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THE HONG KONG
POLYTECHNIC UNIVERSITY
香港理工大學

Department of Applied Physics

Final Year Project Report

Project Title

**Enhanced output power of freestanding ball-based
triboelectric generator through electrophorus effect**

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THE HONG KONG POLYTECHNIC UNIVERSITY**Abstract**

Recent development of Internet of Things and related sensor technologies have greatly impacted on the logistics tracking, structural health monitoring, environment analysis, and data extraction. It is highly imperative to develop a technology to allow the sensor node to operate independently, sustainably, and maintenance-free by harvesting the energy from the ambient environment. Here we demonstrate a triboelectric device as a high-efficient and durable kinetic energy harvester from ubiquitously mechanical vibration. We construct a cylinder coated with polytetrafluoroethylene (PTFE), and place a number of metal balls inside the cylinder. This ball-based triboelectric generator (B-TEG) converts the mechanical shaking into the electricity. By grounding the metal-freestanding-layer, the output power shows 16 times improvement through the electrophorus effect. This triboelectric nanogenerator can charge a 100 μF capacitor within 100 second, providing potential for supplying sustainable power to wireless sensor nodes.



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Chapter 1 Introduction

1.1 Self-powered sensor: triboelectric nanogenerator

Wireless sensor networks (WSNs) are widely used in logistics data logging [1], construction health monitoring [2], environment status monitoring [3], and healthcare monitoring [4]. With the limited lifetime of batteries, power source has become a big barrier for further implementation of WSNs. Exploiting sustainable power source from the ambient is the ideal and most demanding challenge for future industries. Energy harvesting devices convert ambient energy sources, such as, solar light [5], mechanical vibrations [6-7], heat [8] etc., into electricity.

Solar cell is a well-developed mature technology for harvesting ambient light and supplying electricity. However, it cannot supply electrical power under the environment without light exposure, which greatly restricts its application scenarios. When sensor nodes are embedded in dark and inaccessible locations, they require sustainable power sources. For example, the containers in the logistics are typically placed inside the trucks and vessels. They lack of solar light but are rich with mechanical vibration during the transportation. It is important to develop enabling technologies that can harvest kinetic energy to supply power to sensor nodes (inside



containers), which are placed without the exposure to solar light. Among all energy sources, mechanical vibration ubiquitously exists in various environments, such as, vibration of machine, human movement, the flow of the water and wind [9-13]. Piezoelectric and triboelectric harvester can convert the mechanical motion into electricity [14-16].

Triboelectric nanogenerators have attracted significant attention in recent years because of their simple structure and broad materials selection. When a metal and a dielectric contact to each other, electrons transfer from the metal to the dielectric materials. The surface of dielectric material is negatively charged, and the metal surface is positively charged [17-18]. By connecting two materials with a conductor, a high voltage electricity occurs because of contact electrification and electrostatic induction [19]. There are different types of triboelectric generators, including sliding mode [16,20-23], contact mode [15,20,24-30], single-electrode mode [31-33] and freestanding mode [34-35]. To enhance the energy conversion efficiency, Chun *et al.* boosted the output power by 16 times via an electric double layer effect in a configuration of three-layer system [14]. Kim *et al.* designed a powder-based triboelectric nanogenerator, where a rigid acrylic cylinder contains PTFE powder confined between the two aluminum metal plates [36]. The triboelectric nanogenerator based on pressing and sliding structures cover a wide range of mechanical vibrations. While, another form of mechanical vibration, shaking motion, widely exist in broad scenarios, but has been less reported for the use of triboelectric nanogenerator. In this work, we design and construct a so-called ball-based triboelectric generator (B-TEG) for harvesting the shaking motion. To effectively harvest the shaking motion, we place metal balls inside a cylinder



covered with PTFE. This structure enables us to have one more terminal in the middle metal balls for charge exchange.

1.2 Objectives

The main objectives of this project include

- (1) using B-TEG to convert the mechanical vibration into electricity;
- (2) boosting the output power of B-TEG by electrophorus effect; and
- (3) using B-TEG to power up a temperature sensor.

1.3 Organization of report

In this report, we will first introduce the ball-based triboelectric generator (B-TEG) and explain its working mechanism. We also show the output performance of B-TEG. After that, we provide a new configuration of grounded-metal-freestanding-layer triboelectric generator (B-GTEG). This new configuration boosts the output power of B-TEG by Volta's electrophorus. We will explain the reason of output power enhancement and have a comparison of B-TEG and B-GTEG. At the end, we show the 100 μF capacitor charging curve of B-TEG and B-GTEG and discuss the further applications of our device.



Chapter 2 Literature Review

2.1 Triboelectric effect on PTFE and Al

The working principle of triboelectric generator is triboelectric effect [19]. Triboelectric effect is an electrification effect that a material become electrically charged after it contacts and separates with another material. From the table of triboelectric series [37], PTFE has a greater tendency to gain electrons from Al. PTFE can acquire negative charges by contact and separation with Al because of triboelectric effect.

