Simulation and Modelling of Triboelectric Nanogenerator for Self-powered Electronic Devices

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Abstract Triboelectric Nanogenerators has revolutionised the area of energy harvesting and self-powered sensing. In recent years, variety of small scale applications of triboelectric nanogenerators have been explored extensively particularly in self powered electronics, wearable and implantable devices, self-powered biosensors, human motion monitoring, locationevaluation, air quality control etc. This paper discusses simulation and modelling of contact separation mode based triboelectric nanogenerator. In this work, triboelectric nanogenerators are simulated in COMSOL to compare the voltage profile of three different triboelectric materials – Kapton, Teflon and RTV Silicone with respect to Aluminium. Also, the effect of thickness of triboelectric layer on voltage profile is studied to optimize the thickness of the films. The output voltage recorded is 75 V, 60 V and 59 V for RTV Silicone, Teflon and Kapton respectively. It was observed that with increase in thickness of triboelectric layer, output voltage first increases linearly and then starts decreasing. The future research is directed towards fabricating a robust device for realising self – powered electronic devices.

Keywords: Simulation, Modelling, Triboelectric Nanogenerator

1. Introduction
With the advancement of technology, the energy demand is increasing over time globally and it has become essential to look out for renewable sources of energy. Most of the electronic devices usually utilise lithium ion batteries as a power source. Due to limited lifespan of the batteries, they tend to deplete over time and need to be replaced involving extra cost and complexities [1]. Therefore, harvesting energy is a promising technological solution to realise self – powered electronics. Various Energy harvesting technologies has been explored in recent years such as solar [2], pyroelectric [3], thermoelectric [4], electromagnetic [5], biofuel cell [6], piezoelectric [7], Triboelectric [8], hybrid [9], etc. Among all the energy scavenging approaches, Triboelectric Nanogenerators (TENGs) has made a splash due to its low cost, simple design, high output performance and high energy conversion efficiency [10]. The first Triboelectric Nanogenerator was demonstrated in 2012 by Wang group [11]. The Greek word “tribo” refers to friction. Triboelectric Nanogenerator basically operates on the amalgamated principle of triboelectric effect and electrostatic induction. Triboelectric Nanogenerator works in four working modes – Contact Separation Mode (CSM), Lateral Sliding Mode (LSM), Single Electrode Mode (SEM) and Free-Standing Mode (FSM). The contact separation mode is the most simple and widely used mode of operation. A typical Contact Separation Mode (CSM) based triboelectric nanogenerator comprises of two dissimilar triboelectric layers with two metal electrodes deposited on outer surfaces of triboelectric layers. With application of external force, two triboelectric layers make contact with each other leading to charge generation on opposite surfaces. When the two layers are separated due to removal of external
force, electric potential is induced between the electrodes [12]. Therefore, Triboelectric nanogenerators has emerged as new era energy harvesting andsensing devices in variety of applications such as self-powered electronics [13], wearable and implantable devices [14], self-powered biosensors [15], human motion monitoring [16], location evaluation [17], environmental monitoring [18] etc.

This paper deals with design and simulation of triboelectric nanogenerators. In this work, three triboelectric nanogenerator with different triboelectric materials – Kapton, Teflon and RTV Silicone are designed and their output performance is compared in COMSOL. Also, the effect of thickness of triboelectric layer on voltage profile is studied to optimize the thickness of the films. The output voltage recorded is 75 V, 60 V and 59 V for RTV Silicone, Teflon and Kapton respectively. It was observed that with increase in thickness of triboelectric layer, output voltage first increases linearly and then starts decreasing. The future research is directed towards fabricating a robust device to realise self – powered electronic devices.

2. Design of Triboelectric Nanogenerator

The output performance of triboelectric nanogenerator largely depends on the triboelectric materials. For maximum charge transfer, the materials for triboelectric layers are selected in such a way that they are located far apart in triboelectric series and are of opposite tripolarity. In this work, the triboelectric nanogenerator is designed to operate in contact separation mode due to its simple design. Triboelectric nanogenerators (TENGs) are designed by using three different materials – Kapton, Teflon, RTV Silicone. These layers act as negative triboelectric layer. In all the three nanogenerators, Aluminium (Al) is used as positive triboelectric layer as well as second electrode. Another Aluminium film is deposited on top surface of first triboelectric layer to form TENG device. Fig. 1 (a-c) shows three triboelectric nanogenerators.

