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Experimental Study of Surface Roughness of Triboelectric Nanogenerator

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ABSTRACT

Ecoflex Silicone rubber with various surface roughness was prepared and subjected to TENG testing with ITO coated with copper foil. Dektak XT was used to test thickness Pa and Pq values for different surface roughness levels. The samples are labelled as Sample_REF, Sample_P1200, Sample_P500, and Sample_P320 respectively according to the different sandpapers used. TENG devices were used to obtain four sets of samples corresponding to the voltage and current of the TENGs with an active area of 2.5cm × 2.5cm will be assessed under a fixed working condition. Finally, the electrical properties of each sample were compared to obtain the relationship between surface roughness and output performance.

KEYWORDS

Triboelectric Nanogenerator; Power Generation; Surface Roughness; Electrical Properties; Output Performance.

1. INTRODUCTION

1.1. TENG

Triboelectric Nanogenerators, often abbreviated as TENGs, are a novel and innovative technology in the field of energy harvesting and power generation. These devices harness mechanical energy from the environment and convert it into electrical energy through a process called the triboelectric effect. The triboelectric effect is a phenomenon in which two dissimilar materials, when brought into contact and then separated, generate an electric charge due to the transfer of electrons between them.

TENGs can generate electricity through the process of triboelectrification and contact electrification. For triboelectrification, TENGs rely on the principle of triboelectrification, which is the phenomenon where two dissimilar materials come into contact and then separate, causing a transfer of electrons between them. The triboelectric effect is due to a phenomenon when material becomes electrically charged after it is contacted with a different material through friction. When two different materials coming into contact, a chemical bond is formed between some parts of the two surfaces, called adhesion, and charges move from one material to the other to equalize their electrochemical potential. The transferred charges can be electrons or may be ions/molecules. In contrast, when two materials are being separated, some of the bonded atoms have a tendency to keep extra electrons, and some a tendency to give them away, possibly producing triboelectric charges on surfaces. The presence of triboelectric charges on dielectric surfaces can be a driven force for driving electrons in the electrode to flow in order to balance the created electric potential drop. This transfer of electrons results in one material becoming positively charged (due to losing electrons) and the other becoming negatively charged (due to gaining electrons). When these materials come into contact and then friction occurs, they undergo triboelectrification, where electrons are transferred between them. For contact electrification, when two materials with different electronegativities come into contact with each other, electrostatic charges are generated, which is called contact electrification. The driving force to convert mechanical energy to electrical energy via the change in potential through the mechanical separation between the two materials, this is called electrostatic induction.

1.2. Four Fundamental Operation Modes of TENGs

Generally, there are four fundamental operation modes of TENGs have been developed, i.e., the vertical contact-separation mode, lateral sliding mode, single-electrode mode and freestanding triboelectric layer mode, and have been extensively explored to harvest various mechanical/kinetic energies as shown below.