2.2 Freestanding triboelectric-layer nanogenerator

Freestanding triboelectric-layer mode is a typical mode of triboelectric nanogenerator [38]. A metal/dielectric freestanding layer is placed in the middle of the structure. It is charged due to its contact with the top and bottom layers of another material by triboelectric effect. If we make a pair of electrode on the top and bottom layers and connect 2 electrodes together, the charges flow between 2 electrodes to balance the local potential distribution because of the induction of the charged freestanding layer.



2.3 Volta's electrophorus effect

The electrophorus effect is announced by Volta in 1775 [39]. Generally, PTFE plate and a metal electrode with insulating handle are used for the experiment of electrophorus effect. The surface of PTFE plate is initially, negatively charged. The PTFE plate is placed at the bottom. When the metal electrode contacts the PTFE plate surface, the charges inside the metal electrode are separated into 2 parts, positive charges at the bottom surface and negative charges at the top surface. If we connect the metal electrode to the ground, the negative charges will go to ground and the positive charge will remain in the metal electrode. By this method, the metal electrode can become positively charged after separating from PTFE.



Chapter 3 Fabrication Procedures and Experimental Setups

3.1 Fabrication of Copper thin film electrodes on a piece of dielectric material

PTFE (PTFE, Huasheng) with 1 mm thickness was used as dielectric material. To prepare a coated PTFE sample, the air gun was used to remove the dust. The cleared PTFE was put into MRC sputter with the vacuum at 6 millitorr. The copper was sputtered on the PTFE under 20 sccm Ar flow-rate and 70 W Power for 15 min. The thickness of copper layer is around 70 nm on the one side of PTFE, used as the top and bottom layers.

3.2 Fabrication of triboelectric generator

A piece of PTFE was bended as a cylinder which have 30 mm diameter and 30 mm height. The copper tape with 5 mm width was stuck around the inner surface of the PTFE cylinder in the middle position. The bottom layer, which is a piece of 3.6 cm x 3.6 cm PTFE with copper coating, was used to cover one of sides of cylinder. Different numbers of 1 mm Al metal balls were put into the cylinder before it was sealed by another piece of PTFE with copper coating.



3.3 Characterization and measurements

A linear motor (PS-01-37x120-C, LinMot) which was operated at a cycle of cosine curve and 77 ms at rest was used to create a 3 Hz and 1 N shaking motion to the triboelectric generator. The period of cosine curve is 179.3 ms and the peak to peak value is 30 mm. A 600 MHz Oscilloscope (WaveSurfer 62Xs, LeCroy) and a low-noise current preamplifier (Model SR570, Stanford Research Systems, Inc.) were used for electrical measurements.



Chapter 4 Results and Discussions

4.1 Schematic diagram and Photos of B-TEG

Figure 1(a) shows the schematic diagram of the ball-based triboelectric generator (B-TEG). A paper cylinder has a height of 3 cm and an inner diameter of 3 cm. The surface of this cylinder is coated with PTFE by double side tape. The Al metal balls with a diameter of 1 mm are placed inside the cylinder. The top and bottom surfaces of PTFE cylinder are coated with Cu thin films as top and bottom electrodes. Figure 1(b) and 1(c) show the top-view and side-view photo of the B-TEG structure.

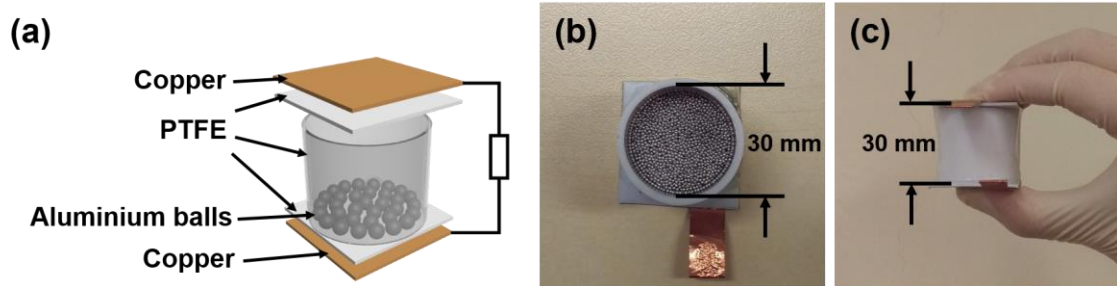


FIGURE 1 Illustration of the ball-based triboelectric generator. (a) Three-dimension schematic diagram of the ball-based triboelectric generator. Photo of (b) Top view and (c) side view of a ball-based triboelectric generator.

