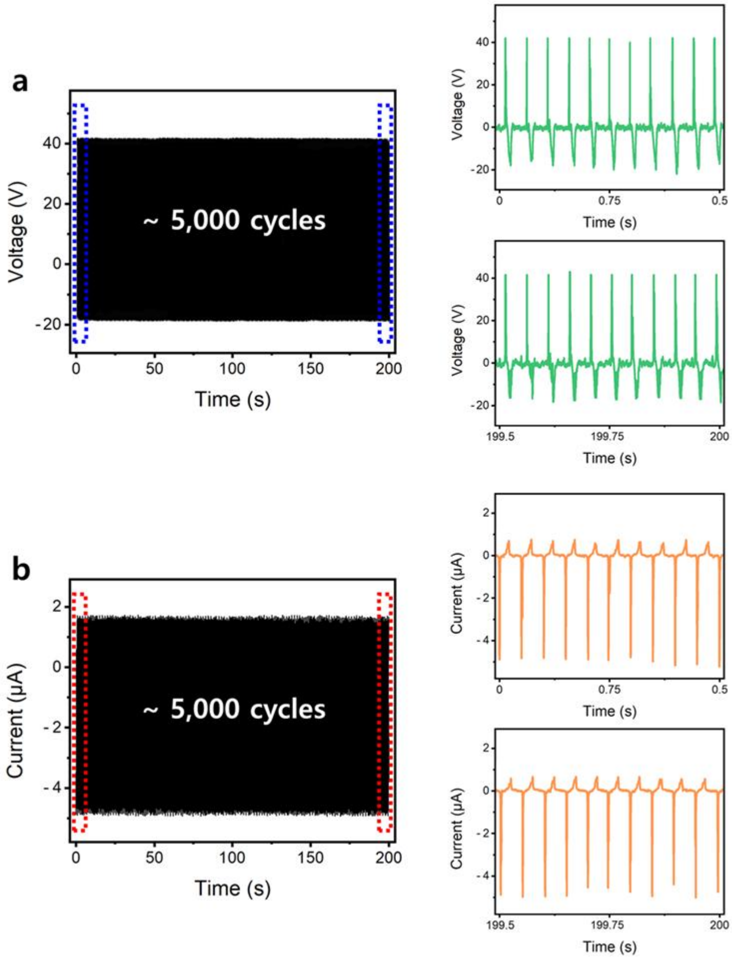

Figure. 3.5. Mechanical durability test for the FS-TENG under 5000 cycles with the first and last 0.5s waveforms enlarged. (a) Output voltage and (b) Current

As shown in Figure 3.5, the output voltage and current values from repetitive contact-separation motions in the STENG were measured using a pushing tester. As shown in Figure 3.5a, by applying a force of approximately 0.1 kgf for 5000 cycles, the output voltage showed an error range of up to 0.6 V. In addition, as shown in Figure 3.5b, the output current showed a low error range of up to 0.4 μA in the same experimental environment. Thus, the STENG exhibited an excellent mechanical durability and stability because it had a constant signal output without significant degradation of the electrical output.

3.2.3. Practical application

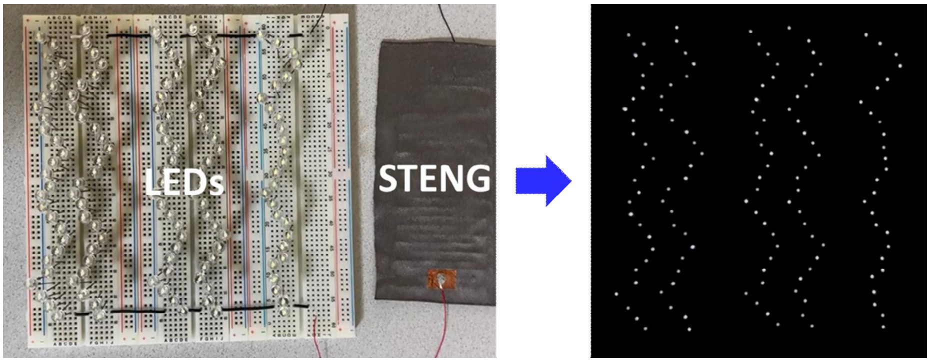

Figure 3.6. Commercial 135 light-emitting diodes (LEDs) directly lighted and visible in a dark environment by hand tapping.

As shown in Figure 3.6, the applications of the STENG were demonstrated by operating a wristwatch and turning on LEDs. These findings could provide a textile-based power source with practical applications in future e-textiles and self-powered electronics.

IV. Conclusion

In this study, a triboelectric nanogenerator with a new structure using paper and textile among flexible materials was developed. The developed TENG can be applied to wearables and portable small electronic devices by harvesting energy through various transformations. Only highly flexible materials were used to improve the durability of the TENG.

First, we fabricated a sandwich-structured foldable paper-based triboelectric nanogenerator (FP-TENG) that used paper as the substrate, PTFE/Si-rubber as the negative triboelectric layer, and aluminum as the positive triboelectric layer. The FP-TENG generated up to 572 mW/m^2 of power, and owing to its flexibility, the frictional surface area increased when it was folded, resulting in an increase in the output by a factor of 1.5. It has proven its excellent durability without degrading the output during 5000 cycles of pushing motion. To evaluate the performance of FP-TENG, a wristwatch and 96 LEDs were operated using the generated power, and the electrical output performance using origami was shown. The new structure and practical application potential of environmentally friendly TENG were demonstrated using paper, a natural material.

