

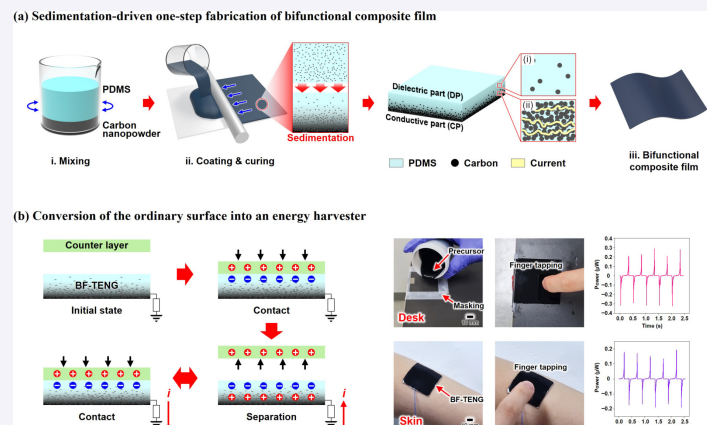
Sedimentation-driven one-step fabrication of bifunctional single-layered triboelectric nanogenerator from sol-state composite precursor

Yoonsang Ra, Dongik Kam, Sunmin Jang, Sumin Cho, Donghan Lee, Dongwhi Choi✉

Cite this article: Ra Y, Kam D, Jang J, et al. *Friction* 2025, 13(2): 9440918. <https://doi.org/10.26599/FRICT.2025.9440918>

ABSTRACT: Although the triboelectric nanogenerator (TENG) has been highlighted as a promising mechanical energy harvester, the requirement of stacking the two individual layers, contact and conductive layers, has been ball and chain around the ankle of unleashing potential and an advantage of TENGs in their application expansion and commercialization. Herein, one-step fabrication of a single-layered bifunctional composite film-based TENG (BF-TENG) driven by the sedimentation of a sol-state precursor is proposed for the extremely facile conversion of various ordinary items into energy harvesters. The BF-TENG consists of the polydimethylsiloxane (PDMS) matrix and a carbon nanopowder filler, and it includes both the dielectric part (DP) and conductive part (CP) in one single layer. The electrical percolation threshold of the incorporated concentration of carbon, I_{C_c} , for CP to act as a passage through which induced charges move in BF-TENGs is determined to be 1.0 wt%. The degree of carbon sedimentation in developing the proposed composite can be controlled by the curing speed and the probability of a crosslinking reaction. The maximum peak power is approximately $0.093 \mu\text{W}$ when the contact surface area is 78.5 mm^2 ; the contact frequency is 8 Hz, and the connected load resistance is $9 \text{ M}\Omega$. Based on these results, the electrical performance of BF-TENGs in response to various physical stimuli is characterized considering the mechanical energy sources available in daily life. Then, converting ordinary surfaces such as desks and human skin into BF-TENGs through a single coating procedure and harvesting energy to power an electric device are demonstrated as a proof-of-concept.

KEYWORDS: triboelectric nanogenerator; one-step fabrication; sedimentation; bifunctional composite film



1 Introduction

With the rapid development of portable and wearable electronic devices, energy harvesting technology has been highlighted as one of the promising strategies to supply electrical energy to electronic devices. Among the various energy harvesting technologies, triboelectric nanogenerators (TENGs) are attracting attention because of their unique advantages, such as diverse options for material selection and facile working mechanisms [1–7]. TENGs can save various types of mechanical energies, which are daily wasted, and convert them easily into the electrical energy we need [8–15]. The operation mechanism of TENGs is based on the sequential contact and separation of two different material surfaces [16–23]. As the surfaces of two different materials come in contact with each other, electric charge pairs are spontaneously

generated at the interface by the triboelectric effect. Therefore, the number of generated charge pairs depends on the difference in the work functions of the two materials. Then, as the two material surfaces separate from each other, the charge pairs are broken, and the net charges remaining on each surface of the materials create an electric field. If a conductive layer is located beneath the contact surface and is wired in this step, opposite electric charges are induced in the conductive layer by the charge induction effect. This inductive movement of electric charges appears in the form of a peak-type electric current, and it can be collected, stored, and utilized to provide electricity to electronic devices [24–27].

As can be assumed from the above-explained working mechanism, a TENG requires the presence of two essential layers, the contact layer and the conductive layer [28–31]. The contact layer comes into contact with the surface of another material and

Department of Mechanical Engineering (Integrated Engineering Program), Kyung Hee University, Gyeonggi 17104, Republic of Korea.

✉ Corresponding author. E-mail: dongwhi.choi@khu.ac.kr

Received: December 23, 2023; Revised: March 25, 2024; Accepted: April 14, 2024

© The Author(s) 2025. This is an open access article under the terms of the Creative Commons Attribution 4.0 International License (CC BY 4.0, <http://creativecommons.org/licenses/by/4.0/>).

produces a triboelectric effect. In this regard, dielectric materials are widely adopted for the contact layer. The conductive layer serves as a passage through which induced charges move, and thus, metal or carbon-based materials are generally used [32–35]. Conventionally, most TENGs employ two individual films, a dielectric film and a conductive film, which are stacked to represent each layer. However, the need for stacking processes, including adhesion and coating multiple films, is an obstacle preventing TENGs from unleashing their potential and advantages, including diverse material choices. Moreover, the traditional method inevitably entails process complexity and is a hurdle that limits the utilization of TENG [30, 36]. Given that, an approach from a different perspective is needed to address these issues.

Herein, we propose sedimentation-driven one-step fabrication of a bifunctional composite film-based TENG (BF-TENG). The proposed bifunctional composite film consists of polydimethylsiloxane (PDMS) as a matrix and carbon nanopowders as fillers. Through the carbon concentration difference caused by natural sedimentation during the curing process, a single sol-state precursor coating procedure on the substrate enables the spontaneous embodiment of both the dielectric and conductive layers of the TENG in the composite without any intentional postprocessing. Moreover, the degree of difference in carbon concentration can be controlled by varying the curing temperature and curing agent since the sedimentation effect, which is the core in the suggested process, occurs during the PDMS curing process. Given the ease with which BF-TENGs can be generated as a film in a single step using a single precursor, the surface of everyday items can be easily turned into a BF-TENG as long as the precursor can be securely cured. Consequently, the BF-TENG produced using a process that effectively reduces inconvenience in the existing manufacturing process is expected to play a significant role in broadening its practical application.