4.2 Working mechanism of B-TEG

This B-TEG operates in a freestanding mode, in which the Al metal balls serve as a freestanding metal layer and the PTFE cylinder works as the counter triboelectric material. Appendix A and Figure 2 illustrate the working mechanism of ball-based



triboelectric generator (B-TEG). In the 1st cycle, as the cylinder with Al balls undergoes mechanical shaking, the inside Al balls contact (Appendix A(a)) with the surface of bottom PTFE and then separate (Appendix A(b)) from it. The electrons in Al balls are attracted to PTFE because of triboelectric effect [40]. Thus, the Al balls carry positive charges and PTFE carries negative charges. The positively charged Al balls bring about electrostatic induction to the electrodes near PTFE. The bottom electrode becomes negatively charged [38]. The charges flow through the external circuit and form current. Then the Al balls move upward and contact with the surface of top PTFE. Similar to the case that the Al balls are contacted with bottom PTFE surface, the contact and separation process generate negative charges on the top Cu electrode, where the direction of current flow is reversed. In the whole cycle, the mechanical shaking generates alternating current (AC) in the external circuit of the B-TEG structure, which can be connected to a rectifier for conversion to DC current.

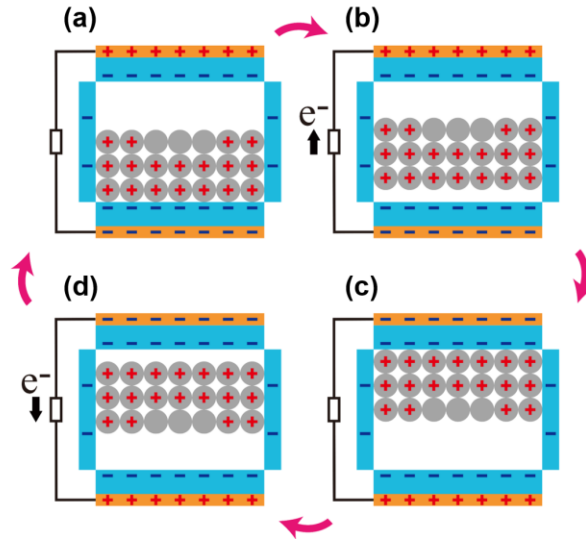


FIGURE 2 Working mechanism of ball-based triboelectric generator (B-TEG). (a) Contact to bottom surface: Al balls contact with bottom inner surface of PTFE cylinder. (b) Separation from bottom surface: Al balls move upwards and leave the bottom inner surface of PTFE cylinder. (c) Contact to top surface: Al balls contact with the top inner surface of PTFE cylinder. (d) Separation from top surface: Al balls move downwards and leave the top inner surface of PTFE cylinder.

4.3 Output performance of B-TEG

We use a linear motor (PS-01-37x120-C, LinMot) to provide a mechanical shaking of 1 N force and 3 Hz frequency to the B-TEG. The B-TEG is filled with the Al balls with the volume ratio of 50% and the ball diameter of 1 mm. Figure 3(a) and 3(b) show the open-circuit voltage (V_{OC}) and short-circuit current (I_{SC}) of the B-TEG under external drive. The B-TEG shows high V_{OC} of 26 V, and high I_{SC} of 1.1 μA . We extract the output power with different load resistors ranging from 1 Ω to 1000 M Ω , as shown in Figure 3(c). The highest output power is 3.77 μW with the use of a 100 M Ω load



resistor.

We investigate the effect of the volume ratio of Al balls on the output performance of B-TEG. Figure 3(d) shows the V_{OC} and I_{sc} of the B-TEG as a function of the volume ratio of the Al balls, from 20% to 80%. When the volume ratio is increased from 20% to 40%, the V_{OC} and I_{sc} is increased from 21.3 V to 27.0 V and from 0.364 μA to 0.557 μA respectively; while the V_{OC} and I_{sc} of B-TEG is decreased when the volume ratio of Al balls is over 40%. With the increase of the volume ratio of Al balls, on one hand, greater contact force will act on the PTFE, which increases the contact area between Al balls and PTFE; on the other hand, the increase of the volume ratio of Al balls decreases the distance between electrodes and Al balls. The electrode, separating from Al balls, is induced negative charges due to a short distance between the electrode and Al balls. The electric potential between two electrodes drops. These two competing factors result in an optimum point. Thus, the output power increases with the volume ratio of the Al balls, but decreases after obtained the maximum output at the volume ratio of 40%.

