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Review paper

TRIBOELECTRIC NANOGENERATORS (TENG): FACTORS AFFECTING ITS EFFICIENCY AND APPLICATIONS

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Abstract. *The demand for energy is increasing tremendously with modernization of the technology and requires new sources of renewable energy. The triboelectric nanogenerators (TENG) are capable of harvesting ambient energy and converting it into electricity with the process of triboelectrification and electrostatic-induction. TENG can convert mechanical energy available in the form of vibrations, rotation, wind and human motions etc., into electrical energy there by developing a great scope for scavenging large scale energy. In this review paper, we have discussed various modes of operation of TENG along with the various factors contributing towards its efficiency and applications in wearable electronics.*

Key words: *TENG (Triboelelctric nanogenerator), PTFE (Poly tetra fluoro ethylene), TET (triboelectric textile), STET (single layer triboelectric textile), PDMS (polydimethyl siloxane), PMMA (polymethyl methacrylate)*

1. INTRODUCTION

With the increase in the energy requirement, various non-renewable resources of energy are depleting day by day causing serious environmental conditions. Solar and wind energies are the targeted renewable sources of energy to provide power in the gigawatt scales. High power density, high efficiency and low cost are the main requirements to harvest these energy sources. For the welfare of the society, it is necessary to find a new and high efficient energy technology that can be able to harvest the energy available in the environment which could be harvested easily to act as prominent source for energy harvesting system [1-4]. All these power sources should be easily available, sustainable, and maintenance-free as well as pollution free. Most of the present day electronic devices use batteries as external power sources with a short span of life time. Till date electromagnetic-induction, piezoelectric and electrostatic effects were the main mechanisms used for major energy harvesting techniques developed during the last few decades [5-11]. More recently, a new energy technology has been invented for harvesting environmental energy known as tribo-electric nanogenerators (TENG) which converts the ambient mechanical energy into electrical energy [12-16]. TENG

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works on the principle of triboelectrification in conjunction with electro-static induction. The concept of TENG was demonstrated by Wang et. al in the year 2012 and since then it has attracted the energy industry to meet the large scale energy demand. Various device structures based on triboelectric-effect and electro-static induction have been reported utilizing mechanical energies from vibrations [17-20], human-motions [21-22], rotation [23-24], wind [25-26], and walking [28]. In this review paper, we have described an overview of the progress in the TENG based devices. We have also discussed the various modes of operation, energy harvesting source along with different parameters affecting its efficiency and applications.

2. Fundamental Modes of TENG

Charge generation takes place between two different materials having distinct affinity to electrons when they are brought in contact with each other and then separated is known as triboelectric effect. When the materials are separated from each other it results in the generation of potential on the surface of two materials. On the other hand, electrostatic induction is the phenomenon of generating electricity when the electrons from one electrode flow to the other electrode through external load to bring equilibrium in the potential difference. In TENG both triboelectric effect and electrostatic induction are used to convert the mechanical energy into electrical energy. Figure 1 below demonstrates the various fundamental modes of TENG such as vertical- contact separation mode [37-40], sliding mode [41-42], single electron mode [43-46] and free- standing triboelectric-layer mode [47-52].

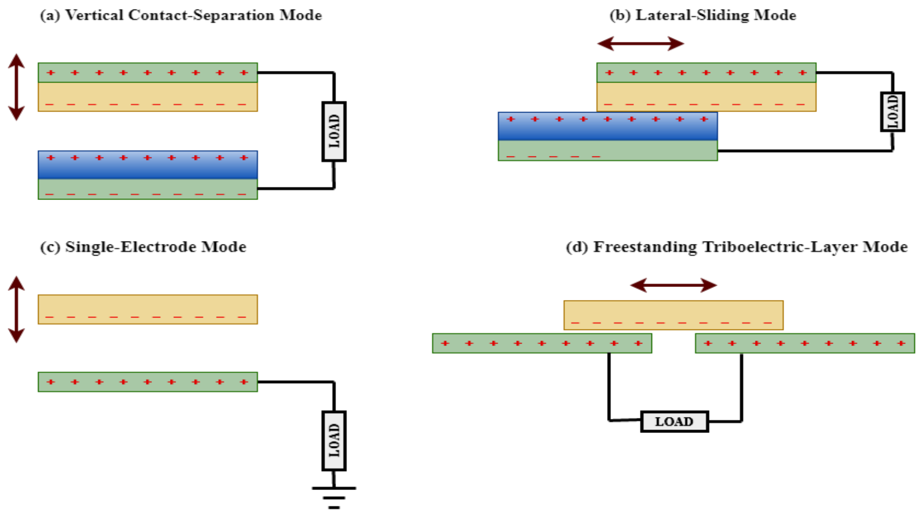


Fig. 1 Fundamental modes of TENG a) The vertical contact separation mode b) The sliding mode c) the single electron mode d) The free- standing mode