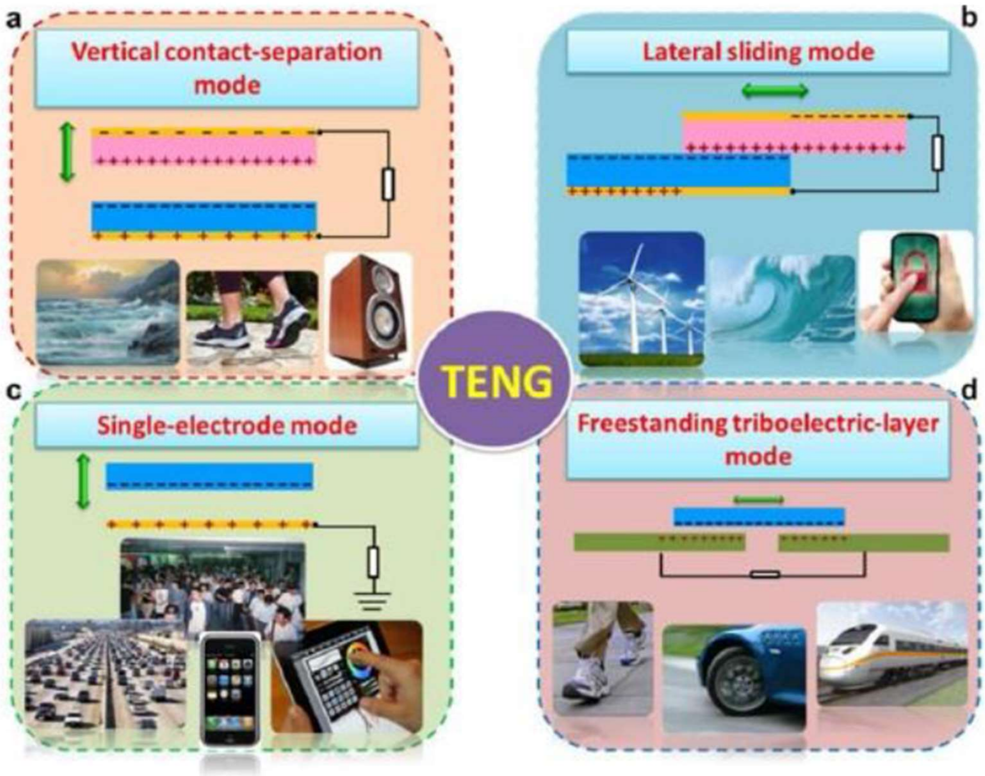

Figure 1. Four fundamental operation modes of TENGs

1) Vertical Contact-Separation Mode – Two dissimilar dielectric films are stacked and have electrodes on the top and bottom of the stacked structure. A physical connection between the two dielectric films creates oppositely charged surfaces. When the two surfaces are separated by a small gap caused by vibration or other mechanical energy, a voltage potential is created, which can be used to power an external load. Once the gap is closed (by an opposite vibration), the triboelectric charge created potential disappears, and the electrons flow back.

2) Lateral Sliding Mode – The structure to start with is the same as that for the vertical contact-separation mode but relies on a sliding motion rather than a vibrational motion to create triboelectric charges on the two surfaces. The sliding can be a planar motion, a cylindrical rotation, or disc rotation.

3) Single-Electrode Mode – This mode is designed for use in mobile systems where the TENG object can't be electrically connected to the load because it is part of the mobile system. For example, to harvest energy from a person walking across a floor, the electrode on the bottom part of the TENG is grounded. Motion between the electrode and ground changes the local electrical field distribution. There are electron exchanges between the bottom electrode and the ground to maintain the potential change of the electrode. This energy harvesting strategy can be in both contact-separation mode and contact-sliding mode.

4) Freestanding Triboelectric-Layer Mode – Triboelectricity (static electricity) is also generated by moving objects resulting from contact with air or other objects such as walking across a carpet. That charge can be harvested using a pair of symmetric electrodes underneath a dielectric layer. The object's oscillating motion relative to the electrodes creates an asymmetric charge distribution in the media, causing electrons to flow between the two electrodes. The moving object does not have to be directly in contact with the top dielectric layer of the electrodes. This mode of operation reduces friction and surface wear and results in highly durable TENGs.

Through referring journal, some additional knowledge about TENGs is obtained. TENGs use triboelectricity, commonly called static electricity, to convert common mechanical energy sources into electric power. In a TENG, electric charges are separated on the contact surfaces, and an electrical potential is generated between the surfaces. The alternating potential resulting from the dynamic mechanical motions can be used to charge a battery or for powering electric devices such as a wireless sensor. In addition, the potential profile, or the current profile, of a TENG can be used as a sensor to monitor motion or various chemicals. TENGs have been fabricated with an area power density up to 500 W/m^2 and instantaneous conversion efficiency of about 70%. In contrast with conventional electromagnetic generators, TENGs have their best performance at low frequencies (<5–10 Hz). They are well suited for harvesting energy from body motions, ocean waves, and similar low-frequency sources of motion. Four fundamental operational modes have been identified for TENGs.

Currently, the most popular TENG models assume idealized flat surfaces that guarantee complete contact and a contact force (or load)-independent response. However, all real surfaces possess some level of surface roughness which is known to produce a load dependent contact area.