We also change the ball diameter from 1 mm to 4 mm. Figure 3(e) shows that the highest output is obtained using the ball with the diameter of 3 mm. The increase of ball diameter increases the mass of Al ball. The Al balls with low mass have a chance to stick on the inner surface of PTFE cylinder by electrostatic force. The stuck Al balls form a protective wall against the contact of PTFE with other Al balls, and the output voltage and current drops. This problem can be solved using high mass Al balls. On the other hand, the contact area depends on the gap between Al balls. There is a larger gap between Al balls with the increase of ball diameter. Thus, the output power of the B-TEG increases with the diameter of balls, while decreases after it reaches the maximum output with the ball diameter of 3 mm. In the rest of the experiments, we use



mechanical shaking of 1 N force and 3 Hz frequency, Al ball volume ratio of 50% and ball diameter of 1 mm as a reference to compare with other structures.

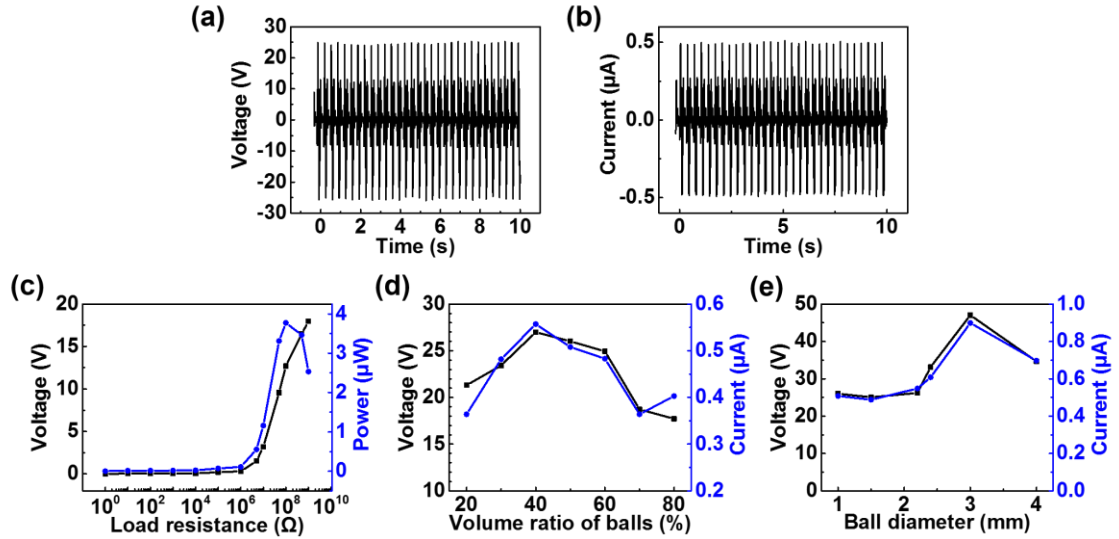


FIGURE 3 Output performance of ball-based triboelectric generator under a mechanical shaking of 1 N force and 3 Hz frequency. (a) Open-circuit voltage, (b) Short-circuit current, (c) output power as a function of load resistance, (d) effect of volume ratios of Al balls on the open-circuit voltage and short-circuit current, and (e) effect of ball diameters of Al balls on the open-circuit voltage and short-circuit current.

4.4 Comparison of B-TEG and B-GTEG

In the B-TEG structure, the Al balls inside the container are generated with abundant charges by the triboelectric effect during the shaking motion. But it lacks an effective way to collect the generated charges. To boost the output, we provide one more terminal in the middle of the container, where a metal tape is wrapped around the middle of the inner surface of the container and connected to the ground, as schematically shown in Appendix B. The metal tape is a bridge to allow the charge



exchange between Al balls and ground during the shaking motion. The charge in Al balls can be extracted by the ground connection for an additional output in this structure. Therefore, a new configuration of ball-based grounded-metal-freestanding-layer triboelectric generator (B-GTEG) is designed and created to collect the abundant charges of the Al balls generated during the mechanical shaking, based on Volta's electrophorus.

Figure 4(a) shows the schematic of B-TEG and B-GTEG. The B-TEG has only one single output (Load A). However, B-GTEG has 2 outputs (Load A and B) because we provide one more terminal of metal tape. We take the Cu metal tape with the width of 5 mm to place in the middle of the cylinder as the additional terminal. The working mechanism of B-GTEG is schematically described in Appendices C and D. It is similar to that of B-TEG. The major difference is that the charges in Al balls are allowed to flow to the ground or go back to Al balls by electrophorus effect. When the Al balls approach PTFE, the positive charges and negative charges in Al balls are separated due to the electrostatic induction of negatively charged PTFE. After the ground connection to the middle terminal of the B-GTEG structure, the Al balls contact with this middle terminal, allowing the negative charges in Al balls to flow to ground. Thus, Al balls become positively charged. This so-called electrophorus effect has been widely used to generate electricity. Figure 4(b) shows the output power of B-TEG and B-GTEG. The Load A of B-GTEG shows much high power of 41.06 μW compared with that of B-TEG (3.77 μW). The total output power of B-GTEG (Load A + Load B) is 59.50 μW . There is a 16-fold output power enhancement. The grounded connection in the middle terminal is needed for electrophorus effect to increase the output current and voltage. Electrophorus effect is used to produce more electrostatic charges in Al balls by electrostatic induction.