2 Materials and methods

2.1 Fabrication of BF-TENG

To fabricate the single-layered TENG, a PDMS elastomer (SYLGARD™ 184 Silicone Elastomer, Sigma-Aldrich, USA), curing agent, and carbon nanopowder (CARB-BLK, Graphene Supermarket, USA) were prepared. The sol-state composite precursor of the BF-TENG was made up by mixing the PDMS elastomer and the curing agent at a mass ratio of 10:1, and carbon nanopowder was incorporated at a 1.0 wt% concentration. Then, the homogeneous precursor was coated on an electrically connected substrate and cured for one day. The bar coating method was applied to make the film-like BF-TENG, and the thickness of the BF-TENG was approximately 170 μm . The size of the BF-TENG fabricated for the parametric study was 40 mm $\times$ 40 mm.

2.2 Elemental analysis of BF-TENG

The mass ratio was measured via cross-sectional surface element mapping by scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDS). The elemental ratio of carbon to silicon was characterized by a color extraction method using EDS mapping images.

2.3 Measurement of electrical output performance

A mechanical shaker (ET-139, Labworks Inc., USA) with a connected amplifier (PA-138, Labworks Inc., USA) and function

generator (DZ1022Z, Rigol, USA) was used for uniform vibration to operate BF-TENG systematically and for conducting parametric studies, including electrical output characterization. The voltage was measured by a directly connecting oscilloscope (DS1074Z, Rigol, USA; internal resistance = 1 M Ω). A low-noise current preamplifier (SR570, Stanford Research Systems, USA) was applied to measure the output current. All experiments related to electrical energy output were conducted at a temperature of 24 ± 0.5 °C and a relative humidity of 50%.

3 Results and discussion

3.1 One-step fabrication of bifunctional composite films as TENGs via sedimentation effect

The proposed bifunctional composite film with the gradient of carbon concentration is schematically shown in Fig. 1(a). One side of the film with the low carbon concentration (as shown in Fig. 1(a)(i)) can act as the dielectric part (DP) due to the relatively insufficient presence of conductive carbon particles in the dielectric PDMS matrix. On the other hand, the high carbon concentration side can have a sufficient conductive network to serve as the conductive part (CP), as shown in Fig. 1(a)(ii). In this regard, at once, the developed film possesses a dielectric contact layer and a beneath-located conductive layer, which are the above-explained two essential layers for the realization of operable TENGs. The operation mechanism of the BF-TENG using the proposed bifunctional composite film is shown in Fig. 1(b). When the surface of the DP comes in contact with the surface of another material (counter layer), electric charge pairs are spontaneously generated at the interface by the triboelectric effect. Then, as the counter layer separates, the charge pairs are broken, and opposite electric charges are induced on the CP by the net charges remaining on the DP. Consequently, through the repeated contact and separation of the counter layer and DP, the movement of the induced charges is measured as a form of alternative current. The proposed bifunctional composite film is basically fabricated by a single coating procedure of the sol-state precursor, which is a homogeneous mixture of the PDMS elastomer, curing agent, and carbon nanopowder. After coating the sol-state precursor on a surface, the gradient of carbon concentration can be spontaneously formed by gravitational force-driven sedimentation of the carbon nanopowder fillers in an uncured PDMS matrix. Over time, the sedimentation of the carbon nanopowder fillers increases the electrical conductivity of the lower part of the film, and at the same time, the sparse presence of nanopowders in the upper part of the film increases the electrical resistance. As a result, both the DP and CP are spontaneously embodied when the curing of the PDMS is complete in the composite film without any intentional postprocessing. The detailed fabrication process is shown in Fig. 1(c).

3.2 Effect of processing parameters on the carbon proportion of each layer in the bifunctional composite film

The photograph of the fabricated bifunctional composite film is shown in Fig. 2(a). Figures 2(b)(i) and 2(b)(ii) show the carbon and silicon element mapping images of the cross-sectional surfaces of DP and CP, respectively, as analyzed by SEM and EDS. Because of the sedimentation effect, the upper and lower parts of the film have relatively sparse and dense carbon, respectively. The carbon concentrations of DP and CP in the proposed bifunctional composite film are supposed to be different depending on the incorporated concentration of carbon (IC_C). In this regard, the