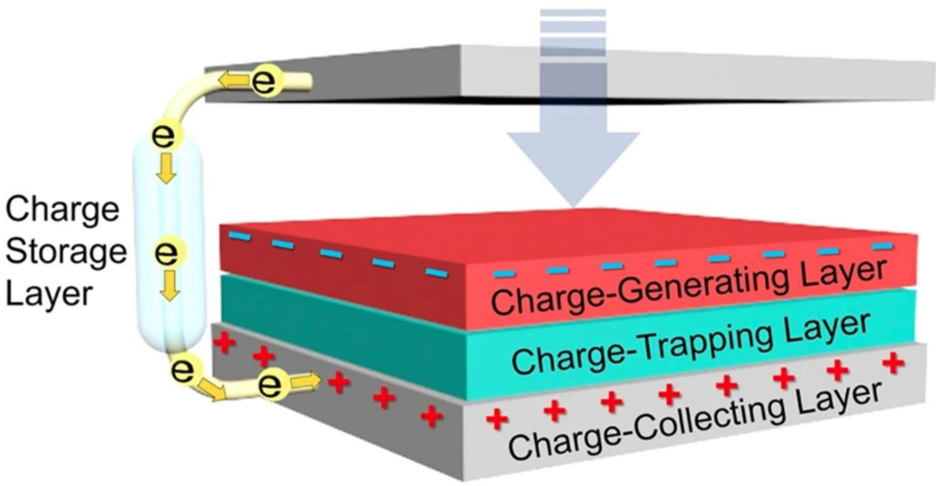

Figure 2. One of the most popular TENG models

1.3. Information Related to the Experiment

In this experiment, Ecoflex Silicone rubber with various surface roughness was prepared and subjected to TENG testing with ITO coated with copper foil. Dektak XT was used to test thickness

Pa and Pq values for different surface roughness levels. The experimental samples are labelled as Sample_REF, Sample_P1200, Sample_P500, and Sample_P320 respectively according to the different sandpapers used. TENG devices were used to obtain four sets of samples corresponding to the voltage and current of the TENGs with an active area of 2.5cm × 2.5cm will be assessed under a fixed working condition. Finally, the electrical properties of each sample were compared to obtain the relationship between surface roughness and output performance.

2. EXPERIMENTAL DETAIL

2.1. Sample Preparation

a. The conductive layer of the ITO glass was determined using a Keithley 6517B Electrometer.

b. A small strip of double-conductive copper (Cu) tape was cut and affixed to the conductive layer of the ITO. The double-sided conductive copper (Cu) tape was slightly extended beyond the edge of the ITO glass to enable the connection of wires in subsequent experiments. Care was taken not to peel off the back of the tape completely beyond the edge.

c. The ITO surface was completely covered with Kapton tape.

d. The clean glass was cut into 2.5cmx2.5cm squares, with a total of four pieces required.

e. The surface of each square piece of glass was entirely covered with double-sided conductive copper (Cu) tape, leaving an additional strip for wire connection in the subsequent experiment. Care was taken not to peel off the back of the tape completely beyond the edge.

f. 2mL of Part A and 2mL of Part B were transferred into the weighing boat, and they were stirred evenly with a toothpick.

g. The mixed liquid was applied to the glass with copper, placed into the spin coater, and the parameters were set to 1000rpm and 20s, ensuring the even distribution of the liquid on the surface of the copper. The other three pieces of glass with copper were treated in the same manner.

h. Cut P320, P500 and P1200 sandpaper into small pieces, each piece should be no smaller than the size of the glass (i.e. 2.5cmx2.5cm). The samples were then sandwiched between the glass substrate and the sandpapers with different roughness grades. The samples were left to dry overnight, and the sandpapers were subsequently removed. Depending on the roughness of the sandpaper used, the samples were alternatively labeled as Sample_REF, Sample_P1200, Sample_P500, and Sample_P320.