As the positive charges in Al balls are reduced after connected to the ground, Al balls are easier to lose their electrons to PTFE during the shaking motion. The surface of PTFE becomes more negative. It makes the potential difference between top and bottom electrodes increase. On the other hand, electrophorus effect can be used to describe the flow of charges in the terminal of metal tape. During the shaking motion, the Al balls contact and separate to inner surface of PTFE cylinder. When the Al balls is approaching to the inner surface of PTFE cylinder, positive charges can be induced to Al balls because of the negative charges on the PTFE surfaces. We can extract more charges from the terminal of metal tape by the electrophorus effect. Thus, the total output power can be enhanced.

We also study the effects of the materials and width of the middle metal tape on the output performance. For Load A, the output current of B-TEG without metal tape is $0.5 \mu\text{A}$. After connecting the Al or Cu metal tape in the middle part of the cylinder, the output current of B-GTEG is increased to around $0.9 \mu\text{A}$. The structures with grounded metal tapes have a higher output current, as shown in Figure 4(c). The ground connection of metal tape is required for electrophorus effect to extract electrons from Al balls. The output currents of the B-GTEG structure with grounded Al metal tape and Cu metal tape are $1.25 \mu\text{A}$ and $1.55 \mu\text{A}$, respectively. From the table of triboelectric series [37], Al has a greater tendency to lose electrons than Cu. Al balls becomes more positively charged and have a higher output current after the contact of Al balls and Cu tape.

By increasing the width of the metal tape from 5 mm to 30 mm, the output current is reduced to $1.45 \mu\text{A}$ (10 mm) and $1.09 \mu\text{A}$ (30 mm), respectively, as shown in Figure 4(d). The increase of the width of metal tape reduces the contact area of inner surface of PTFE cylinder as well as the accumulated charge in Al balls. As a result, the



output power is reduced with the increase of the width of metal tape. The same result is also shown in Load B, as shown in Figure 4(e). Therefore, the optimized output current can be generated by using grounded Cu metal tape.

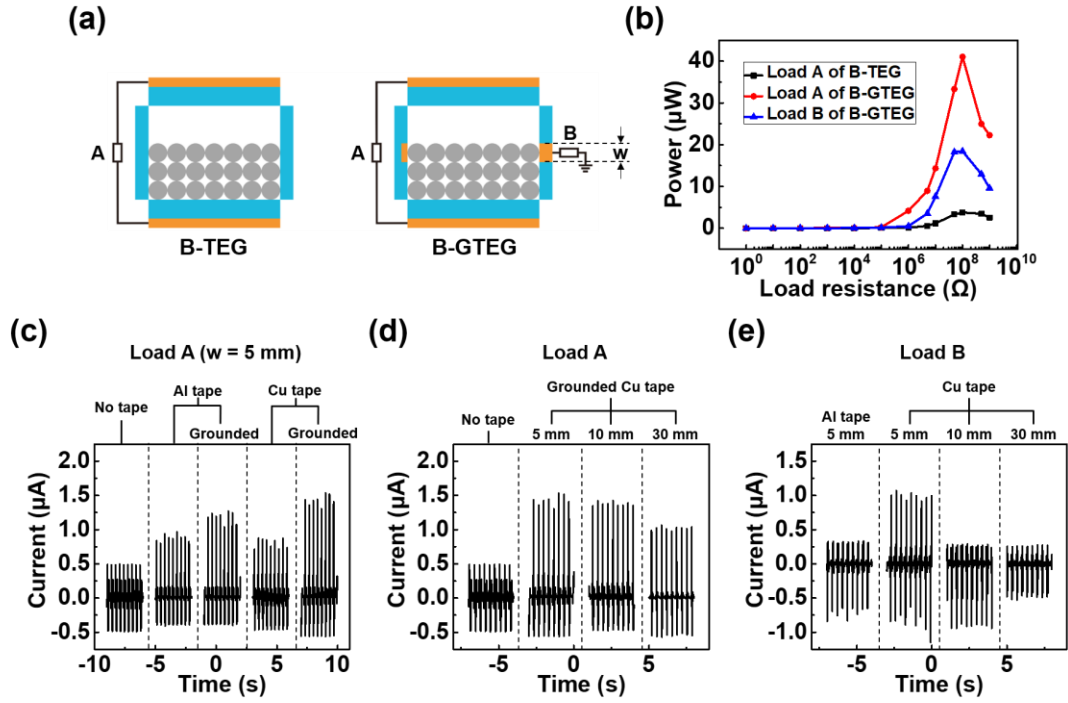


FIGURE 4 (a) Illustration of the B-TEG and B-GTEG. (b) Output power of B-TEG and B-GTEG. Short-circuit current with using (c) different materials of metal tape in Load A, (d) different width of metal tape in Load A, (e) different material and width of metal tape in Load B.