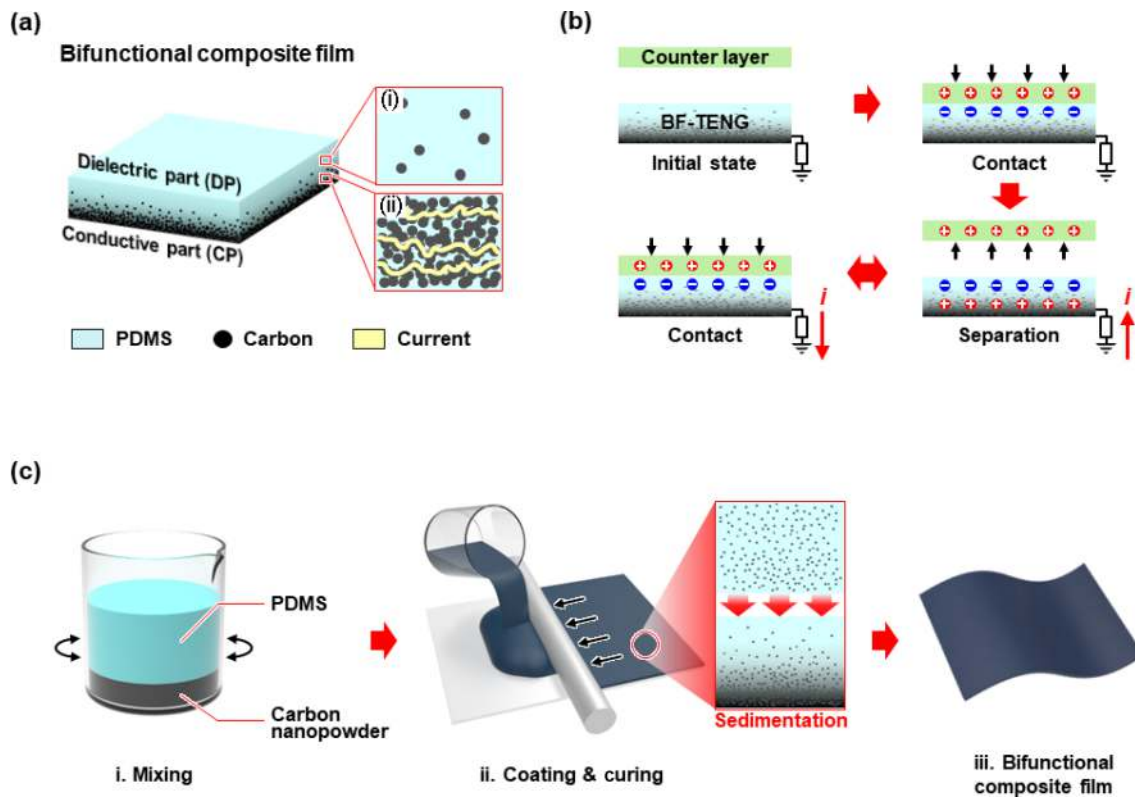


Fig. 1 (a) Schematic of proposed bifunctional composite film with gradient of carbon concentration, including (i) DP and (ii) CP. (b) Operation mechanism of BF-TENG using proposed bifunctional composite film. (c) One-step fabrication process of bifunctional composite film with sedimentation-driven gradient of carbon concentration.

carbon mass ratio of each layer was analyzed by varying the IC_C using EDS, and the results are plotted in Fig. 2(c). As IC_C increases, the amount of carbon in both DP and CP increases, and more importantly, the difference in the carbon mass ratio, which directly indicates the carbon concentration of each layer, between DP and CP also gradually increases. To act as CP, the carbon in the lower part of the film must be electrically connected, necessitating research into the corresponding lower limit of carbon concentration, which is called the electrical percolation threshold. In this regard, we tested whether each composite film operates as a TENG for samples with various IC_C . As a result, the electrical percolation threshold for CP to act as a passage through which induced charges move is determined to be 1.0 wt% of the IC_C . Interestingly, at higher IC_C , the bifunctional composite film does not function as a TENG since the carbon concentration in the upper part of the film also increases, as plotted in Fig. 2(c), preventing the DP from functioning as a dielectric. In this regard, the optimum IC_C is determined to be 1.0 wt% for further analyses.

Since the sedimentation effect, which is the core of the proposed process, works only when the PDMS is in its uncured state, the degree of difference in carbon concentration between DP and CP in the proposed bifunctional composite film can be varied by controlling the curing temperature and the concentration of the curing agent. The carbon concentrations in DP and CP are investigated by varying the curing temperature and concentration of the curing agent. Figures 2(d) and 2(e) show the carbon and silicon element mapping images of the cross-sectional surfaces of DP and CP, respectively, as analyzed by EDS when the curing temperatures are 85 and 20 °C, respectively. The figures labeled with (i) and (ii) are the mapping images of DP and CP, respectively. The analysis results of the carbon ratio (CR) based on the element mapping results obtained by varying the curing

temperature are shown in Fig. 2(f). The difference in CR between DP and CP is defined as d_{CR} in this study for quantitative analysis. d_{CR} indicates the difference in carbon content and electrical conductivity of DP and CP. A high d_{CR} means that the DP and CP have a large difference in electrical conductivity. Based on the d_{CR} , the degree of sedimentation of carbon can be investigated. When the degree of sedimentation is large, the difference in carbon concentration between DP and CP appears large, and thus, the d_{CR} also increases. As shown in Fig. 2(f), the d_{CR} is 0.94% in the composite film when the curing temperature is 85 °C. On the other hand, when the curing temperature is 20 °C, the d_{CR} reaches 22.69%. When the precursor is cured under high-temperature conditions, the curing rate is fast, and the curing process is completed before the sedimentation effect occurs sufficiently. On the other hand, the sedimentation effect proceeds excessively under low-temperature conditions. Furthermore, the carbon and silicon element mapping images of DP and CP depending on the concentration of the curing agent were also analyzed. Figures 2(g) and 2(h) show the mapping results for each case in which the ratios of the PDMS elastomer to the curing agent (PDMS mixing ratio) are 5:1 and 20:1, respectively. The figures labeled with (i) and (ii) are the mapping images of DP and CP, respectively. The analysis results of the CR based on the element mapping results obtained by varying the PDMS mixing ratio are shown in Fig. 2(i). When the PDMS mixing ratios are 5:1 and 20:1, the d_{CR} are 8.92% and 33.41%, respectively. Since the high proportion of curing agent results in a high probability of a crosslinking reaction in the PDMS, the sedimentation of carbon may not be sufficient. However, excessive sedimentation occurs when the amount of incorporated curing agent is insufficient. Consequently, these results indicate that the curing speed and the probability of a crosslinking reaction are important factors that affect the material