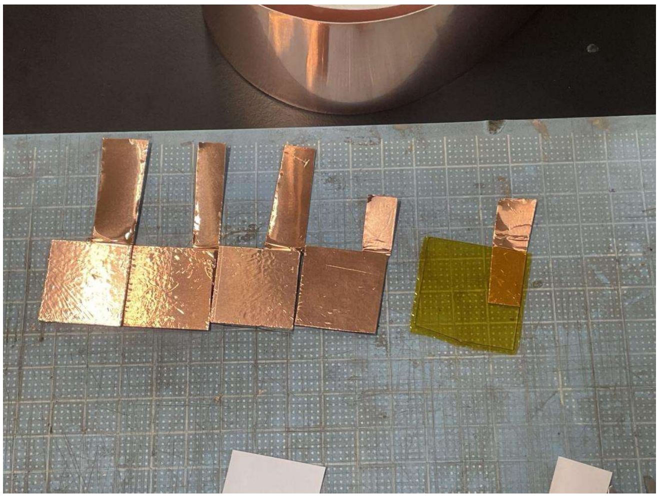

Figure 3. Prepared samples and ITO

2.2. Sample Area and Thickness Measurement

a. A photo was taken using a camera. The working area of the electrode was evaluated using Image J software, as per the instructions.

b. A Dektak XT stylus profiler meter and Mitutoyo digital microscrew gauge were used to measure the thickness of the thin and thick films. P_a and P_q value for each sample were obtained.

Figure 4. Dektak XT stylus profiler meter

2.3. Fabrication of TENG Devices

a. The ITO glass was attached to the back of the transparent glass at the upper end of the electrodynamic shaker. It was noted that the side with the Kapton tape was facing down. The white wire was clipped to the extension of the ITO glass copper.

b. The end of the Sample with the copper protruding upward was placed in the middle of the black surface of the electrodynamic shaker. The red wire was clipped to the extension section of the copper to ensure it was facing the ITO glass. The screw height for preloading was adjusted. Subsequently, the height of the three screw posts was adjusted to 4.5cm.

c. The parameters of the Waveform Generator were set to DC, 1000000Hz, and 4000Vpp, and testing was initiated.

d. The above operations were repeated for each group of Samples.

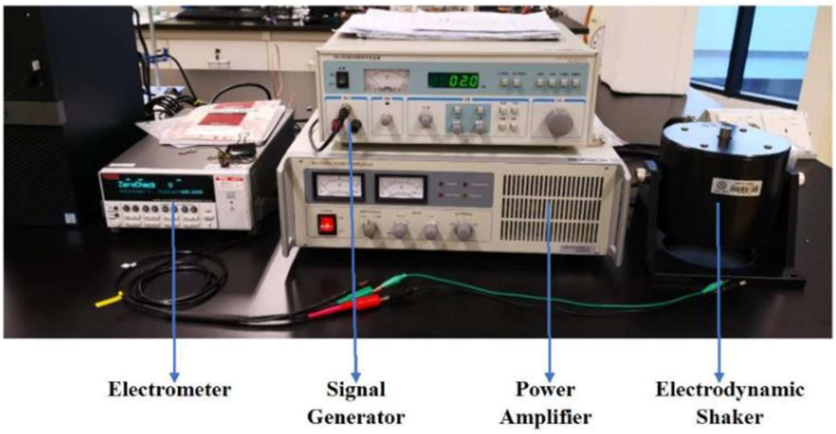

Figure 5. Some of the instruments involved in the experiment

2.4. Result Analysis

a. The computer Origin software was utilized to determine the V_{oc} and Q_{sc} values corresponding to each Sample. They were compared, and the relationship between surface roughness and output performance was obtained.

3. RESULT AND ANALYSIS

3.1. Surface Roughness (Table 1)

Table 1. Surface roughness of different samples

		Trial 1	Trial 2	Trial 3	Average	Root mean square
Sample_REF	P_a (nm)	150.83	180.56	195.46	175.62	176.59
	P_q (nm)	221.28	249.71	266.76	245.92	246.63
Sample_P1200	P_a (nm)	2233.01	3047.27	3089.49	2789.92	2817.63
	P_q (nm)	2846.37	3804.82	3843.39	3498.19	3528.46
Sample_P500	P_a (nm)	4780.42	5002.72	5540.89	5108.01	5117.98
	P_q (nm)	5751.55	6191.65	7545.71	6496.30	6541.01
Sample_P320	P_a (nm)	14110.89	12257.60	8148.48	11505.66	11772.34
	P_q (nm)	18576.67	15152.66	10270.57	14666.63	15057.45

3.2. Electrical Properties

Table 2. Open circuit voltage and short circuit charge density of different samples