4.5 Capacitor charging curve of B-TEG and B-GTEG

The ambient mechanical vibration is usually intermittent and unpredictable. It is important to store the harvested energy in an energy storage device. To harvest the mechanical energy for powering a sensor node, we use a 100 μF capacitor to test the different configurations. Figure 5(a) shows the circuit configurations of B-TEG and B-



GTEG to charge a capacitor using different number of rectifiers. Capacitor charging curves of different configurations of B-TEG in 100 s are shown in Figure 5(b). B-GTEG has a better performance and it can charge up the capacitor to 0.86 V in 100 s. B-TEG only charge up the capacitor to 0.49 V in 100 s.

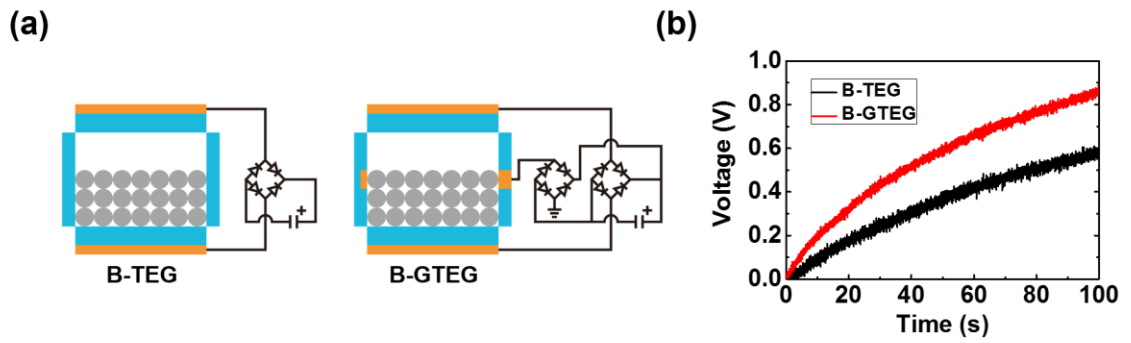


FIGURE 5 (a) The circuit diagram of charging capacitor in B-TEG and B-GTEG. (b) Plot of 100uF capacitor charging with B-TEG and B-GTEG in 100 s.



Chapter 5 Conclusions and Future Recommendation

5.1 Conclusions

In summary, we design and construct a freestanding ball-based triboelectric generator and create a grounded metal-freestanding-layer. Cu tape is used as the bridge to connect Al balls to the ground. The B-GTEG can boost the output power by the Cu-Al interaction and electrophorus effect. The output power is increased from $3.77 \mu\text{W}$ (B-TEG) to $59.50 \mu\text{W}$ (B-GTEG). There is a 16-fold output power enhancement. Grounded metal-freestanding-layer is the easiest way and cheapest method to boost a freestanding triboelectric generator. Our works provide great advantages over conventional power boost method on triboelectric generator.

5.2 Future recommendations

In our device, it is hard to apply the B-GTEG to real applications. The output power is still low to power up a sensor. The output characteristics with high voltage and low current is the problem of application of B-GTEG. A common sensor needs around 3.5 V and a certain current. If we convert the output voltage and current of B-GTEG with a transformer, there is a huge power loss. Therefore, B-GTEG cannot be a power source of a sensor. To enhance the power of B-GTEG, we can make some nano-pattern on the PTFE and Al balls. It can increase the contact surface area of PTFE and Al balls to improve the output performance of B-GTEG.