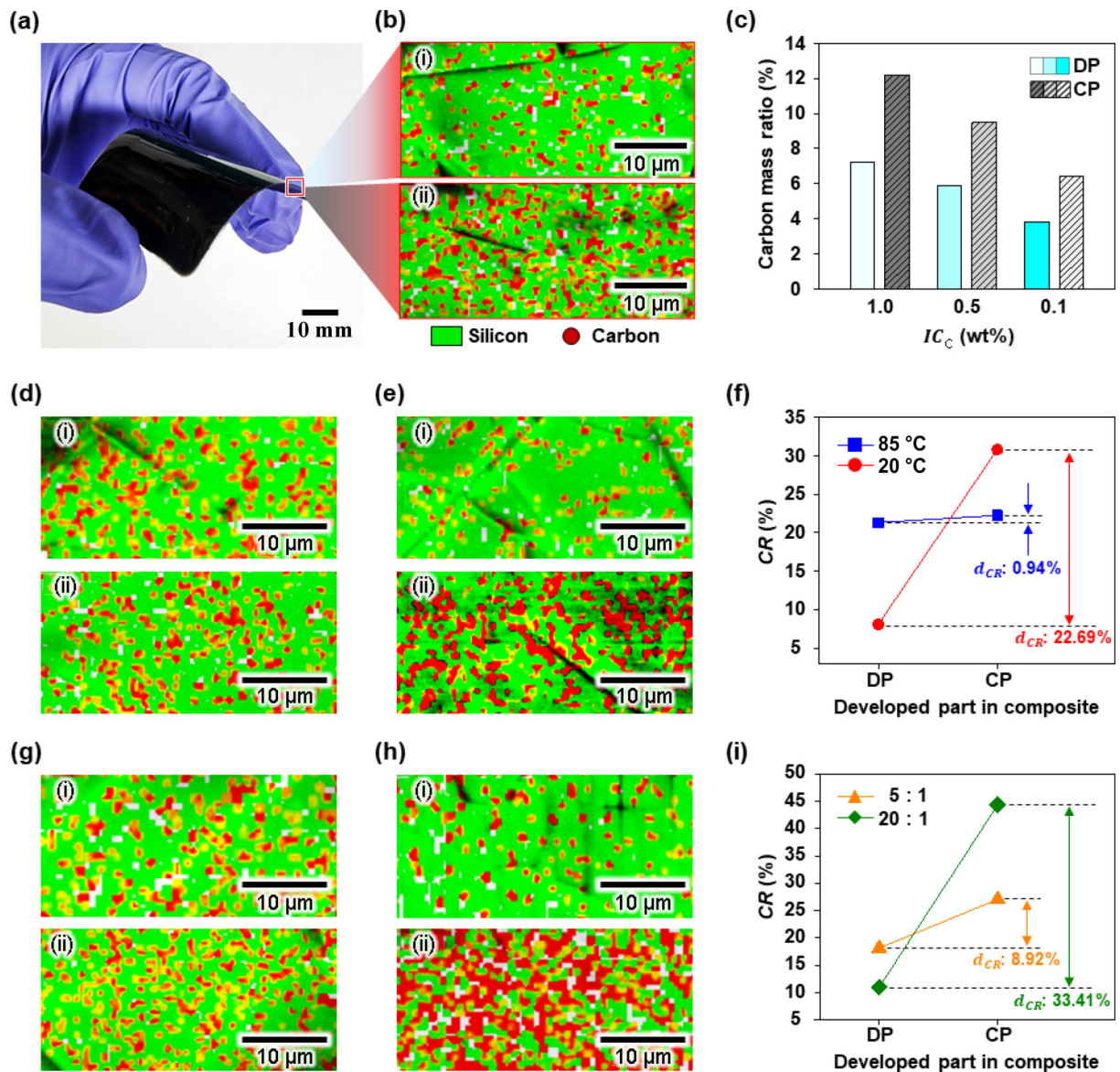


Fig. 2 (a) Photograph of fabricated bifunctional composite film and (b) EDS element mapping images of (i) DP and (ii) CP. (c) Carbon mass ratio of each layer with varying IC_c . (d, e) EDS element mapping images of (i) DP and (ii) CP when curing temperatures are 85 and 20 °C, respectively. (f) Analysis of CR depending on curing temperature. (g, h) EDS element mapping images of (i) DP and (ii) CP when ratios of PDMS elastomer to curing agent are 5:1 and 20:1, respectively. (i) Analysis of CR depending on ratio of PDMS elastomer to curing agent.

characteristics of sedimentation-based composite fabrication. In this respect, the characteristics of bifunctional composites, such as the gradient of carbon content, carbon concentration, dielectricity, and conductivity of each layer, can be controlled on demand by simple modifications of the curing temperature and curing agent concentration.

3.3 Electrical output performance of BF-TENG

Figure 3(a) shows the output voltage of the BF-TENG. As explained above, the electrical output is measured as a peak-type alternative current, which is converted into a voltage value for quantitative investigation in this study when the contact and counter layers come in contact and separate from each other. The amount of generated output depends on the difference in the work function between the materials of the contact and counter layers. In this regard, the output obtained by varying the material of the counter layer is shown in Fig. 3(b). Since the material of the BF-TENG contact layer is fixed as the composited PDMS, the output behavior follows the trend of the well-known triboelectric

series, which is based on the electronegativity properties of various materials, as shown in Table S1 in the Electronic Supplementary Material (ESM) [10, 19, 37, 38]. The materials used in this study are marked in red letters. The slight difference between the experimental results and the triboelectric series can be attributed to the carbon contained in the composite. The output current of the BF-TENG, when it comes into contact and is separated from the abovementioned materials with an f of 8 Hz, is shown in Fig. S1(a) in the ESM. Figure S1(b) in the ESM shows the transferred charges when contact occurs only once. Based on these results, the rest of the experiments were conducted using nylon as the counter layer. Although the amount of generated charges on the contact surface, Q , depends on the contact materials in the TENG, the output voltage varies in accordance with the frequency of sequential contact and separation, f , as shown in Eqs. (1)–(3):