2.1. Vertical contact-separation mode

The process of energy conversion by triboelectrification was first demonstrated by Zhu et. al., in January 2012 [13]. The operation of TENG can be explained on the basis of coupling between electrostatic induction and contact electrification. Figure 2(a-b) clearly indicates the process of generation of electricity using contact-separation mode. The materials used for vertical contact-separation mode include PMMA (poly methyl methacrylate) and kapton. Both open-circuit voltage and short circuit current have been demonstrated in this mode of TENG. In the open circuit condition, when no force is applied between these two materials, no electric potential difference is produced as shown in figure 2(a). But when an external force is applied, transfer of charge takes place from one surface to another as soon as these two materials come in contact with each other. Because of triboelectric-effect, electrons will be transferred from PMMA to the kapton surface thereby making PMMA as positive electrode and kapton as negative electrode (refer Figure 2(a)). Further, when these two materials are separated with the release of force, a potential difference is created between these two electrodes. The open-circuit voltage (Voc) so produced can be expressed as: -

$$Voc = \sigma\, d / \epsilon_o \tag{1}$$

Where, σ is the triboelectric charge density; ϵ_o is the permittivity and d is the distance between the two surfaces.

Voc can reach its maximum value when the force is released of the free space. Now, when the force is applied again, the potential difference decreases and reaches its minimum value when the two materials come in contact/closer to each other. This depicts the whole cycle of generating electricity in vertical contact-separation mode. Under the short circuit condition, the electrons flows from top electrode to the bottom electrode, so as to balance the electric potential difference so generated resulting in the flow of instantaneous current in the process of releasing. Thus, the positive charge will accumulate on the top electrode and negative charge will accumulate on the bottom electrode. The charge density during full released process can be expressed as:

$$\sigma' = \sigma\, d'\, \epsilon_{rk}\, \epsilon_{rp} / d_1\, \epsilon_{rp} + d' \epsilon_{rk}\, \epsilon_{rp} + d_2\, \epsilon_{rk} \tag{2}$$

Where,

ϵ_{rp} = relative permittivity of PMMA; ϵ_{rk} = relative permittivity of kapton

d_1 = thickness of the kapton layer; d_2 = thickness of the PMMA layer

Now, when the force is applied again, the electrons will move from bottom electrode to the top electrode reducing the induced charge due to which a negative instantaneous current appears. The whole induced charge gets neutralized when these layers come in contact with each other.

2.2. Sliding mode

Siding mode of operation was demonstrated by Wang et al in the year 2013 [42] in which two surfaces slide over one another in the lateral direction. The mechanism of generation of electricity has been demonstrated in Figure 3 (I-IV). In this case one layer is of PTFE (Poly tetra fluoro ethylene) and the other layer consists of Nylon plate. In the initial position, when the two plates are placed over one another having full contact with each other, no transfer of electron takes place from Nylon to PTFE, thus no potential difference is generated between the two electrodes as shown in figure 3(I). When the positively charged top surface starts sliding in the outward direction, relative displacement in the lateral direction takes place. Thus, PTFE electrode will be having a higher potential as compared with the Nylon electrode, hence the electrons from the PTFE film will move towards the Nylon film through the external load, until full mismatch, as shown in Figure 3(II-III), the potential difference and charge transfer will reach the maximum value. Now, the Nylon plate is moved in the inward direction and the whole process will get reserved and the electrons moved from Nylon film to PTFE film through external load which produces a negative current when the equilibrium is achieved, no transfer of charge take place and the two plates reaches its original position. Several advantages of sliding mode have been observed as compared to vertical contact separation mode such as higher energy conversion efficiency and increased power enhancement.