Sample	V_{oc} (V)	Q_{sc} (nC/cm^2)
Sample_REF	67.99	3.50
Sample_P1200	93.35	10.95
Sample_P500	193.82	11.03
Sample_P320	178.78	10.99

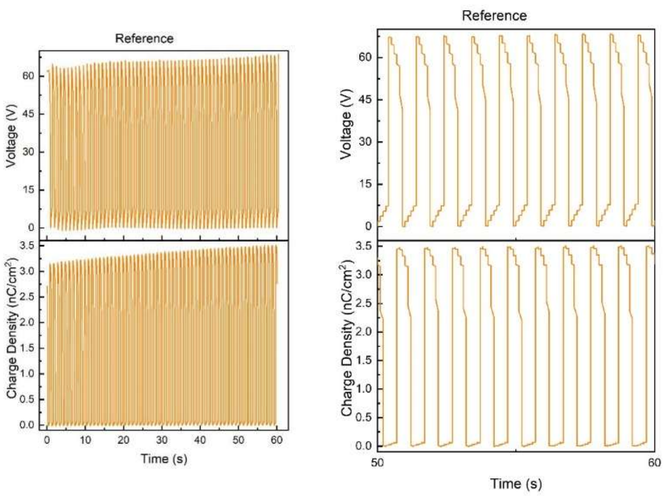

Figure 6. Changes of voltage and charge density over time for Sample_REF

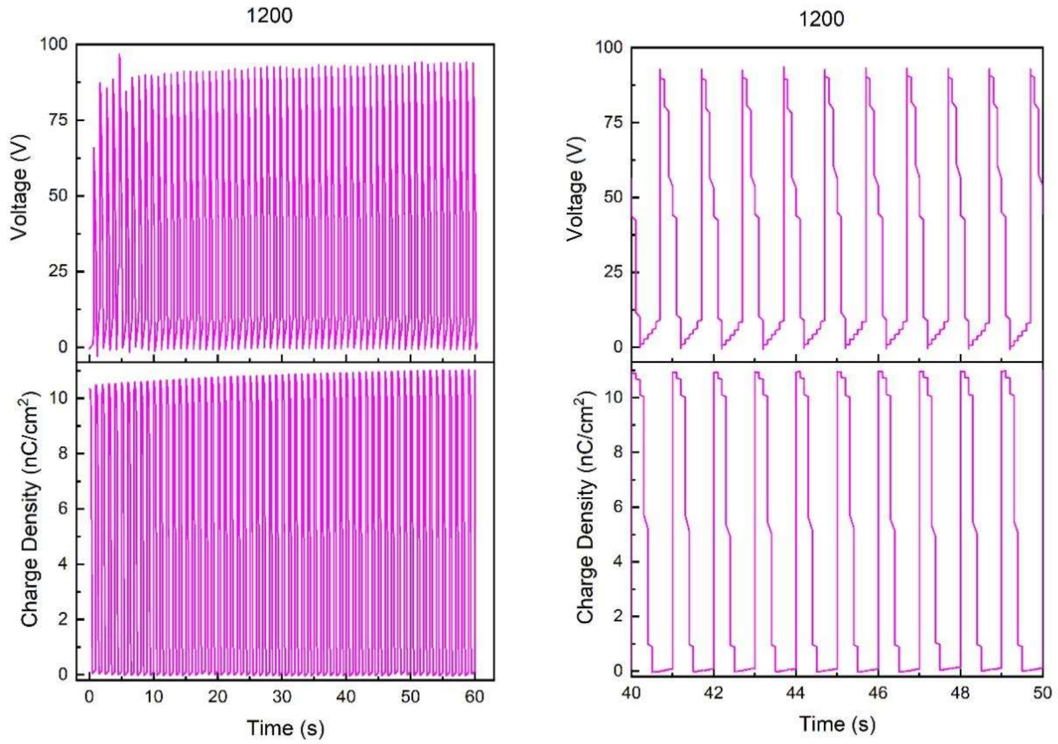

Figure 7. Changes of voltage and charge density over time for Sample_P1200

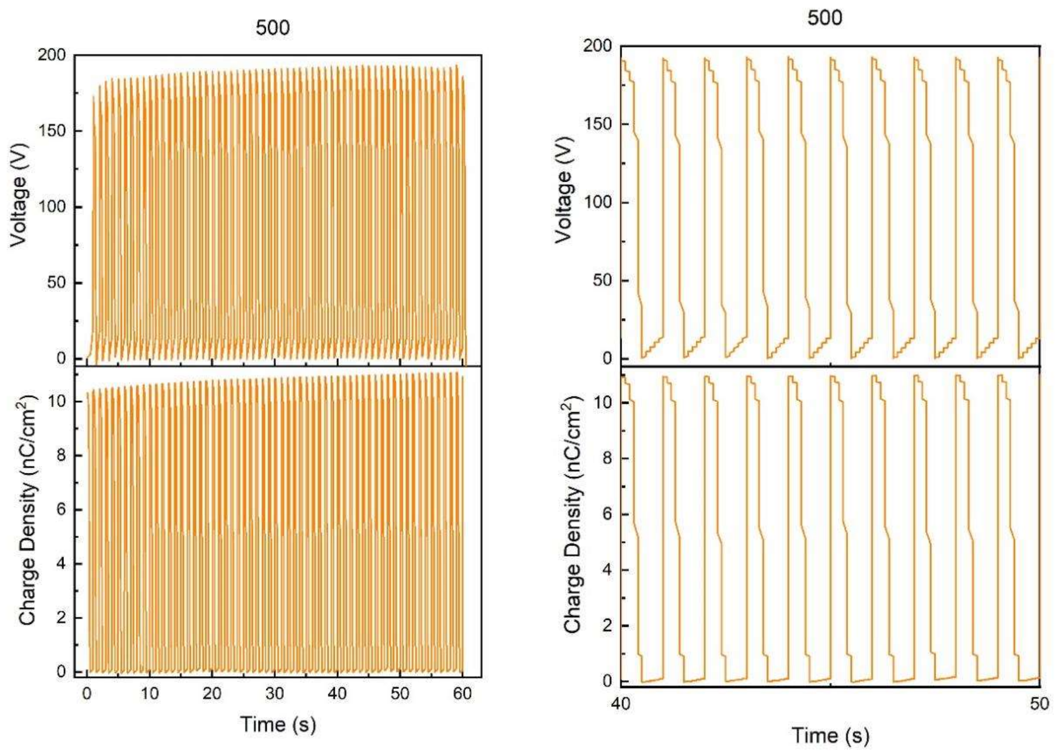

Figure 8. Changes of voltage and charge density over time for Sample_P500

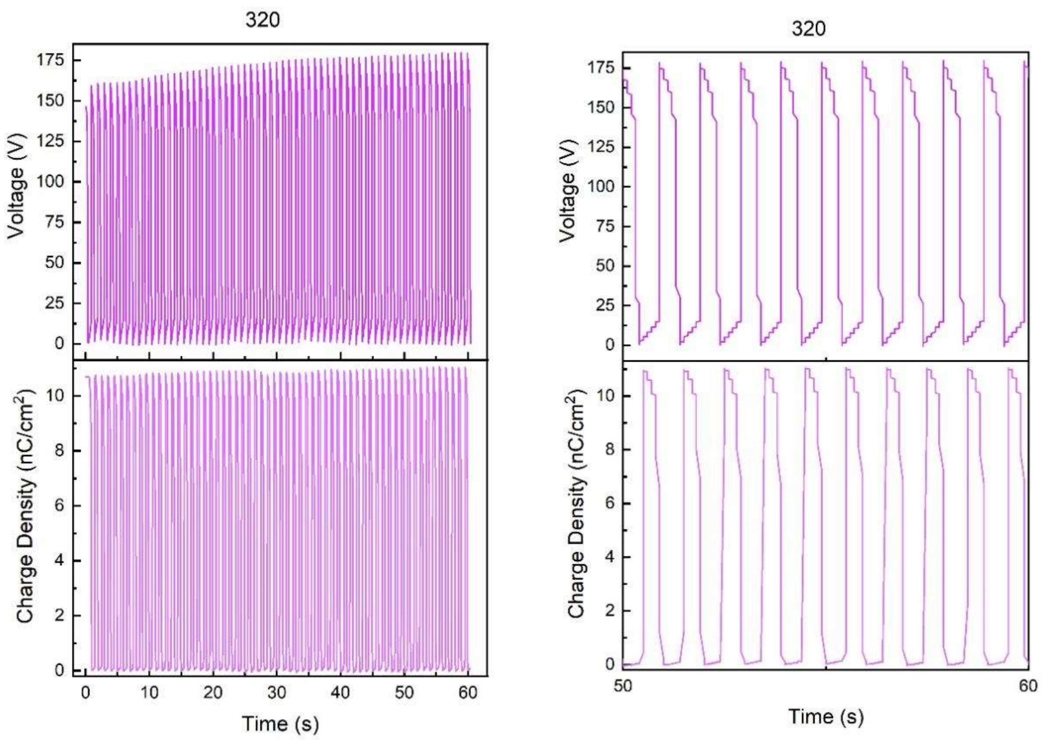

Figure 9. Changes of voltage and charge density over time for Sample_P320

For the voltage peak V_{oc}, the Sample_P500 group has the largest V_{oc} value of 193.82V, then is the Sample_P320 group of 178.78V, followed by the Sample_P1200 group of 93.35V and the Sample_REF group of 67.99V. For the charge density peak Q_{sc}, the results obtained are equally incredible. Sample_P500 group has the largest Q_{sc} value of 11.03nC/cm^2. Then is the Sample_P320 group of 10.99nC/cm^2, followed by the Sample_P1200 group of 10.95nC/cm^2 and the Sample_REF group of 3.50nC/cm^2.

4. DISCUSSION

Triboelectric Nanogenerators (TENGs) are energy harvesting devices that convert mechanical energy into electrical energy through a process known as the triboelectric effect. The triboelectric effect is based on the generation of an electric charge when two