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MODELING OF TRANSIENT BEHAVIOR OF SINGLE FRICTION SURFACE TRIBOELECTRIC GENERATOR

B.R. Verma[1], B.P. Chandra[2] and R.N. Baghel[2]

[1]Department of Physics, Government Post Graduate College, Kurud (Dhamtari) - 493663 (C.G.)

[2]School of Studies in Physics and Astrophysics, Pt. Ravishankar Shukla University, Raipur 492010 (C.G.)

Corresponding author E-mail: bhunesh.verma@gmail.com

ABSTRACT

The present paper reports the modeling of transient behavior of single friction surface triboelectric generator (STEG). The STEG is transparent and flexible, making possible the use of triboelectric generators in an extended range of applications. This device can be fabricated in a simple and very low-cost way**.** In recent research novel energy harvesting devices termed triboelectric generator are attracting significant interest. Now-a-days, extensive research of energy harvesting devices have been developed to capture and convert mechanical energy into electrical energy which are based on the mechanisms of energy conversion and they include piezoelectricity, electromagnetic induction and electrostatic induction. In fact, STEG have also been developed to harvest mechanical energy from human motion and ambient vibrations. In this paper, we propose the modeling of transient behavior of single friction surface triboelectric generator (STEG).

KEY WORDS: Triboelectric generator, electrostatic and Electromagnetic induction, Modeling of STEG.

INTRODUCTION

In fact, harvesting energy from ambient is a promising approach to powering wireless sensor nodes, implanted medical devices, and other low-power electronics without the use of batteries. In recernt years, energy harvesters which convert mechanical energy into electrical energy based on piezoelectric (Wang etal 2006), electromagnetic and electrostatic (Chang etal 2010, Chen etal 2012, Yang etal 2009) operating principles have been developed. In the recent past, the well-known phenomenon of contact electrification (Suzuki 2011) was exploited for energy harvesting use, in which the novel energy harvesting devices termed triboelectric generator (Tvedt etal 2010). These devices have been developed to harvest mechanical energy from human motion and ambient vibrations. The triboelectric generators operate based on the effects of contact electrification and electrostatic induction. Compared to other electrostatic induction based energy harvesting devices, contact electrification provides an extremely simple method for electrostatic charging and makes it feasible the low-cost mass production of flexible generators. The triboelectric generators have reported to achieve high power density and efficient (Baytekin etal 2011). In this paper, we present a mathematical modeling of single-friction-surface triboelectric generator (STEG). This device incorporates only one single micro structured polydimethylsiloxane (PDMS) or flat polyethylene terephthalate (PET) friction surface. When an active object such as finger, glove, pen, clothes, or similar contacts with the fixed friction surface, the surface of the contacting object serves as the second friction surface in the friction pair. The motion of the contacting object will thus stimulate the STEG. This STEG can be fabricated on transparent and flexible materials using a very simple process and achieving low cost.

Mechanism of STEG

The schematic diagram of STEG with a micro-structured PDMS friction surface with human body as the conduit is shown in Figure 1. and Figure 2. respectively. The device has been fabricated on a 125 μm thick PET substrate. A PDMS film patterned with an array of micro-pyramids serves as the friction surface (Meng etal 2014) .

Figure 3 shows the energy harvesting mechanism of the STEG . This device works based on the effects of contact electrification and electrostatic induction. When an active object such as a finger, glove or pen contacts with the friction surface of PDMS or PET by touching, tapping or sliding, the surface of the active object and the fixed friction

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surface create a friction pair. Due to the difference in electron-attracting abilities between the two surfaces, electrons will be transferred from one surface to another surface, thus making the friction pair electrostatically charged. When the charged active object separates from the friction surface, a potential difference forms between the induction electrode and the grounded reference electrode.

