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3D-printed biomimetic-villus structure with maximized surface area for triboelectric nanogenerator and dust filter

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ABSTRACT

A biomimetic-villus structure that has been fabricated using a three-dimensional (3D) printer, which is a high-resolution additive-manufacturing process, is here introduced for the realizing of a large increase of the surface area beyond the structural limitations, and the intestinal-villus structure that can be produced only by a 3D printer is imitated. The surface area of the 3D-printed biomimetic-villus structure was increased by approximately 300% compared with the planar structure, and to achieve the full contact of this increased surface area, polytetrafluoroethylene (PTFE) powder was used as the triboelectric material, resulting in fivefold and fourfold increases of the electric power output performance in the vertical-direction mode and the rotational-direction mode, respectively. In addition, a dust-filtration system was designed using the large electrostatic charge that formed between an acrylonitrile butadie n styrene (ABS) surface and PTFE powders, and dust particles of various sizes were efficiently adsorbed. Further, because of the use of the polymer-based ABS and the PTFE powders, the dust filter is stable and easily reusable, and it was experimentally confirmed after a washing that the filtration efficiency of 41% is nondecreasing. As a result, a successful validation of the use of the 3D-printed biomimetic-villus structure with the maximized surface area as an ecofriendly dust-adsorption system as well as a triboelectric nanogenerator was achieved.

1. Introduction

Airborne fine particles are one of the serious problems of environmental public health. Fine dust, classified as particulate matter (PM) 2.5 or PM 10 depending on the diameter, is invisible and stays in the atmosphere [1,2]. In addition, it has been reported that it can be fatal to human health if it enters into the lungs through the respiratory tract, or if it moves into the body along the blood vessels due to the smallness of the microscale particle size [3–5]. A conventional air filter, based on electrostatic-induction, is used to remove fine particles [6]. Although its filtering characteristic may be restored after washing, it costs power with using electric field, or a complete restoration of filtering function seems difficult. Among strategies, the triboelectricification can induce a level of electric field to restore filter’s performance.

Recently, various studies have reported the generation of contact electrification for triboelectric nanogenerators (TENGs), a touch sensor [7], a pressure sensor [8], and a field-effect transistor [9]. To improve triboelectricification, the major challenge is the increasing of both the surface area and the structural design of triboelectric materials for the generation of a huge surface charge and the achievement of a high power conversion efficiency with a low mechanical energy, respectively [10–12]. The powder-contact-type structure-based TENGs have attracted much attention due to their large contact area, low friction coefficient, high efficiency, durability, and reliability for a long-term operability [13]. The focus of the previous reports, however, is either a flat two-dimensional (2D) structure, a straight tubular cylinder, or an unpacked structure, because the fabrication of these structures is performed using the forging or casting manufacturing method; furthermore, it is challenging to increase the surface area for the enhancement of the surface charge in TENGs that are based on powder-contact-type structures.

3D printing is basically an additive manufacturing process that uses stacked material with respect to the 3D-object manufacturing process for which digital data are used. The advantages of 3D printing are a low manufacturing cost, time saving, and a simple manufacturing process that allows users to reduce the assembly cost accordingly. In addition, complex structural manufacturing is important for the realization of a dramatic increase of the contact area for triboelectricification.
Herein, a newly designed 3D-printed biomimetic-villus structure-based TENG (BV-TENG) with a polytetrafluoroethylene (PTFE)-powder contact is demonstrated. Both the PTFE powder and acrylonitrile butadiene styrene (ABS) were used as active triboelectric materials within the inside area of the fully packaged BV-TENG. Furthermore, different BV-TENG columns and layers were fabricated, and their electric power generation performances were investigated under the conditions of the amplitude, the frequency in the vertical-direction mode, the powder volume, and the revolutions per minute (RPM) in the rotational-direction mode with the optimized condition. With the results of the present study, the triboelectric effect of the BV-TENG between the PTFE powder and the ABS surface is sufficient. The results of this study also confirm the possibility of the use of the electrostatic-effect-based dust-filtration function. The triboelectric charge that formed on the PTFE and the ABS surface reacted with the triboelectric charge that formed in the dust, and the electrostatic force adsorbed the dust onto the surfaces of a PTFE ball and the ABS, thereby resulting in the attainment of a dust-adsorption function within the BV dust filter (BV-DF).