Second, We fabricated an STENG with stretchability and full flexibility for wearable energy harvesting. Through friction between the micropatterned Ecoflex and acetate, STENG harvested mechanical energy in contact-separate, stretching, and rubbing modes. An output of 361.4 V and 58.2 μA in the contact-separate mode, 166.1 V and 23 μA in the stretching mode, and 119.5 V and 17 μA in the rubbing mode were observed. This is the result of a 250% improvement in the output performance compared to the that of the flat Ecoflex-based STENG without nanopatterns (214.7 V, 25 μA). The STENG exhibited an excellent durability without degrading the output during 5000 cycles of pushing motion. In the vertical contact, stretching, and rubbing modes, up to 135 LEDs were operated with the STENG output alone. These findings could provide a textile-based power source with practical applications in future e-textiles and self-powered electronics.

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List of Publications

Paper

1) **Da Eun Kim**, Jiwon Park and Youn Tae Kim, Flexible Sandwich-structured Foldable Triboelectric Nanogernerator based on Paper Substrate for Eco-friendly Electronic Device, submitted to Energies

2) **Daeun Kim**, Jiwon Park and Youn Tae Kim, "Fully stretchable textile based triboelectric nanogenerator", will be submitted to Energies

3) Jiwon Park, **Daeun Kim** and Youn Tae Kim, Soft and transparent triboelectric nanogenerator based E-skin for wearable energy harvesting and pressure sensing, Nanotechnology, 32, 385403 (2021)

4) Jiwon Park, **Daeun Kim** and Youn Tae Kim, Ultra-stretchable on-body-based soft triboelectric nanogenerator for electronic skin, Smart Materials and Structures, 29, 115031 (2020)

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Conference

1) "Fully Stretchable Textile-based Triboelectric Nanogenerator with a Crepe Paper-induced Surface Microstructure", **D. Kim**, J. Park and Y. T. Kim, 2022 MRS Fall Meeting & Exhibit, November 2022.

1) "Triboelectric nanogenerator based E-skin for wearable energy harvesting and pressure sensing", J. Park, **D. Kim** and Y. T. Kim, IEEE NANO, July 2021.

2) "Foldable paper based triboelectric nanogenerator for green energy harvesting", **D. Kim**, J. Park and Y. T. Kim, IEEE NANO, July 2021.

3) "On-skin based soft triboelectric nanogenerator for electronics skin", J. Park, **D. Kim** and Y. T. Kim, IEEE-NEMS, September 2020.

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Patent

1) 김윤태, **김다은**, 박지원, “종이기반 마찰전기 발전 소자 및 이의 제조방법”, 10-2022-0009366, 2022

2) Youn Tae Kim, Ji Won Park, **Daeun Kim**, “Body attachable triboelectric generating device and manufacturing method thereof”, US 17/534,044, 2021

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Abstract

A study of Flexible Material-based Triboelectric Nanogenerators for Self-powered Systems

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Recently, as the use of wearable devices and the demand for eco-friendly energy have increased, many studies have been conducted on triboelectric nanogenerators (TENGs), which can economically harvest energy. In this paper, we proposed a flexible material-based nanogenerator that can be easily fabricated using readily available materials and can be applied in various fields. In particular, a method for improving durability that can efficiently generate energy in spite of repeated external force and twisting or bending deformation was presented. To this end, in this paper, TENG based on paper and textile among flexible materials was fabricated and the effects of each parameter were analyzed by measuring the physical and electrical properties. The fabricated device generates power of up to 572 mW/m^2 by the contact-separation process of the triboelectric electrified body at the top and bottom, and as it folds, the friction cross-sectional area becomes wider, increasing the electrical output. In addition, it exhibits excellent durability without degrading output even in the repetitive pushing motion of 5000 cycles. In addition, we successfully demonstrated the operation of the electronic clock panel and the light emitting diode only with the output of the manufactured device without an external power source. Therefore, the developed nanogenerator is expected to be used as a sustainable and promising eco-friendly

energy source for small electronic devices, and is expected to provide a textile-based power source that can be practically applied in e-textile and self-powered electronics in the future.

감사의 글

본 논문이 완성되기까지 많은 분들의 도움과 격려가 있었습니다. 제가 올바른 길로 갈 수 있도록 누구보다도 많은 도움을 주시고, 언제나 저의 부족한 점을 세심히 따뜻한 손길로 지적해주신 김윤태 교수님께 진심으로 감사드립니다. 또한 바쁘신 와중에도 논문에 대해 유익한 말씀과 충고를 주신 반성범 교수님과 최현식 교수님께 감사드립니다.

석사과정 동안 여러모로 서툰 저에게 언제나 따뜻한 격려와 조언을 해주신 정재효 교수님, 박지원 박사님, 신시호 박사님께 감사드립니다. 연구를 진행하면서 어려움에 부딪혀 낙심한 순간들이 많았지만 포기하지 않도록 이끌어주셔서 감사드립니다.

지난 2년이 넘는 시간 동안, 저에게 많은 도움을 주신 인공지능 헬스케어연구센터 연구원분들에게 감사의 말씀을 전합니다. 석사과정 동안 가벼운 고민거리라도 진지하게 생각해 주고 격려해준 강민구, 장경가 연구원에게 고마운 마음을 전합니다.

마지막으로 항상 저의 의견을 존중해주시고, 제가 바른 길로 나아갈 수 있도록 늘 곁에서 든든하게 지켜주신 부모님께 감사드리며, 이 작은 결실을 바칩니다.

2022년 6월

김다은 올림