![Design of three Triboelectric Nanogenerator using different negative triboelectric layer](image)

**Figure 1.** Design of three Triboelectric Nanogenerator using different negative triboelectric layer

3. Modelling and Simulation

The mathematical modelling of a typical TENG is performed that consists of two plates with opposite charges shuttling towards each other. The TENG shows capacitive behaviour with output voltage varying corresponding to change in distance between plates. The output voltage of TENG is inversely proportional to the capacitance whereas it is directly proportional to the corresponding distance between plates. The structure of a typical TENG with two dielectric (triboelectric) layers and two metal electrodes is depicted in Fig. 2, where the distance ‘D’ is the distance between the two triboelectric layers.
The functioning of TENG involves coupling effect of triboelectrification and electrostatic induction, along with diffusion characteristics and charge transfer. With no external force initially, the Kapton, Teflon and RTV-silicone film will not be in contact with other triboelectric layer, thereby creating an air-gap between them. With application of external force, the two layers that are not absolutely smooth or flat come in contact with each other resulting in generation and accumulation of charges due to deformations in the interfacial structure. As a result of triboelectrification, inner surfaces of the two dielectric layers experience generation of equivalent positive and negative charges that get spread over the triboelectric surfaces because of the tunnel effect. The theory of work function states that the amount of charges on the surface are associated with the work function and the amount of the dielectric layers as per the following equation:

$$Q_t = A \left( \hat{W}_1 - \hat{W}_2 \right)$$  \hspace{1cm} (1)

where $Q_t$, $A$, and $\hat{W}$ are, respectively, denoted as the amount of tribo-charges formed on the dielectric surface, contact area of TENG, and work function of the dielectric materials. Work function mainly depends on the applied force and separation between the two dielectric layers.

$$\text{Work function} = \text{Force}(F) \times \text{Distance} (D)$$  \hspace{1cm} (2)

$F =$ applied force  
$D =$ distance between two dielectric layers

During this period, polarization happens on the surface of the dielectric layer with a certain thickness, and a quite small amount of charges diffuse into the dielectrics to fill the inner charge hole or non-charged region, leading to spacer charges distributing with a distance from the interface layer. It is reasonable to assume that the tribo-charge density is uniform and the spacer charge distribution near the interface obeys the Poisson distribution; space charges per unit area can be given by:

$$Q(p) = 2\Delta \hat{W} \epsilon \frac{\varepsilon_m}{\varepsilon_0 q_e}$$  \hspace{1cm} (3)

where, $\varepsilon_m$ and $\varepsilon$ are the permittivity of dielectric material and air respectively. Therefore, the dielectric surfaces accumulate equal and opposite charges and some charges remain dispersed inside the materials at the final contact.

With removal of external force, interfacial deformation between the triboelectric surfaces is released resulting in separation of two triboelectric materials. This causes generation of equal and opposite charges on the surface (i.e., $Q_s$) and some charges are dispersed inside the materials (denoted by $Q_l$). During the separation process of two triboelectric materials, an electric potential difference is developed between the Kapton/Teflon/RTV-silicone film and the Aluminium layer, which forms

Figure 2. Structure of a typical TENG with two metal electrodes and two dielectric layers
the dynamics of the whole TENG device prompting swift flow of electrons between the two metal electrodes. The charges transferred between the two electrodes can be obtained from Eqs. (1) and (2).

\[ Q_T = Q_t + Q_l \]

\[ Q_T = Q_t + \sum_{\varphi>0} Q(\varphi) \quad (4) \]

When the distance between the two dielectric plates is maximum, an electrical equilibrium is attained and there is no flow of electrons. The maximum output voltage of the TENG device is attained from the following equation:

\[ V = \frac{-Q_T}{A\varepsilon} (d_t + D) + \frac{\sigma D}{\varepsilon} \quad (5) \]