$$V = IR \quad (1)$$

$$I = dQ/dt \quad (2)$$

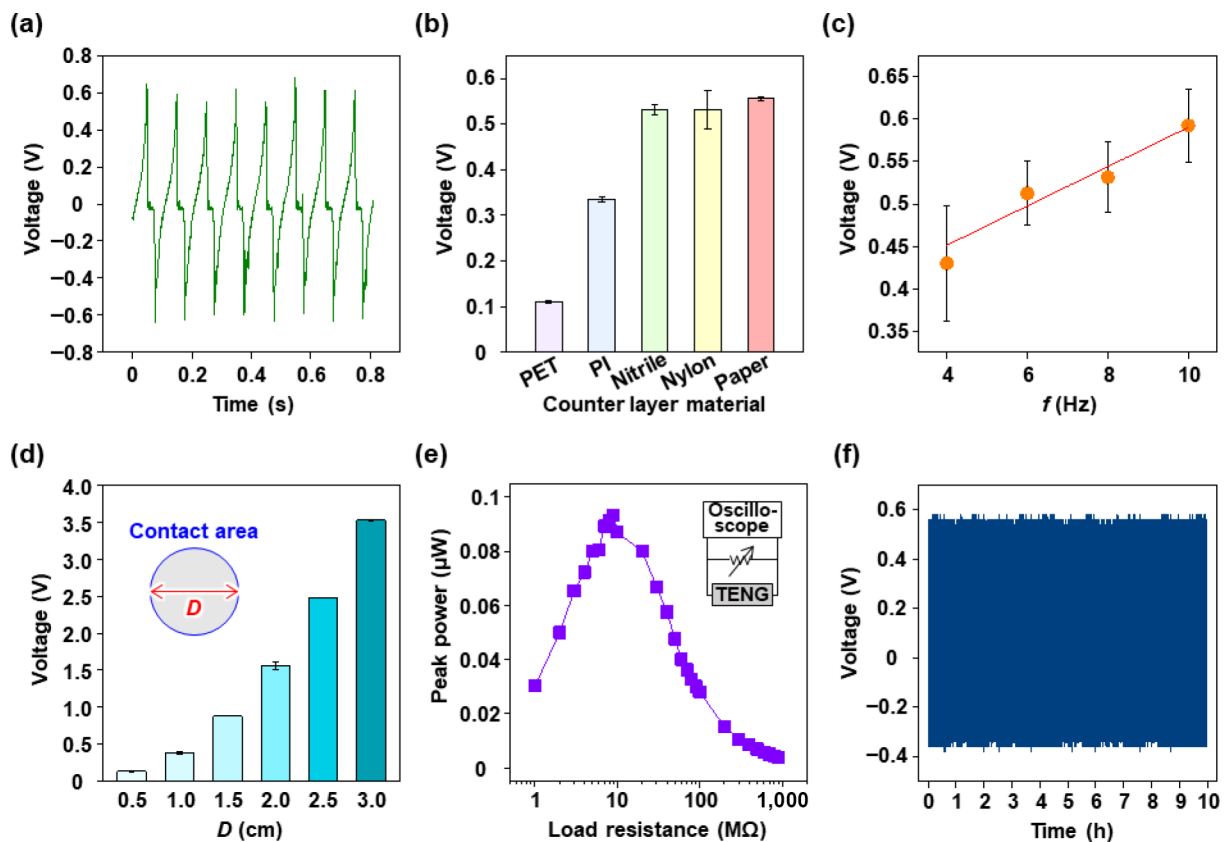


Fig. 3 (a) Output voltage of the BF-TENG. Average and standard deviation of the output voltage depending on (b) material of counter layer, (c) f , and (d) D . (e) Peak power generated from BF-TENG by varying the external load resistance. The inset schematic is a circuit diagram of the connection of BF-TENG, variable load resistance, and oscilloscope. (f) Durability test of BF-TENG.

$$t \propto f^{-1} \quad (3)$$

where V , I , R , and t are the output voltage, current, load resistance of the oscilloscope, and time that the material surfaces are in contact with each other, respectively. In this respect, the output behavior of the BF-TENG exhibits a linear tendency with f , as shown in Fig. 3(c). Moreover, since Q is directly dependent on the area of the contact surface, the output performance increases in proportion to the square of the diameter, D , of the circular contact area, as shown in Fig. 3(d), according to Eq. (4):

$$A = \pi D^2/4 \quad (4)$$

where A and π are the area of the contact surface and the circular constant, respectively. Figure 3(e) shows the changing behavior of the peak power with varying external load resistance. Given that the fundamental principle of TENGs is based on the methodology of their capacitor-like structure and charge movement, it is necessary to investigate the output performance depending on the connected external load resistance and impedance matching phenomenon. The inset circuit diagram in Fig. 3(e) shows the measurement method using a variable external load resistance. The maximum peak power is approximately 0.093 μW when the connected load resistance is 9 M Ω . The user can estimate the ability of the BF-TENG to supply electrical power via an impedance-matching process based on the experimental results. The BF-TENG fabricated in this study can work for at least 10 h with an f of 8 Hz without performance degradation, as depicted in Fig. 3(f).

3.4 Conversion of ordinary surfaces to energy harvesters

Figure 4 shows some examples of practical applications of

BF-TENGs as proof-of-concept demonstrations. The surfaces of everyday items such as desks, chairs, and floors can be easily turned into BF-TENGs since BF-TENGs can be made by a single coating procedure without any intentional postprocessing. Moreover, BF-TENGs can be formed by coating a bifunctional composite directly on the surface of another object or forming an energy harvesting film by coating the bifunctional composite on an available film. Figure 4(a) is a photograph showing the direct coating of the sol-state precursor on a desk. A mask is used to develop the desired area of the desk in the BF-TENG with a uniform thickness. One day after coating the precursor, the surface of the desk successfully functions to harvest mechanical energy with the coated BF-TENG, as shown in Fig. 4(b). Figure 4(c) shows the generated output power when its surface is tapped by a finger. The BF-TENG-coated desk can turn on an electrical device such as a light-emitting diode (LED) just by touching it with one finger, as shown in Video S1 in the ESM. Furthermore, BF-TENGs can also be directly fabricated on flexible films and can be attached to another item even if the surface is bent, as in human skin, as shown in Fig. 4(d). Then, it can work as an energy harvester by simply touching it, as shown in Figs. 4(e) and 4(f). Figure 4(f) shows the output power when touching the BF-TENG attached to human skin. As shown in Video S2 in the ESM, an LED can be driven by tapping a BF-TENG attached to human skin; thus, the LED can be applied to a self-powered outdoor emergency device to send a distress signal. The scope of the application of BF-TENGs and the manufacturing scale of the developed BF-TENGs are not limited to the demonstrated examples. Based on its facile fabrication process and diverse functionalities, the BF-TENG can be developed on the surface of various everyday items on demand of the user and can serve as a power source for operating electronic devices.