2. Materials and methods

2.1. 3D printing and device fabrication

The BV-TENG was prepared using the Master Plus J 845 DLP-type 3D printer (Carima, Korea) with the 3DR-A83Y commercial-photopolymer ABS resin. The diameter and the height of the fabricated cylindrical structure are 42 mm and 38 mm, respectively. To fabricate the TENG, an Ag paste was coated on the outside of the villus-shaped columns. The driving mode can be easily adjusted by changing the external arrangement of the electrode. In the vertical mode, the first and second electrode layers are connected, while the third and fourth electrode layers are also connected. In the rotational mode, assuming that the device is cut in half in the z-axis direction, the electrodes in each half region are connected. A commercial PTFE powder, with the mean particle sizes of 0.1, 10, and 500 μm, was used as the triboelectric material to achieve full contact with the complex villus-shaped-column structure of the ABS. To fabricate the dust filter, a mesh-type design was used for the top and bottom and this enables the smooth flow of the dust air. A 3000.062–1/16” PTFE ball (Precision Plastic Ball Company, USA) was also used as a triboelectric material instead of the PTFE powder.

2.2. Characterization and measurements

A characterization using the JSM-6701F field emission SEM instrument (Jeol Ltd., Japan) was performed to confirm the ABS-surface roughness, the shape of the PTFE powder, and the amount of dust that was adsorbed onto the surface of the PTFE ball. The pa-151 vibration tester (Labworks Inc., USA) and the AFG 3021 digital function generator (Tektronix, USA) were used to vertically shake the device. The high-precision laser sensor of the JCY012M air-quality detector (PM 2.5; Xiaomi, China) that can detect impurity sizes that are less than 2.5 μm was used to sense the ultrafine dust. The Tektronix DPO 3052 digital phosphor oscilloscope and the SR570 low-noise current preamplifier (Stanford Research Systems, Inc., USA) were used for the electrical measurements. Kelvin probe force microscopy (KPFM) measurements were performed using the XE100 commercial atomic force microscopy (AFM) system (Park Systems, Korea). The measurements were performed in the noncontact mode using the Multi75E-G conductive probe (Budget Sensors, Bulgaria) at the 2-V signal of 17 kHz. To confirm the original condition of the AFM tip, the potential difference between the AFM tip and the highly oriented pyrolytic graphite was measured prior to the analysis. The operating conditions during the KPFM analysis are the temperature of 21 °C and the humidity of 17%.

3. Results and discussion

3.1. 3D-printed BV structure

An increased surface area is the most important factor for the enhancement of TENG’s power output performance, so various approaches for the increasing of the surface area including complex structures, surface patterning, and pillar-array architecture were carried out [14,15]. But, the limitations of micro-to-millimeter-scale patterning, 3D-structure construction, and nanopillar durability need to be considered. To overcome these limitations, the introduction of a new 3D-printed device that has been fabricated by a Digital Light Processing (DLP)-type 3D printer is presented here. The previously presented 3D-printed devices were simply fabricated as molds and were used only for the collection of external energy rather than an active material [16–19]. In this paper, however, the proposed 3D-printed device is used as a practical active material, and to improve the efficiency of the friction-induced triboelectricity, a newly designed 3D-printed BV structure with an extremely wide surface area that cannot be manufactured using the conventional molding method due to its complicated structure is introduced.

Fig. 1(a) shows a schematic image of the 3D-printed BV-TENG and a cross-sectional view of the device. The 3D structure is produced using the DLP-type 3D printer, and based on the ABS photopolymer, the BV-TENG with the maximized surface area was fabricated with the use of silver (Ag) as the electrode, as is shown in Fig. 1(b). Fig. 1(c) shows a schematic illustration of the fabrication procedures of the DLP-type 3D printer. As shown in Fig. 1(d), the printing process comprises four main parts, as follows: First, the projector that applies a constant light energy onto the photopolymer; second, the board that holds the 3D-printed part for the polymerization; third, the liquid-photopolymer area that supplies and stores the photopolymer; and lastly, the Z-stage with the motor for the raising of the board during the 3D-printing process. At first, the ABS photopolymer is attached to the board, as shown in Fig. 1(d) (i). Next, the attached photopolymer is subject to a reflection beam from the projector, thereby polymerizing the beam-projected parts, as can be seen in Fig. 1(d) (ii). The same process is then repeatedly carried out layer-by-layer with the gradual elevation of the Z-stage, and this is shown in Fig. 1(d) (iii); consequently, a laminated structure in the Z-axis direction is created (see Fig. S1). Finally, when the 3D printing is finished, the 3D-printed villus structure is detached from the board, as is shown in Fig. 1(d) (iv). The fabricated device consists of 24 villus-shaped columns with a diameter of 15 mm and a bottom radius of 6 mm, and these are arranged obliquely inside, thereby reducing the screen effect and resulting in a surface-area increase of approximately 300% compared with the cylinder-planar structure. In addition, the PTFE powder was used as an internal friction material to achieve the full contact with the villus-shaped columns.