Where, \( \varepsilon \) is the permittivity of free space, \( \sigma \) is the surface charge density, and \( D \) is the distance between the two dielectric plates. The total capacitance of the TENG is mainly influenced by two factors: the surface area of the plates (A) and the distance between the dielectric plates (D).

\[ C_T = \frac{A\varepsilon}{d_t+D} \quad (6) \]

where ‘A’ is the area of TENG, \( d_t \) is the total thickness of the two plates i.e. summation of \( d_1 \) and \( d_2 \), and the relative permittivity of the dielectrics is denoted by \( \varepsilon_1 \) and \( \varepsilon_2 \), respectively. \( d_t \) is defined as:

\[ d_t = \frac{d_1}{\varepsilon_1} + \frac{d_2}{\varepsilon_2} \quad (7) \]

The material characteristics of a TENG are defined by Equations (1) (2), and (3). For generation of electricity from the TENG device and analyse its performance, it is necessary to perform modelling of output voltage of TENG. The output voltage \( V \) of the TENG device is defined as

\[ V = \frac{-Q_t}{C_T} + \frac{\sigma D}{\varepsilon} \quad (8) \]

From equation (4)

\[ V = \frac{-Q_t}{A\varepsilon} (d_t + D) + \frac{\sigma D}{\varepsilon} \quad (9) \]
4. Result and Discussion

In order to analyse the output performance of triboelectric nanogenerators and variation in voltage profile with change in thickness of negatively charged triboelectric (dielectric) layer, the three nanogenerators were modelled in COMSOL. Table 1 shows TENG modelling parameters. Fig. 3 compares voltage profiles of three nanogenerators with respect to variation in thickness and shows that for the same force applied (15N in each case) across the load resistance of 15 MΩ, the output voltage is observed to be highest in the case of RTV Silicone-Aluminium TENG i.e 75 V with dielectric layer thickness of 0.04 mm whereas the output voltage is 60 V and 59 V for Teflon-Aluminium and Kapton-Aluminium TENG device respectively.

All the three devices depicted an increase in the output voltage with increase in thickness of triboelectric layer varying from 0.04 mm to 0.12 mm. The simulated result shows that with further increase in thickness of triboelectric layer from 0.12mm to 0.2 mm, the output voltage starts decreasing and this decrease in voltage is less prominent in case of Kapton-Aluminium TENG device. Therefore, this indicates that 0.12 mm thickness is the optimum thickness of triboelectric layer for designing of TENG devices. The results are in congruence with the Distance Dependent Electric Field Model (DDEF) which states that with increase in thickness of dielectric layer, output voltage tends to decrease significantly.

![Table 1. TENG modelling parameters](image)

**Table 1. TENG modelling parameters**

| Variable | Value                  |
|----------|------------------------|
| A        | 10.16 x 7.62 x 10^{-4} seq. meter |
| ε        | 8.854 x 10^{-12} F/m   |
| ε₁       | 2.1                    |
| ε₂       | 1.8                    |
| d₁       | 100 x 10^{-6} m        |
| d₂       | 80 x 10^{-6} m         |
| σ        | 50 x 10^{-6} C/m²      |

![Figure 3. Simulation results comparing output performance of Kapton – Al TENG, Teflon – Al TENG, RTV Silicone TENG with variation in thickness of negative triboelectric layer](image)
5. Conclusion

Triboelectric Nanogenerators have shown great potential for scavenging energy from ambient environment in variety of applications. This work successfully modelled three different TENG devices by varying negative triboelectric layer with different materials – Kapton, Teflon, RTV Silicone in order to compare their output performance. It is concluded that RTV silicon shows highest surface charge density among the three materials which is evident by its maximum output voltage of 75 V. The Thickness of Kapton, Teflon and RTV Silicone was varied from 0.04 mm to 0.20 mm and the effect on output voltage was studied. It is concluded that initially voltage increases with increase in thickness but thereafter output voltage tends to decrease with further increase in thickness. Therefore, 0.04 mm is the optimum thickness showing maximum output voltage for the TENG device. The future research direction could be fabrication of a robust device for self-powered electronic devices.

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