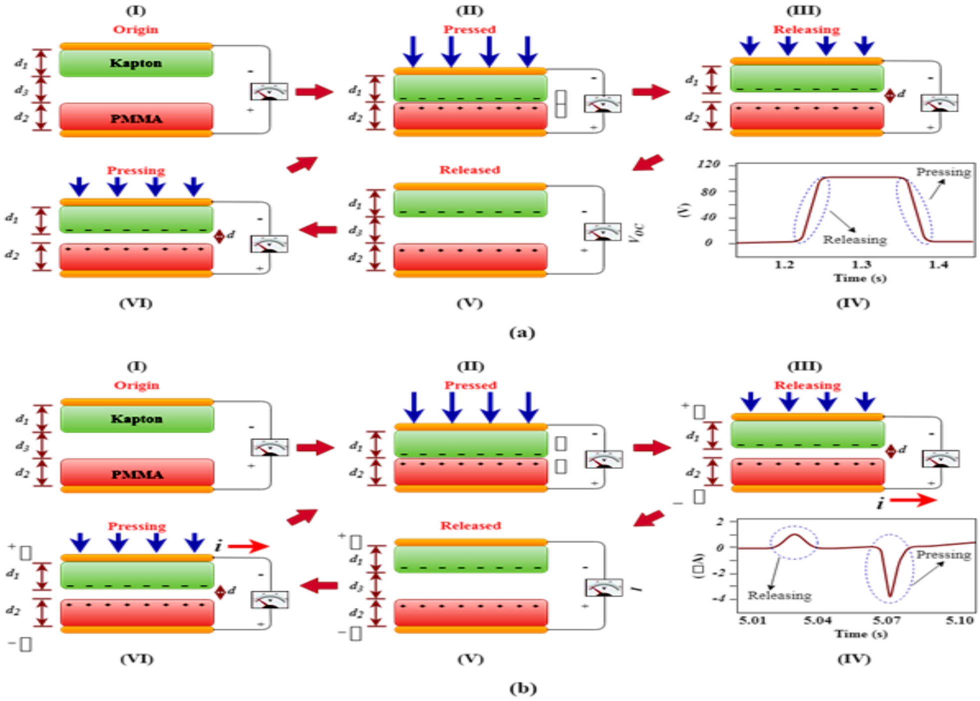


Fig. 2 (a-b) Process of generation of electricity using contact-separation mode of TENG

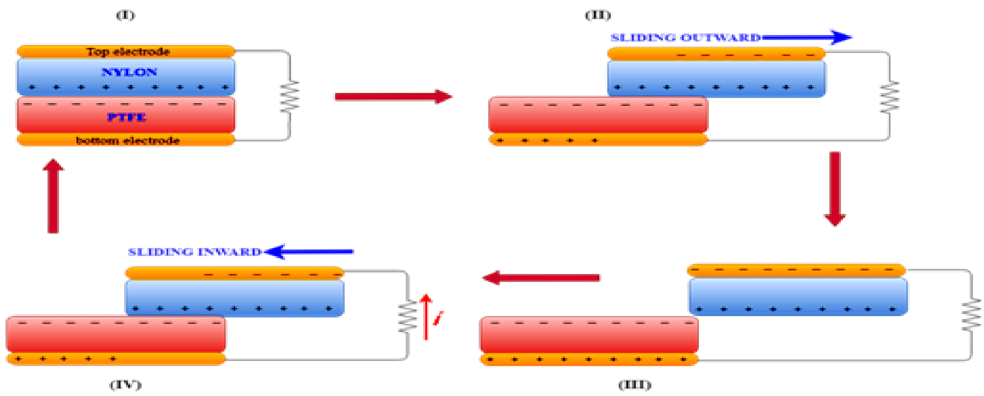


Fig. 3 (I-IV) The basic mechanism of generation of electricity

2.3. Single electron mode

Figure 4(a) show the single electron mode operation [45] consisting of PDMS layer having micro pyramids over its surface serving the purpose of providing friction and the other contact surface consists of human skin. The layer of PDMS is deposited on the ITO coated PET substrate and with change in the distance between the two surfaces, transfer of charge take place in between ITO and the ground and hence flow of electrons take place.