3.2. Operating mechanism of the BV-TENG

To produce the 3D-printed BV structure as a TENG, the inside of the device was packed with the PTFE powder, and the Ag was thinly coated on the outside of the columns to form the external-circuit electrode. The BV-TENG can be driven in both the vertical and rotational directions according to the arrangement of the outer-coated electrodes (see Fig. 2). Fig. 2(a) shows the vertical-direction mode, where the first and second ABS layers are the “A” part and the third and fourth layers are the “B” part in the initial state, the PTFE powder is in full contact with the A part, and the triboelectric effect is caused at the interface between the PTFE powder and the ABS surface, resulting in a negative charge on the PTFE powder and a positive charge on the ABS [20], as shown in Fig. 2(a) (i) and Fig. S2.

As the PTFE powder moves upward to the z-axis direction in accordance with the linear vertical movement, a region where the PTFE powder rubs against the B part is newly generated in the middle state,
Fig. 1. 3D-printed BV structure. (a) Schematic description of a 3D-printed biomimetic structure and a cross-sectional diagram. The inset (scale bar: 2 mm) shows photographs of the shape of the PTFE powder. (b) Photographs of the fabrication of the BV-TENG. (c) Schematic description of the DLP-type 3D-printing process. (d) Details of the four main parts: (i) Photocuring of one layer, (ii) post photocuring Z-stage movement, (iii) completion of all of the photocuring, and (iv) detachment of the fabricated device from the Z-stage.

Fig. 2. 3D-printed BV structure as a TENG and its electric power generating performance. (a) Schematic diagram showing the vertical-direction working principle of the BV-TENG. (i) The BV-TENG is in the static state and the PTFE powder is in contact with the villus-shaped columns. (ii) The BV-TENG is moving under a vertical mechanic force. (iii) The PTFE powder is fully moved to the top. (b) The output current produced by the BV-TENG of the vertical-direction mode. (c) Schematic diagram showing the rotational-direction working principle of the BV-TENG. (i) The BV-TENG is in the static state and the PTFE powder is in contact with the villus-shaped columns. (ii) The BV-TENG is moving under a rotational mechanic force. (iii) The PTFE powder is rotated 180°. (d) The output current produced by the BV-TENG of the rotational-direction mode.
breaking the electrical neutralization. At this time, the electron flow in the external circuit is driven by the potential difference [20], as shown in Fig. 2(a) (ii). When the PTFE powder is completely separated from the A part but is in full contact with the B part, the electron flow is interrupted because the electrical equilibrium is matched, and this is shown in Fig. 2(a) (iii). Fig. 2(b) shows the output current according to the mechanism of the vertical-direction mode. The peaks of the output voltage and the current in the vertical-direction mode are asymmetrical, where the positive peak is broader than the negative peak. The integrated-peak area, however, shows that the peaks are the same as each other, and this means that the output performances of both the positive and negative peaks are similar, and only the driving time is different because the electrostatic force between the ABS surface and the PTFE powder delays the time for the dropping of the powder (see Fig. S3).

Fig. 2(c) shows the rotational-direction mode with a working principle that is similar to that of the vertical-direction mode. The top-view of the device is considered for the division of the A and B parts into a half of the ABS. In the initial state, the triboelectric effect is induced at the interface between the PTFE powder and the A part with the negative and positive charges, respectively, and this is shown in Fig. 2(c) (i). As the device is rotated, the PTFE powder gradually moves to the B part, and the potential difference indicates that electrons flow in an external circuit, as can be seen in Fig. 2(c) (ii). When the PTFE powder is in full contact with the B part, the electron flow is interrupted, as shown in Fig. 2(c) (iii). Fig. 2(d) shows the output current according to the mechanism of the rotational-direction mode. The fabrication of a TENG through the coating of Ag on the outer surface of a device was easily achieved, and the possibility of various working modes is due to the changing of the electrode arrangement.