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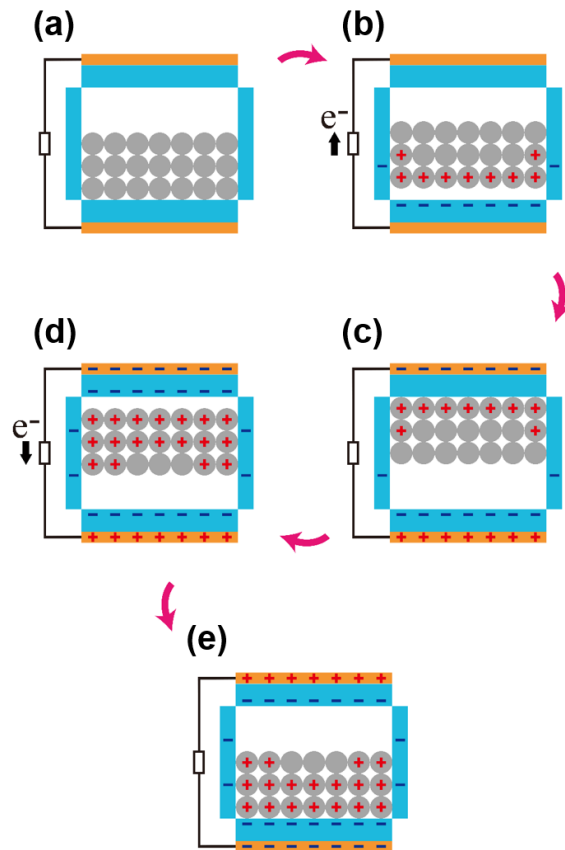
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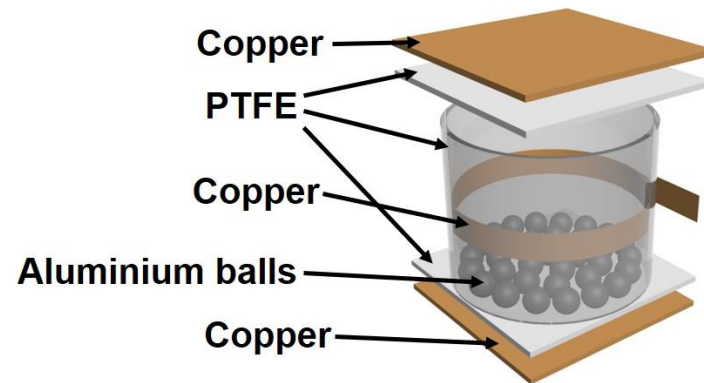
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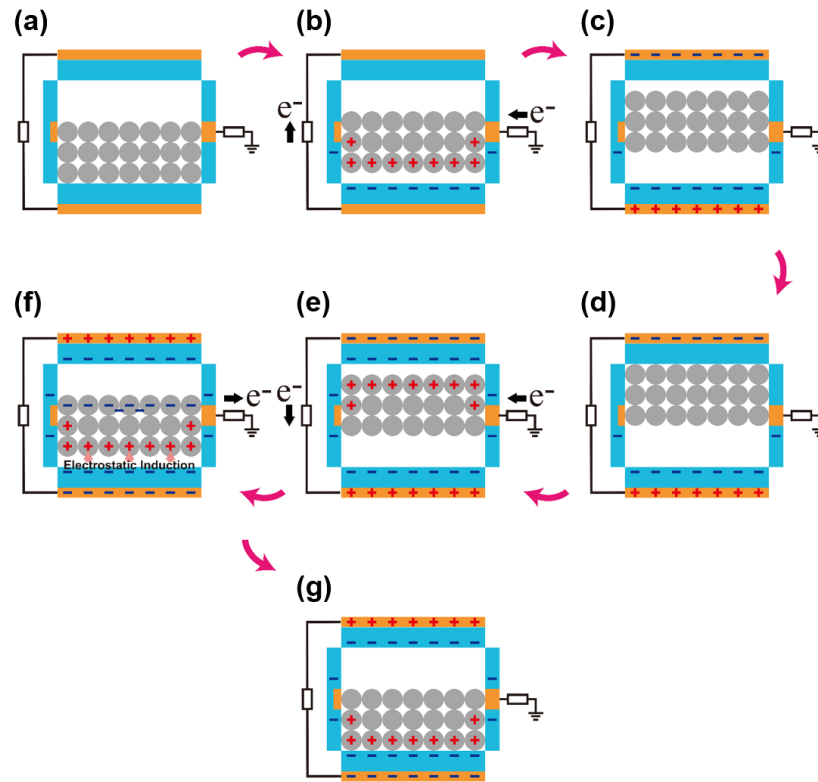
Appendices



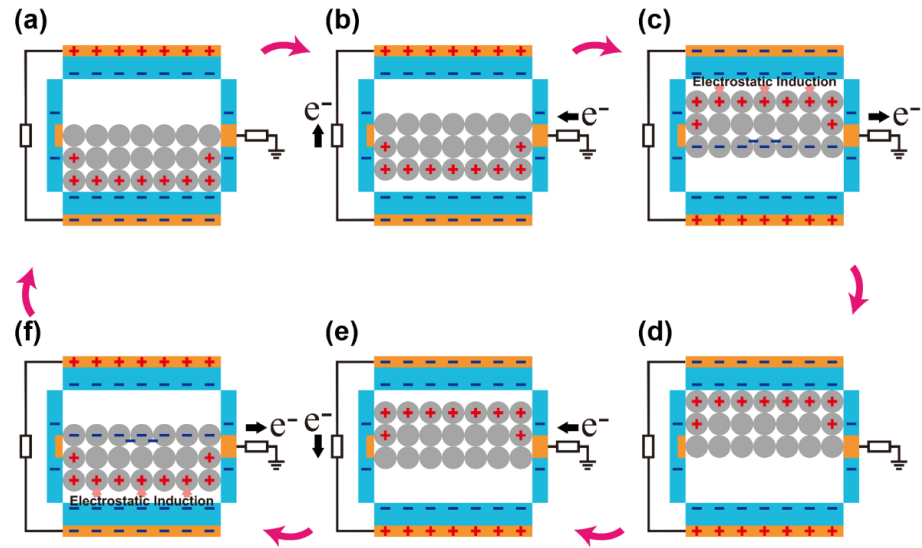
APPENDIX A Working mechanism of ball based triboelectric generator (B-TEG) at 1st cycle. (a) Initial state: Al balls contact with bottom inner surface of PTFE cylinder. (b) First separation: Al balls move upwards and leave the bottom inner surface of PTFE cylinder. (c) First contact: Al balls contact with the top inner surface of PTFE cylinder. (d) Second separation: Al balls move downwards and leave the top inner surface of PTFE cylinder. (e) Contact to bottom surface: Al balls contact with bottom inner surface of PTFE cylinder.