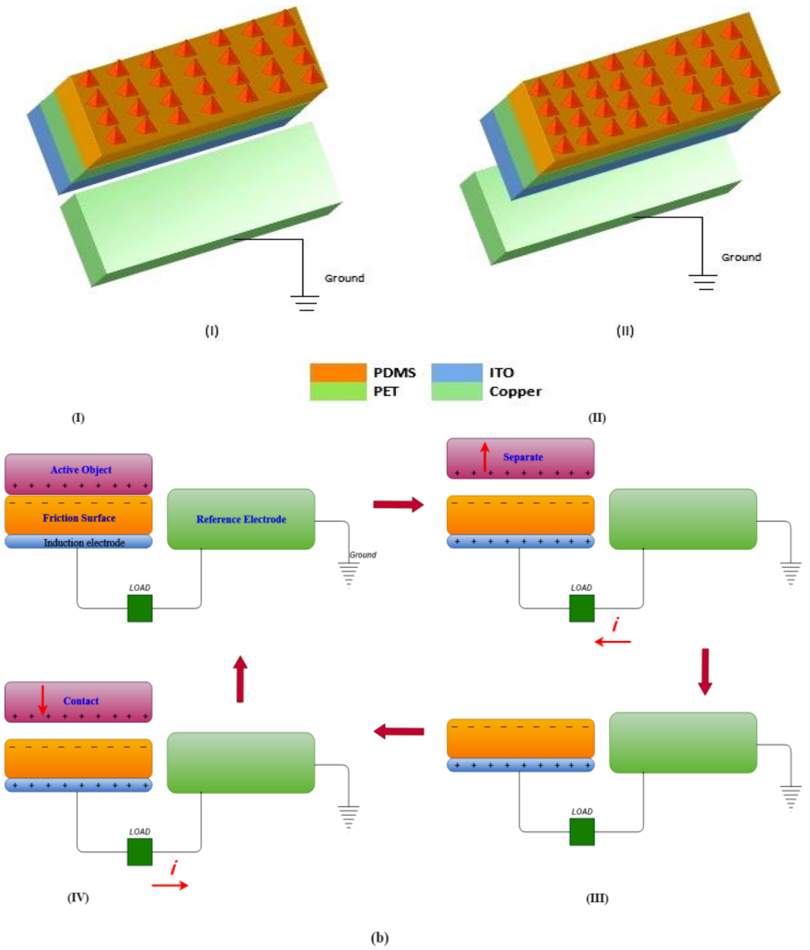


Fig. 4 (a) Schematic illustration showing the single electron mode TENG [45], (b) The electricity generation cycle

Figure 4(b) indicates the mechanism of generation of electricity in the single electron mode. With the bringing of a finger near the PDMS surface, a negative charge appears on its surface as PDMS is more negatively charged as compared to human skin and thus more electrons will be transferred from the human skin to the PDMS surface. This negative charge can be preserved on the PDMS surface due to its insulating nature. Now, when the finger is separated from the PDMS surface, a potential difference between the ITO and the reference electrode gets generated. This results in the flow of free electrons from the ITO electrode to the ground/reference electrode to maintain the equilibrium as shown in Figure 4(b). Again, when the finger is made to approach the PDMS, the movement of free electron takes place from the reference electrode to the ITO resulting in the production of negative current/voltage. This is how the cycle gets completed for the single-electron mode operation.

2.4. Freestanding triboelectric layer mode

The free standing triboelectric layer mode have distinct advantages over the other modes of operations as far as its versatility and applicability in the process of energy harvesting from a moving object or from the motion of human walking without an attached electrode. This mode also has very high energy conversion efficiency and high robustness. In this mode, the generation of electricity depends upon the change in position of the tribo charged surface between two electrodes resulting in change of induced potential difference as depicted in Figure 5(a). The main structure consists of two metal films and a free-standing dielectric layer. When the FEP (Fluorinated ethylene propylene) layer is aligned with the left-electrode of aluminum (Al) a negative charge will be developed on the inner surface of the FEP layer and a positive charge on the left-electrode surface as shown in Figure 5(b).