materials with different electrostatic properties come into contact and then separate. TENGs typically consist of two materials with contrasting triboelectric properties and are designed to facilitate controlled contact and separation.

In the experiment, TENG was used to determine the relationship between different surface roughness and output performance.

By referring the journals, generally the higher the roughness of the material, the higher the max/highest power output. In other words, max/highest power output performance is positively related to the roughness of the material. Therefore, according to surface roughness test, the Sample_P320 group should have the largest data, followed by the Sample_P500 group, followed by the Sample_P1200 group and Sample_REF group. However, experimental data show some very different results. For the voltage peak V_{oc}, the Sample_P500 group has the largest V_{oc} value of 193.82V, then is the Sample_P320 group of 178.78V, followed by the Sample_P1200 group of 93.35V and the Sample_REF group of 67.99V. For the charge density peak Q_{sc}, the results obtained are equally incredible. Sample_P500 group has the largest Q_{sc} value of 11.03nC/cm^2. Then is the

Sample_P320 group of 10.99nC/cm^2, followed by the Sample_P1200 group of 10.95nC/cm^2 and the Sample_REF group of 3.50nC/cm^2.

By analyzing the anomalies in the experimental results, several possible reasons were obtained. First of all, the experimental results should be obtained on the premise that the material surface is as flat as possible. Because in data sorting, each set of charge values was divided by the same area (2.5cmx2.5cm=6.25cm^2 in this experiment). Uneven materials or incomplete coverage will lead to different contact areas between materials, causing errors. In addition, under normal circumstances, max/highest power output performance is positively related to the roughness of the material. Because within a certain limit, the rougher the surface, the more contact points and the larger the contact area. However, if the surface is too rough, its contact points with the Si rubber will be reduced, thereby reducing the contact area and resulting in reduced results.

To improve the electrical performance, we have some methods. By referring to “A conventional triboelectric series and an experimentally determined triboelectric series of oxide dielectric materials” appendix, the greater the polarity difference between the two materials, the better the electrical performance produced by TENGs.

For example, glass has extremely high positive triboelectricity, while PTFE has extremely high negative triboelectricity. By making the two into a TENG, excellent electrical performance can be obtained.