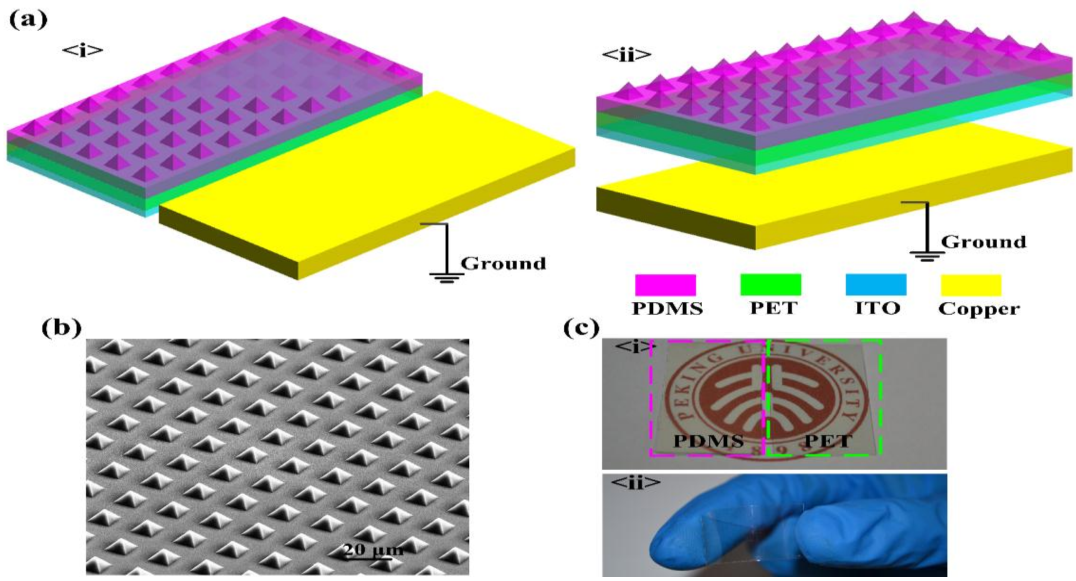

Fig. 1 (a) Schematic of the STEG using a micro-structured PDMS friction surface with the grounded reference electrode placed (i) beside or (ii) beneath the induction electrode. (b) SEM image of the micro-patterned PDMS film. (c) Photographs of the STEGs with PDMS surface and PET surface showing their high transparence and high flexibility (after Meng etal ref. 9).

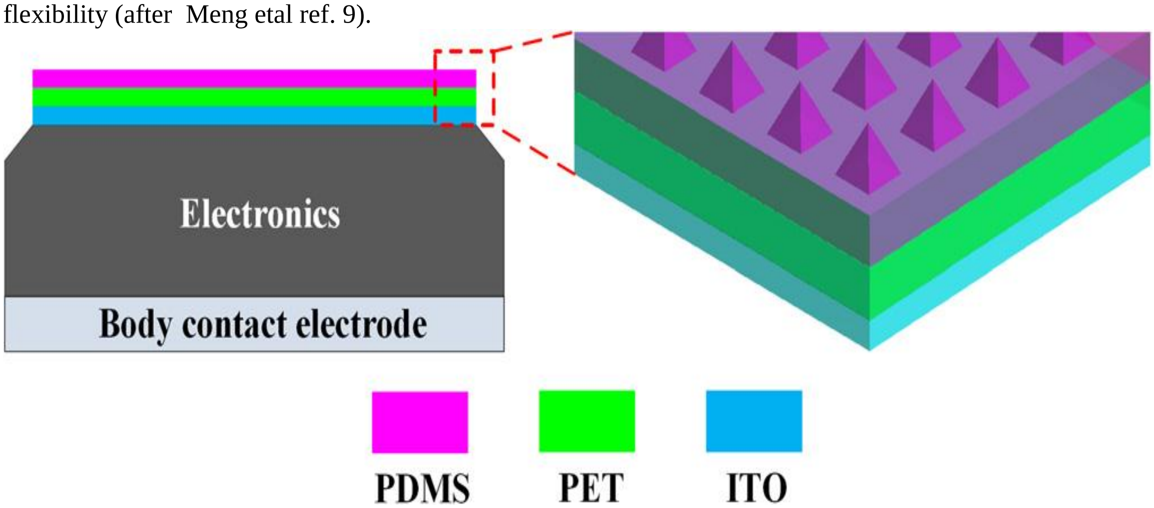

Fig. 2. Schematic of the STEG with human body as the conduit (after Meng etal ref. 9).

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Charge will transfer via the external load from one electrode to the other in order to reach an electrostatic equilibrium state. When the active object contacts with the friction surface again, an inverse charge transfer occurs. Figure 3a depicts the condition when the friction surface shows a tendency to attract electrons in contact electrification. Electrons transfers from the reference electrode to the induction electrode during contacting and moves back to the reference electrode during separating.