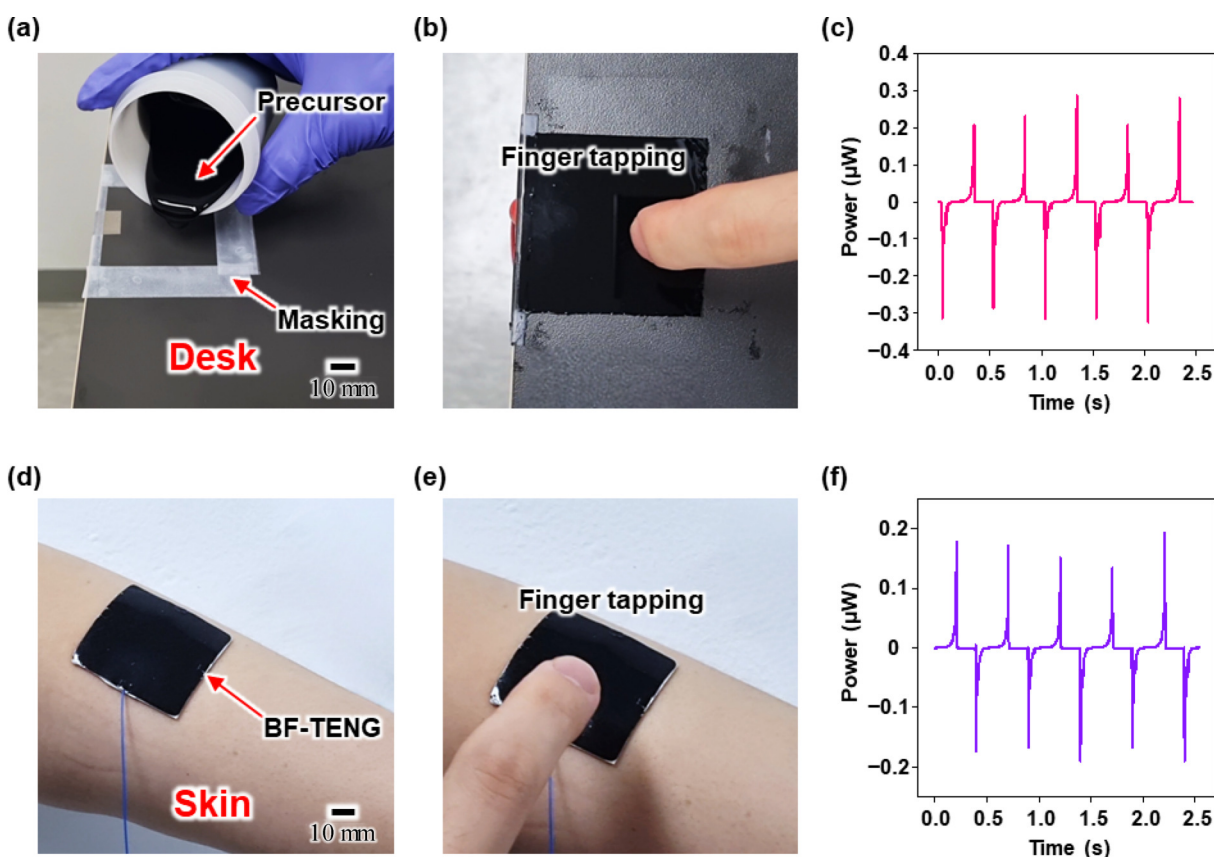


Fig. 4 Examples of practical applications of BF-TENGs. (a) Photograph of the coating of sol-state precursor on desk. (b) Conversion of the surface of desk into energy harvester and (c) generated power from BF-TENG-coated desk. (d) Photograph of attaching the film-like BF-TENG to human skin. (e) Energy harvesting by tapping and (f) generated power from BF-TENG attached to the human body.

4 Conclusions

In this study, a bifunctional composite film-based triboelectric nanogenerator (BF-TENG), which is a bifunctional composite film-based TENG with sedimentation-driven one-step fabrication, is proposed. Bifunctional composite films consisting of polydimethylsiloxane (PDMS) and carbon nanopowders and BF-TENGs can be developed through the carbon concentration difference caused by natural sedimentation during the curing process of a single sol-state precursor. BF-TENGs contain both dielectric part (DP) and conductive part (CP), which act as the dielectric and conductive layers, respectively, in one single layer. In this regard, the proportions of carbon and silicon in DP and CP were analyzed. The mass ratio of the carbon contained in each part was investigated, and strategies to control the carbon ratio (CR) in each part were studied in terms of the incorporated concentration of carbon (IC_C), curing temperature, and PDMS mixing ratio. The electrical performance of BF-TENGs was investigated by varying the various external mechanical stimuli, including the contact materials, contact frequency, contact area, external load resistance, and operation time. Then, the conversion of the surfaces of the desk and human skin into an energy harvester using the BF-TENG is shown as a proof-of-concept demonstration.

Acknowledgements

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (No. RS-2024-00344920). This work was supported by the Human Resources Development of the Korea Institute of Energy Technology Evaluation and Planning (KETEP) grant funded by

the Ministry of Trade, Industry and Energy of Korea (No. RS-2023-00244330).

Declaration of competing interest

The authors have no competing interests to declare that are relevant to the content of this article.

Electronic Supplementary Material

Supplementary material is available in the online version of this article at <https://doi.org/10.26599/FRICT.2025.9440918>.