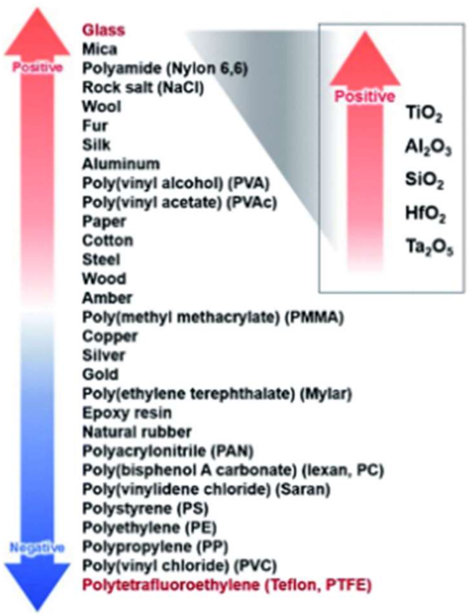

Figure 10. A conventional triboelectric series of oxide dielectric materials

Instead of material aspect, TENGs' output performance will be affected by many factors. Chief among them are temperature, humidity, pressure control and surface patterns.

Temperature can influence the mechanical properties of the materials used in TENGs. Extreme temperatures can affect material flexibility and friction characteristics. It's important to choose materials that can perform well within the expected temperature range of the application. In addition, temperature variations can lead to thermal expansion and contraction of TENG components, which can affect the contact and separation mechanisms.

Humidity affects the triboelectric properties of the materials in TENGs. High humidity can improve charge transfer between materials by enhancing the triboelectric effect. However, excessively high humidity can lead to water absorption and reduce the charge separation. Therefore, there is an optimal humidity range for TENG operation.

Surface roughness, wear, and surface geometry will affect the contact area between materials, thereby affecting the efficiency of TENG. Therefore, a properly designed surface pattern can enhance charge generation during the contact process and improve TENG performance.

Controlling the pressure or force applied during contact and separation can impact the power output of the TENG. Adjusting the mechanical parameters can enhance its performance.

5. CONCLUSION

For surface roughness test, the average P_a value of Sample_REF is 175.62nm, the root mean square P_a value is 176.59nm, the average P_q value is 245.92nm, and the root mean square P_q value is 246.63nm. The average P_a value of Sample_P1200 is 2789.92nm, the root mean square P_a value is 2817.63nm, the average P_q value is 3498.19nm, and the root mean square P_q value is 3528.46nm. The average P_a value of Sample_P500 is 5108.01nm, the root mean square P_a value is 5117.98nm, the average P_q value is 6496.30nm, and the root mean square P_q value is 6541.01nm. The average P_a value of Sample_P320 is 11505.66nm, the root mean square P_a value is 11772.34nm, the average P_q value is 14666.63nm, and the root mean square P_q value is 15057.45nm. It can be concluded from the data that the smaller the number of the sandpaper model, the higher the surface roughness. In addition, it can also be seen that the root mean square value is larger than the average value. The reason is that the square is used in the calculation of root mean squre, which turns negative values into positive values.

At the TENG part. For the voltage peak V_{oc}, the Sample_P500 group has the largest V_{oc} value of 193.82V, then is the Sample_P320 group of 178.78V, followed by the Sample_P1200 group of 93.35V and the Sample_REF group of 67.99V. For the charge density peak Q_{sc}, the results obtained are equally incredible. Sample_P500 group has the largest Q_{sc} value of 11.03nC/cm^2. Then is the Sample_P320 group of 10.99nC/cm^2, followed by the Sample_P1200 group of 10.95nC/cm^2 and the Sample_REF group of 3.50nC/cm^2. By analyzing the anomalies in the experimental results, several possible reasons were obtained. First of all, the experimental results should be obtained on the premise that the material surface is as flat as possible. Because in data sorting, each set of charge values was divided by the same area (2.5cmx2.5cm=6.25cm^2 in this experiment). Uneven materials or incomplete coverage will lead to different contact areas between materials, causing errors. In addition, under normal circumstances, max/highest power output performance is positively related to the roughness of the material. Because within a certain limit, the rougher the surface, the more contact points and the larger the contact area. However, if the surface is too rough, its contact points with the Si rubber will be reduced, thereby reducing the contact area and resulting in reduced results.

All in all, the experiment was considered as successful.

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