3.3. Characteristics of the BV-TENG optimization

The BV-TENG comprises a maximized surface area, and the PTFE powder was used to achieve the full contact for it. In this regard, the behaviors of the triboelectric effect and the electrostatic effect vary depending on the particle size of the PTFE powder. Fig. 3 shows the shape of the PTFE-powder particle sizes of about 0.2, 100, and 500 μm. Theoretically, the smaller particle size of the powder, the further that the contact area is increased and the greater the triboelectric charge that is formed; therefore, it can be expected that the output performance will be increased. The experiment, however, showed a level of electrostatic force between the PTFE powder of the 0.2- and 100-μm sizes and the ABS surface owing to the triboelectric charge, which is greater than the gravity depending on the powder weight, resulting in a lack of separation between the ABS and the PTFE powder that is problematic and results in the decreasing of the output performance. Regarding the PTFE powder of the 500-μm size, while a large number of triboelectric charges were also generated, it can be easily separated from the ABS because its gravity is relatively larger than the electrostatic force; this results in the higher output-root mean square (RMS) voltages of 1.7 V and 2.3 V in the vertical-direction mode and the rotational-direction mode, respectively, and this is shown in Fig. 3(a), (b). Therefore, the powder size should be considered to be important regarding the powder-type TENGs, and a diameter of at least hundreds of micrometers should be used for a smooth contact separation.

To investigate the difference of the output performance according to the number of villus-shaped columns, four types of TENG were fabricated, as follows (N(#) refers as a number of villus structure at one layer, all four types of TENGs consist 4 layers): 0 (N = 0; flat cylinder), 8 (N = 2), 16 (N = 4), and 24 (N = 6) villus. Output performance of BV-TENGs depends on a number of villus as shown in Fig. 3(c), (d). BV-TENGs with 0, 8, 16, 24 villus structure performs 1.1, 2.9, 4.2, 5.4 nC...
under vertical-direction mode, and 1.3, 2.7, 3.7, 4.9 nC under rotational-direction mode. As the villus number is increased, both the active triboelectric area and the generated triboelectric charge increase, so the large potential-difference inducement means that many electrons flow back and forth between the electrodes [21]. This tendency was identically shown for both the vertical-direction and rotational-direction modes, where the induced charges from the 24-villus BV-TENG are approximately five and four times higher than 0-villus BV-TENG respectively.

Regarding the 24-villus BV-TENG, Fig. 4 shows the optimization process of the electrical-output characteristic for the vertical-direction and rotational-direction modes. First, in the vertical-direction mode, as the amplitude of the z-axis direction was increased to 10 mm, the freestanding mode became fully operational along with the increasing of the output charge density and power density up to 1.15 μC/m² and 0.74 mW/m², respectively, as shown in Fig. 4(a). The increasing of the frequency to 3 Hz contributed to the increasing of the output current [22], thereby increasing the output charge density and power density up to 1.7 μC/m² and 1.4 mW/m², respectively, and this is shown in Fig. 4(b). From these measurement data, it is evident that the output performance increases in the vertical mode as the moving distance and frequency of the PTFE powder are increased. In the rotational mode, the output performance was maximized as the volume ratio of the PTFE powder was close to 50%, because the freestanding mechanism is fully operational at this point, as shown in Fig. 4(c), where the output charge density and powder density reached 0.75 μC/m² and 13.9 μW/m², respectively.

If the volume ratio is less than 50%, the static charge on the ABS and the PTFE powder decreases along with the electrostatically induced charge in the electrode, and the latter reduces the electron flow in the external circuit. But if the volume ratio of 50% is exceeded, the negative charge on the PTFE powder neutralizes the positive charge on the opposite ABS surface, while the actual electrostatically-induced charge in the electrode is reduced along with the electron flow in the external circuit (see Fig. S5). Furthermore, with the placement of more PTFE powder into the BV-TENG, the contact force that is applied onto the ABS by the powder is increasingly strengthened, increasing both the contact area and the triboelectric charge [13,23]. Therefore, the output-rate decrease after the volume ratio of 50% is lower than that below the volume ratio of 50%.