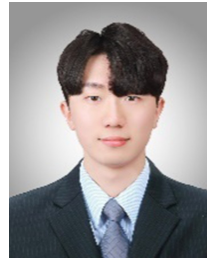
References

- [1] Wang Z L. Triboelectric nanogenerator (TENG)—Sparking an energy and sensor revolution. *Adv Energy Mater* 10(17): 2000137 (2020)
- [2] Wan D, Yang J, Cui X J, Ma N C, Wang Z S, Li Y P, Li P W, Zhang Y X, Lin Z H, Sang S B, et al. Human body-based self-powered wearable electronics for promoting wound healing driven by biomechanical motions. *Nano Energy* 89: 106465 (2021)
- [3] Hwang H J, Hong H, Cho B G, Lee H K, Kim J S, Lee U J, Kim W, Kim H, Chung K B, Choi D. Band well structure with localized states for enhanced charge accumulation on Triboelectrification. *Nano Energy* 90: 106647 (2021)
- [4] Ahmad Lone S, Lim K C, Kaswan K, Chatterjee S, Fan K P, Choi D, Lee S M, Zhang H L, Cheng J, Lin Z H. Recent advancements for improving the performance of triboelectric nanogenerator devices. *Nano Energy* 99: 107318 (2022)
- [5] Barman S R, Chan S W, Kao F C, Ho H Y, Khan I, Pal A, Huang C C, Lin Z H. A self-powered multifunctional dressing for active infection prevention and accelerated wound healing. *Sci Adv* 9(4): eadc8758 (2023)

- [6] Chang K B, Parashar P, Shen L C, Chen A R, Huang Y T, Pal A, Lim K C, Wei P H, Kao F C, Hu J J, et al. A triboelectric nanogenerator-based tactile sensor array system for monitoring pressure distribution inside prosthetic limb. *Nano Energy* **111**: 108397 (2023)
- [7] Choi D, Lee Y, Lin Z H, Cho S, Kim M, Ao C K, Soh S, Sohn C, Jeong C K, Lee J, et al. Recent advances in triboelectric nanogenerators: From technological progress to commercial applications. *ACS Nano* **17**(12): 11087–11219 (2023)
- [8] Wang Y Q, Yu X, Yin M F, Wang J L, Gao Q, Yu Y, Cheng T H, Wang Z L. Gravity triboelectric nanogenerator for the steady harvesting of natural wind energy. *Nano Energy* **82**: 105740 (2021)
- [9] Luo J, Gao W, Wang Z L, Wang Z L. The triboelectric nanogenerator as an innovative technology toward intelligent sports. *Adv Mater* **33** (17): e2004178 (2021)
- [10] Ra Y, Oh S, Lee J, Yun Y, Cho S, Choi J H, Jang S, Hwang H J, Choi D, Kim J G, et al. Triboelectric signal generation and its versatile utilization during gear-based ordinary power transmission. *Nano Energy* **73**: 104745 (2020)
- [11] Son J H, Heo D, Goh D, Lee M, Chung J, Choi S, Lee S M. Wind-driven bidirectional fluttering triboelectric nanogenerator via dual flagpole and slot structure design. *Adv Mater Technol* **8**(1): 2200453 (2023)
- [12] Khan A, Joshi R, Sharma M K, Ganguly A, Parashar P, Wang T W, Lee S M, Kao F C, Lin Z H. Piezoelectric and triboelectric nanogenerators: Promising technologies for self-powered implantable biomedical devices. *Nano Energy* **119**: 109051 (2024)
- [13] Li D X, Yadav A, Zhou H, Roy K, Thanasekaran P, Lee C K. Advances and applications of metal-organic frameworks (MOFs) in emerging technologies: A comprehensive review. *Glob Chall* **8**(2): 2300244 (2024)
- [14] Liang Q Q, Zhang D, He T, Zhang Z X, Wang H P, Chen S Y, Lee C K. Fiber-based noncontact sensor with stretchability for underwater wearable sensing and VR applications. *ACS Nano* **18**(1): 600–611 (2023).
- [15] Pal A, Ganguly A, Wei P H, Barman S R, Chang C C, Lin Z H. Construction of triboelectric series and chirality detection of amino acids using triboelectric nanogenerator. *Adv Sci* **11**(4): 2307266 (2024)
- [16] Heo D, Son J H, Kim D, Song M, Ryu H, Kim S, Choi K, Lin Z H, Kim D, Hong J, et al. Charge-accumulating-flutter-based triboelectric nanogenerator via discharge gateway. *Adv Energy Mater* **13**(14): 2204239 (2023)
- [17] Yoo D, Jang S, Cho S, Choi D, Kim D S. A liquid triboelectric series. *Adv Mater* **35**(26): 2300699 (2023)
- [18] Yoo D, Kim S J, Joung Y, Jang S, Choi D, Kim D S. Lotus leaf-inspired droplet-based electricity generator with low-adhesive superhydrophobicity for a wide operational droplet volume range and boosted electricity output. *Nano Energy* **99**: 107361 (2022)
- [19] Kim W G, Kim D W, Tcho I W, Kim J K, Kim M S, Choi Y K. Triboelectric nanogenerator: Structure, mechanism, and applications. *ACS Nano* **15**(1): 258–287 (2021)
- [20] Roy Barman S, Lin Y J, Lee K M, Pal A, Tiwari N, Lee S M, Lin Z H. Triboelectric nanosensor integrated with robotic platform for self-powered detection of chemical analytes. *ACS Nano* **17**(3): 2689–2701 (2023)
- [21] Sun Z D, Zhang Z X, Lee C K. A skin-like multimodal haptic interface. *Nat Electron* **6**(12): 941–942 (2023)
- [22] Xiao Z A, Liu W X, Xu S Y, Zhou J K, Ren Z H, Lee C K. Recent progress in silicon-based photonic integrated circuits and emerging applications. *Adv Opt Mater* **11**(20): 2301028 (2023)
- [23] Zhang Z X, Liu X M, Zhou H, Xu S Y, Lee C K. Advances in machine-learning enhanced nanosensors: From cloud artificial intelligence toward future edge computing at chip level. *Small Struct* **5**(4): 2300325 (2024)
- [24] Zhang C G, Liu Y B, Zhang B F, Yang O, Yuan W, He L X, Wei X L, Wang J, Wang Z L. Harvesting wind energy by a triboelectric nanogenerator for an intelligent high-speed train system. *ACS Energy Lett* **6**(4): 1490–1499 (2021)
- [25] Heo D, Song M, Chung S H, Cha K, Kim Y, Chung J, Hwang P T J, Lee J, Jung H, Jin Y, et al. Inhalation-driven vertical flutter triboelectric nanogenerator with amplified output as a gas-mask-integrated self-powered multifunctional system. *Adv Energy Mater* **12**(31): 2201001 (2022)
- [26] Walden R, Kumar C, Mulvihill D M, Pillai S C. Opportunities and challenges in triboelectric nanogenerator (TEENG) based sustainable energy generation technologies: A mini-review. *Chem Eng J Adv* **9**: 100237 (2022)
- [27] Kim J, Cho H, Han M, Jung Y, Kwak S S, Yoon H J, Park B, Kim H, Kim H, Park J, et al. Ultrahigh power output from triboelectric nanogenerator based on serrated electrode via spark discharge. *Adv Energy Mater* **10**(44): 2002312 (2020)
- [28] Lee J W, Jung S, Jo J, Han G H, Lee D M, Oh J, Hwang H J, Choi D, Kim S W, Lee J H, et al. Sustainable highly charged C₆₀-functionalized polyimide in a non-contact mode triboelectric nanogenerator. *Energy Environ Sci* **14**(2): 1004–1015 (2021)
- [29] Ra Y, You I, Kim M, Jang S, Cho S, Kam D, Lee S J, Choi D. Toward smart net zero energy structures: Development of cement-based structural energy material for contact electrification driven energy harvesting and storage. *Nano Energy* **89**: 106389 (2021)
- [30] Lee Y, Lim S, Song W J, Lee S D, Yoon S J, Park J M, Lee M G, Park Y L, Sun J Y. Triboresistive touch sensing: Grid-free touch-point recognition based on monolayered ionic power generators. *Adv Mater* **34**(19): e2108586 (2022)
- [31] Hwang H J, Kim J S, Kim W, Park H, Bhatia D, Jee E, Chung Y S, Kim D H, Choi D. An ultra-mechanosensitive visco-poroelastic polymer ion pump for continuous self-powering kinematic triboelectric nanogenerators. *Adv Energy Mater* **9**(17): 1803786 (2019)
- [32] Hwang H J, Yeon J S, Jung Y, Park H S, Choi D. Extremely foldable and highly porous reduced graphene oxide films for shape-adaptive triboelectric nanogenerators. *Small* **17**(9): 1903089 (2021)
- [33] Chung J, Heo D, Shin G, Choi D, Choi K, Kim D, Lee S M. Ion-enhanced field emission triboelectric nanogenerator. *Adv Energy Mater* **9**(37): 1901731 (2019)
- [34] Chatterjee S, Burman S R, Khan I, Saha S, Choi D, Lee S, Lin Z H. Recent advancements in solid-liquid triboelectric nanogenerators for energy harvesting and self-powered applications. *Nanoscale* **12** (34): 17663–17697 (2020)
- [35] Lee J H, Lee J H, Xiao J, Desai M S, Zhang X, Lee S W. Vertical self-assembly of polarized phage nanostructure for energy harvesting. *Nano Lett* **19**(4): 2661–2667 (2019)
- [36] Park H, Oh S J, Kim D, Kim M, Lee C, Joo H, Woo I, Bae J W, Lee J H. Plasticized PVC-gel single layer-based stretchable triboelectric nanogenerator for harvesting mechanical energy and tactile sensing. *Adv Sci* **9**(22): 2270134 (2022)
- [37] Hatta F F, Haniff M A S M, Mohamed M A. A review on applications of graphene in triboelectric nanogenerators. *Int J Energy Res* **46**: 544–576 (2021)
- [38] Kanik M, Say M G, Daglar B, Yavuz A F, Dolas M H, El-Ashry M M, Bayindir M. A motion- and sound-activated, 3D-printed, chalcogenide-based triboelectric nanogenerator. *Adv Mater* **27**(14): 2367–2376 (2015)