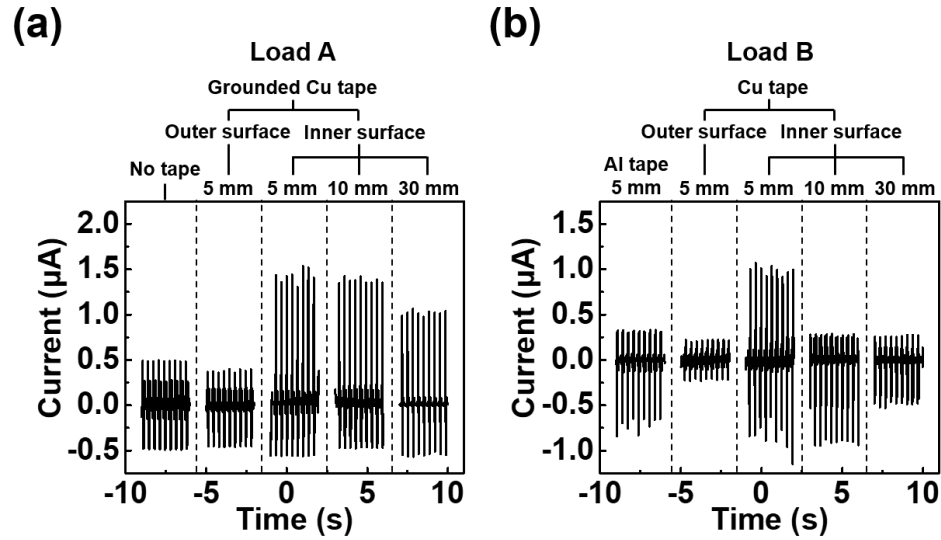
APPENDIX B Illustration of the ball-based grounded-metal-freestanding-layer triboelectric generator (B-GTEG).



APPENDIX C Working mechanism of ball-based grounded-metal-freestanding-layer triboelectric generator (B-GTEG) at 1st cycle. (a) Initial state: Al balls contact with bottom inner surface of PTFE cylinder. (b) First separation: Al balls move upwards and leave the bottom inner surface of PTFE cylinder. (c) Electrostatic induction (X): There is no electrostatic induction at the 1st cycle. (d) First contact: Al balls contact with the top inner surface of PTFE cylinder. (e) Second separation: Al balls move downwards and leave the top inner surface of PTFE cylinder. (f) Electrostatic induction: Electrophorus effect is occurred when Al balls are approaching the bottom inner surface of PTFE cylinder by electrostatic induction. (g) Contact to bottom surface: Al balls contact with bottom inner surface of PTFE cylinder.



APPENDIX D Working mechanism of ball based grounded-metal-freestanding-layer triboelectric generator (B-GTEG). (a) Contact to bottom surface: Al balls contact with bottom inner surface of PTFE cylinder. (b) Separation from bottom surface: Al balls move upwards and leave the bottom inner surface of PTFE cylinder. (c) Electrostatic induction: Electrophorus effect is occurred when Al balls is approaching the top inner surface of PTFE cylinder by electrostatic induction. (d) Contact to top surface: Al balls contact with the top inner surface of PTFE cylinder. (e) Separation from top surface: Al balls move downwards and leave the top inner surface of PTFE cylinder. (f) Electrostatic induction: Electrophorus effect is occurred when Al balls is approaching the bottom inner surface of PTFE cylinder by electrostatic induction.



APPENDIX E (a) different width of metal tape in Load A, (b) different material and width of metal tape in Load B.

To verify the effect of metal tape, we also tried to wrap around the middle of the outer surface of the container by Cu metal tape. However, the output current with outer metal tape is smaller than that without metal tape, as shown in Appendix E. Electrophorus effect does not work without a directly ground connection of Al balls. It proves that the metal tape must be connected to Al balls directly to boost the output current.