As the centrifugal force became stronger than the gravitational force at the higher rotational speeds, the output performance was reduced in
3.4. Dust-adsorption systems

The internal surface area of the 3D-printed BV structure was maximized through the completion of the DLP-type 3D-printing process, thereby forming a large triboelectric charge on the ABS surface and the PTFE powder. The strong electrostatic charge can be utilized not only as a triboelectric generator but also as a dust-adsorption system [24]. For an efficient dust adsorption, the BV-DF was packaged with a PTFE ball with characteristics that are similar to those of the PTFE powder.

Fig. 5(a) shows a schematic description of the triboelectric dust filtering. When the BV-DF is moved in any direction by an external mechanical energy (linear/rotational/vibrational motion), the triboelectric effect leads to a negatively charged PTFE ball and a positively charged ABS. When the fine and ultrafine dust that are already self-charged flow through the inside of the mesh-type BV-DF [25,26], the positively charged dust adsorb onto the PTFE ball and the negatively charged dust adsorb onto the ABS due to the electrostatic force, and this is shown in Fig. 5(b). The experimental setup for the BV-DF is shown in Fig. S7(a). Scanning electron microscopy images of the surface of the dust-adsorbed PTFE ball confirmed that a level of electrostatic force induced the considerable adsorption of the fine and ultrafine dust onto the surface of the PTFE ball compared with the bare PTFE ball, and this is shown in Fig. 5(c) and Fig. S7(b).

Fig. 5(d) shows the simulation of the BV-DF potential distribution for which the COMSOL Multiphysics modeling software was used. The simulation results show the immense triboelectric potential of the BV-DF that can efficiently adsorb self-charged dust. Fig. 5(e) and Fig. S7(c) show the dust-adsorption experiment results for which a BV-DF that is driven by the rotational mode was used. The PM-2.5 level of 107 μg/m³ gradually decreased and reached 63 μg/m³ after 75 min. Furthermore, since the ABS and the PTFE ball were not damaged even after the washing, and the experiment showed a stable postwashing adsorption efficiency, this BV-DF can be easily reused after a washing procedure. To support the above experiment result, as shown in Fig. S8, the COMSOL Multiphysics simulations were performed with respect to the BV-DF dust-flow behavior and the characteristics of the dust-particle

Fig. 5. (a) Schematic description of the BV-DF. (b) Internal schematic diagram of the BV-DF, the self-charged dust adsorbed onto PTFE ball and ABS. (c) Scanning electron microscopy images of the surface of the dust-adsorbed PTFE ball. The inset (scale bar: 3 μm) shows an SEM image of the ultrafine dust on the PTFE ball. (d) COMSOL Multiphysics simulation results. (e) Experimental data of the PM-2.5 level change with time (before and after washing).
percentage according to the charge density of the self-charged ultrafine dust.

4. Conclusion

In conclusion, a new type of bio-mimicked TENG and a dust filter with a maximized surface area have been developed via a powerful fabrication method for which a high-resolution DLP-type 3D printing process is applied. Regarding the BV-TENG with the 24 villus-shaped columns, a surface-area increase of 300% was shown compared with the flat cylindrical structure, and it is driven by various types of mechanical energy, where not only the linear vertical motion but also the rotational motion are employed. It was experimentally confirmed that the output performance increased fivefold and fourfold in the vertical-direction mode and the rotational-direction mode, respectively, together with the verification of a stable operation over 10,000 cycles. Further, the 3D-printed BV structure can be utilized for the design of an ecofriendly self-powered dust filter, and this was proved using experimental measurements and COMSOL simulations. Using the electrostatic attraction, ultrafine dust under the diameter of 2.5 μm can be efficiently filtered over 75 min at a rate of approximately 40%. In summary, the 3D-printed BV structure with the maximized surface area can be actively used not only for TENGs but also for self-powered dust-filtration systems. Because of the convenient fabrication process, time saving, and customizability, the 3D-printing technology provides an efficient method for the fabrication of TENGs and various applications where triboelectrification and electrostatic induction are used.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.nanoen.2019.103857.

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