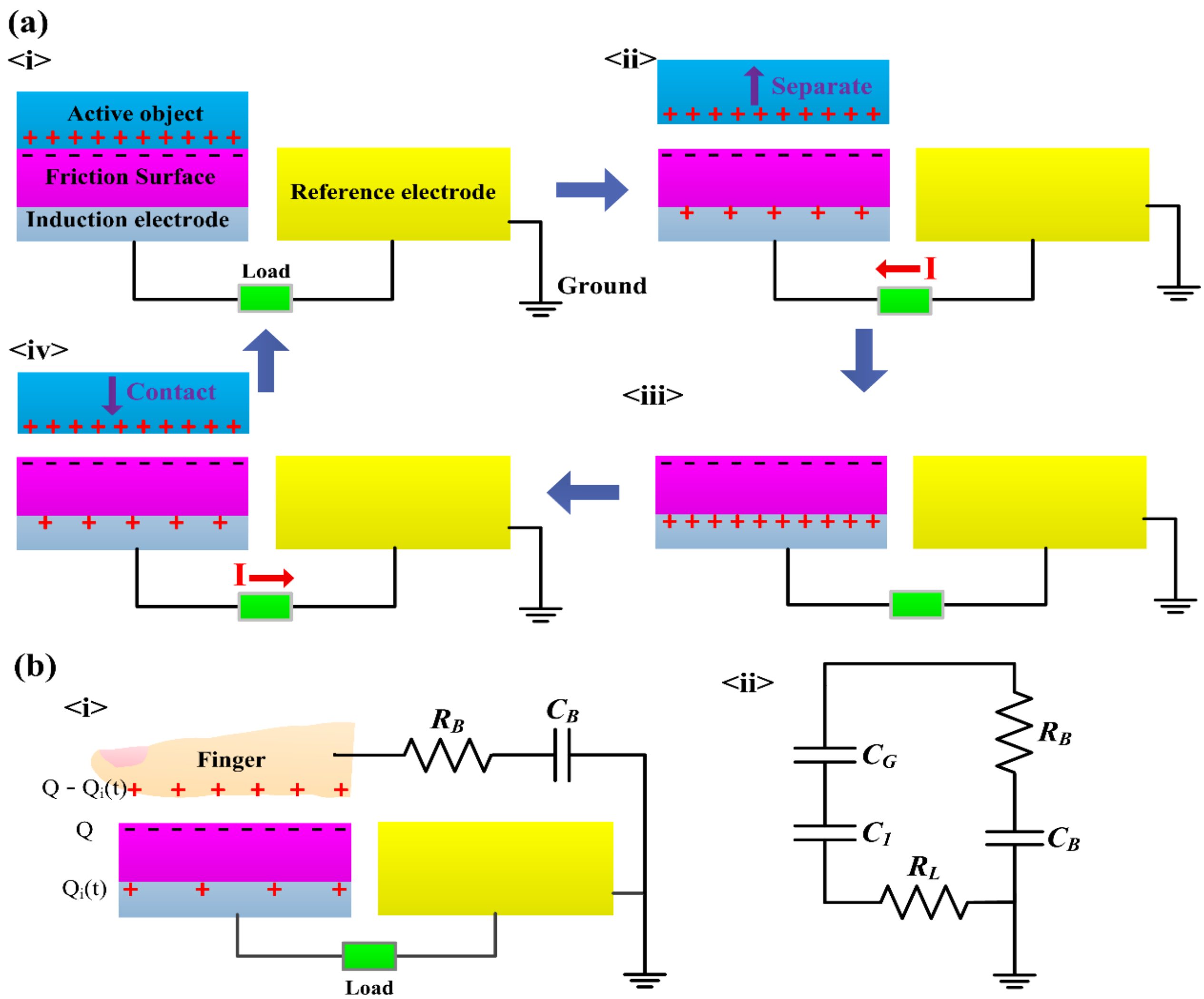

Fig. 3. Energy harvesting mechanism of the STEG (a) when the friction surface shows a tendency to attract electrons in contact electrification. (b) The schematic and equivalent circuit of the system when the friction surface is stimulated by human finger (after Meng etal ref. 9).

Mathematical Approach

The mechanism of energy harvesting from mechanical energy to electrical energy is based on two processes - STEG with human finger and STEG with human body conduit.