Yoonsang Ra received his Ph.D. degree from the Department of Mechanical Engineering, Kyung Hee University, Republic of Korea. He has worked as a postdoctoral researcher at Kyung Hee University. His research interests are based on contact electrification phenomena in machine components and self-powered sensing mechanisms.



Sumin Cho is currently pursuing a Ph.D. candidate under the supervision of Prof. Dongwhi Choi, Kyung Hee University, Republic of Korea. He started his academic studies in the field of mechanical engineering and received his B.S. and M.S. degrees from Kyung Hee University. His research interest is based on biomechanical energy harvesting and its applications of self-powered sensors and hybridization of energy harvesters.



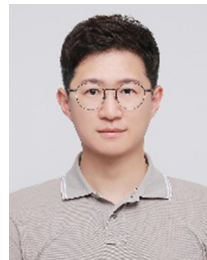
Dongik Kam is currently pursuing a Ph.D. candidate under the supervision of Prof. Dongwhi Choi, Kyung Hee University, Republic of Korea. He started his academic studies in the field of mechanical engineering and received his B.S. and M.S. degrees from Kyung Hee University. His research interests are based on the design and fabrication of 3D structure by mechanically guided geometry transformation and its applications.



Donghan Lee is currently pursuing a Ph.D. candidate under the supervision of Prof. Dongwhi Choi, Kyung Hee University, Republic of Korea. He started his academic studies in the field of mechanical engineering and received his B.S. and M.S. degrees from Kyung Hee University. His research interest is based on mechanical design for effective energy harvesting using triboelectricity and its application in the wireless sensor networks.



Sunmin Jang is currently pursuing a Ph.D. candidate under the supervision of Prof. Dongwhi Choi, Kyung Hee University, Republic of Korea. He started his academic studies in the field of mechanical engineering and received his B.S. and M.S. degrees from Kyung Hee University. His research interest is based on triboelectric phenomena between liquid and solid.



Dongwhi Choi is currently an associate professor in the Department of Mechanical Engineering, Kyung Hee University, Republic of Korea. He received his Ph.D. degree from Pohang University of Science and Technology (POSTECH), Republic of Korea, in 2016 by developing the platforms for utilization of liquid-solid contact electrification. His research is based on development of energy harvesters and self-powered sensors with functional polymer platforms fabricated by multi-scale advanced material processing.