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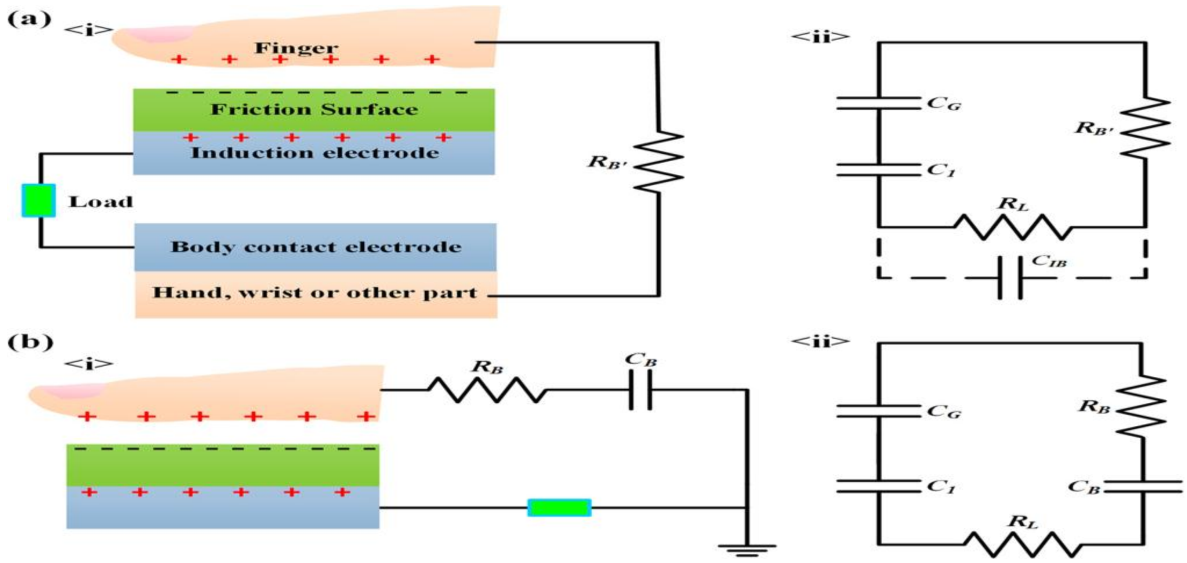

Fig. 4. Energy harvesting mechanism and equivalent circuit of the (a) STEG with human body conduit and (b) the STEG with grounded electrode when finger taps the friction surface and showing a tendency to donate electrons (after Meng etal ref. 9).

STEG with human finger

When the friction surface is contacted by human finger, the fact that the human body is a conductor should be considered. Here, we employ the simplest human body model (HBM) (Zhu etal 2012) which adopts a series RC circuit as shown in Fig. 3b(i), n which, R_B represents the body resistance and C_B is the body capacitance. Since the lateral dimension of the friction surface is much larger than the thickness, in a small variation range of the gap between finger and the friction surface, the two contacted surfaces and the induction electrode can be assumed as infinitely large planes. Thus, the system is simplified into the equivalent circuit described in Fig. 3b(ii), in which $C_G(t)$ corresponds to the capacitance between finger surface and the friction surface, C_1 is the corresponding capacitance between the friction surface and the induction electrode, and R_L is the load resistance. According to Kirchhoff's law, the equivalent equation of the circuit can be expressed as

$$\frac{Q-Qi\,(t)}{CG(\mathrm{t})} = \frac{Qi(t)}{CB} + \frac{Qi(t)}{C1} + (R_{B\,+}R_L)\ \frac{dQi(t)}{dt} \qquad \text{......................................(1)}$$

where Q is the charge on the friction surface, and Q_i (t) is the charge on the induction electrode. Taking an account of leakage of the charge on human body into consideration, the transient equation can be modified as

$$\frac{Q-Qi\,(t)}{CG(\mathrm{t})} = \frac{Qi(t)-\Delta Q}{CB} + \frac{Qi(t)}{C1} + (R_{B\,+}R_L)\ \frac{dQi(t)}{dt} \qquad \text{.......................(2)}$$

where ΔQ is the charge that is leaked.

We know that, in the case of steady state , the rate of change in charge will be zero, and therefore, Eq. (2) can be written as

$$\frac{Q-Qi}{CG} = \frac{Qi-\Delta Q}{CB} + \frac{Qi(t)}{C1} \qquad \text{......................................(3)}$$

Using the above steady-state equation, we can find out Qi which varies with the gap between the two contacted surfaces:

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$Qi(C1CG + CBCG + CBC1) = (QCBC1 + \Delta Q\, C1CG)$ ....(4)

$Q_i = \frac{QCBC1 + \Delta Q\, C1CG}{CBC1 + C1CG + CBCG}$ ....(5)

Now, the charge that is transferred via the load in half cycle can be expressed as

$Q_T = Q_{i\,max} - Q_{i\,min}$

$= Q - \frac{\Delta Q C1}{CB + C1}$ ....(6)

It is evident from the above discussion that, with the finger motion of repeated contacting and separating, charge moves forward and back between the induction electrode and the grounded reference electrode via the external load. Therefore, the applied mechanical energy is transformed into electric energy and the leak of charge from the human body would partly weaken the performance of the device.

STEG with human body conduit

Assuming that the surface charge density is unique, the contacted surfaces and the induction electrode are infinitely large planes during the operating of the STEG. An equivalent circuit of the device can be figured out as shown in Fig. 4a(ii), in which R_L represents the load resistance, R_B' corresponding to the body resistance between two hands, C_G is the capacitance between finger skin and the friction surface, C_1 is the capacitance between the friction surface and the induction electrode, and C_{IB} is the capacitance between the induction electrode and the body contact electrode. As the gap between the two electrodes is comparatively large, C_{IB} is very small. Thus, it can be neglected in the following analysis. For the comparison, the equivalent circuit of the previously reported STEG with the electrode grounded is illustrated in Fig. 4(b), in which R_B corresponds the body resistance and C_B presents the body capacitance.
The transient equation of Fig.2(b) is discussed in above equation 1 and 2.

Case -I For the open-circuit condition, there is no charge transferred, and Q_i is 0. then from Eq. (2), the open circuit voltage comes out to be

$V_{OC} = \frac{Q}{CG(t)} + \frac{\Delta Q}{CB}$ ....(7)

Case -II For the short-circuit condition, in regardless of the influence of body resistance and assuming that the charge leaked very quickly, the short-circuit current can be expressed

$I_{SC} = \frac{(\Delta QC1^2CB - QC1^2CB - QCB^2C1)\, dCG(t)}{(CBC1 + C1CG(t) + CBCG(t))^2}$ ... .(8)

The charge that transferred in a single cycle can be calculated by

$Q_T = 2(Q_{i\,max} - Q_{i\,min})$

$= 2\,(Q - \frac{\Delta QC1}{CB + C1})$ ....(9)

For the simplest human body model (HBM), the body resistance RB is generally used as 1 to 2 kilo-ohm, while the optimal load resistance of TEGs is usually very large. As the load resistance and body resistance are connected in series, the small body resistance would have little influence on the performance of the STEG. In regardless of the difference between R_B and R'_B, the equivalent circuit in Fig. 4(a) can be considered as a special case of the one in Fig. 4(b) with an infinitely large body capacitance C_B. Thus, for the STEG with human body conduit, The open circuit voltage is given by

$V_{OC} = \frac{Q}{CG(t)}$. ....(10)

The short-circuit current is given by

$I_{SC} = \frac{-Q\, C1\, dCG(t)}{(C1CG(t))^2}$ ....(11)

Now, the charge that transferred in a single cycle can be given by

$Q_T = 2Q$ ....(12)

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In heoretically, the STEG with grounded electrode shows a small offset of $\frac{\Delta Q}{CB}$ in the open-circuit voltage compared to the case with human body conduit. While the optimized STEG with human body conduit shows a better performance in short-circuit current and the amount of charge than the case with grounded electrode. It is to be noted that the leak of charge from human body has no influence on the performance of the case with human body conduit.

CONCLUSION

Using human body as human finger as well as the conduit, a mathematical modeling of transient behavior of single-friction surface triboelectric generator. The facility of employing human body conduit to replace the use of grounded electrode, not only makes the STEG more practical for applications in portable electronics but also leads to a significant output improvement. In the case of finger tapping, the STEG with micro-patterned PDMS surface achieved an output voltage of over 200 V. Significant increases in output current and the amount of charge that transferred were obtained. Using human body conduit, this optimized STEG is suitable for potential applications in low-power portable electronics and medical devices.

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