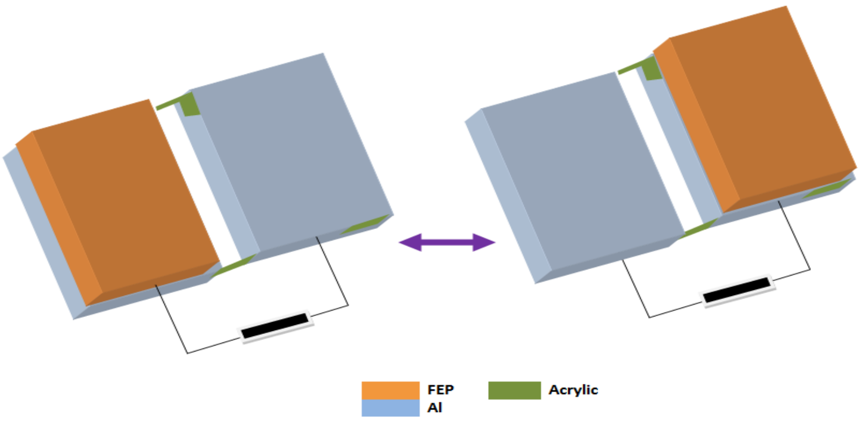
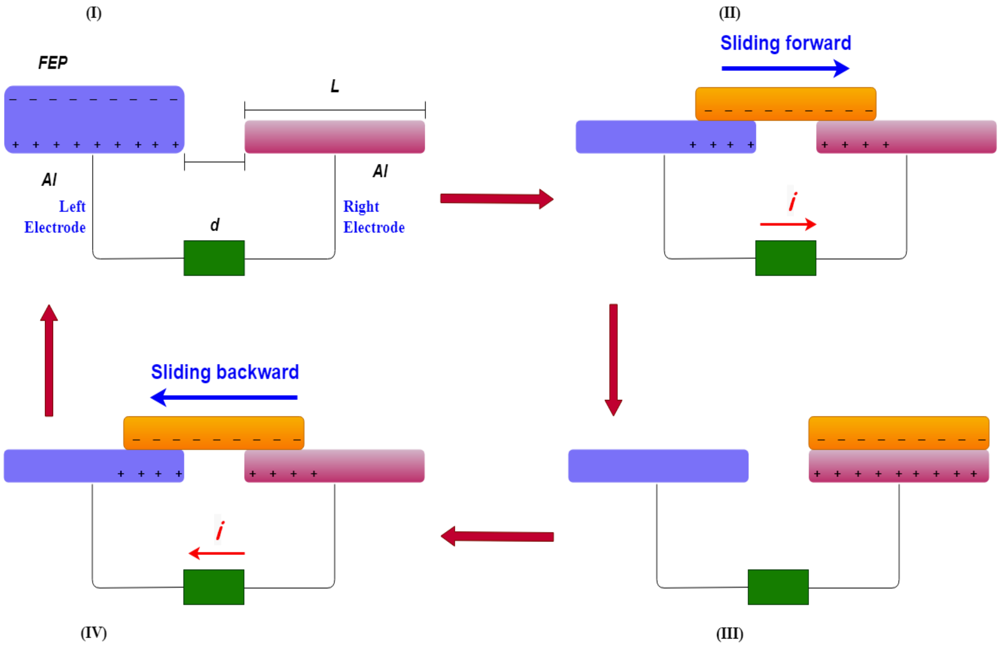


Fig. 5 (a) Two electrodes resulting in change of induced potential difference in the free-standing triboelectric layer mode

When the FEP layer slides towards the right-electrode, the potential difference between the left and the right electrodes will be reduced causing the flow of current from left electrode towards the right electrode as shown in Figure 5(b). When the FEP layer reaches on the top of right electrode, no electric potential difference appears and hence no current flows. Finally, when the FEP layer slides towards the left electrode, an electric potential difference will appear between the two electrodes, causing flow of current between them, thus completing the whole cycle of generating electricity in free-standing triboelectric layer mode.



(b)

Fig. 5 (b) Working principle of a free-standing triboelectric layer mode

3. Energy Harvesting Sources Using TENG

3.1. Energy harvesting through waste water flow

The energy from the waste water flow can be harvested using a rotatory TENG as shown in Figure 6. It consists of PTFE (Poly tetra fluoro ethylene) and Nylon being the tribo-electric materials. With the use of triboelectric effect and electrostatic induction, energy can be harvested by contact and sliding modes of the TENG operation. The devices so far demonstrated has the ability to light up 50 LEDs connected in series [46]. When the water is allowed to flow through the tube, the fan connected to the shaft starts rotating. As shown in Figure 6, different triboelectric materials are placed on the eight different poles. With the rotation of the shaft, the triboelectric materials come in contact with each other thereby causing the flow of current [46]. Energy from the water waves can be harvested as demonstrated by Jiang et al., [47] where they designed a spring based TENG to store the potential energy present in the water waves. Actually, the energy is produced by translating the low frequency wave motion energy of water into high frequency kinetic energy by the use of a spring. In order to achieve higher efficiency, the various parameters like spring rigidity and spring length must be taken into account. Water driven TENG based on water electrification has been demonstrated and developed by Kim et al., [48] which are capable of producing energy even under adverse environmental conditions and rarely affected by humidity and friction.

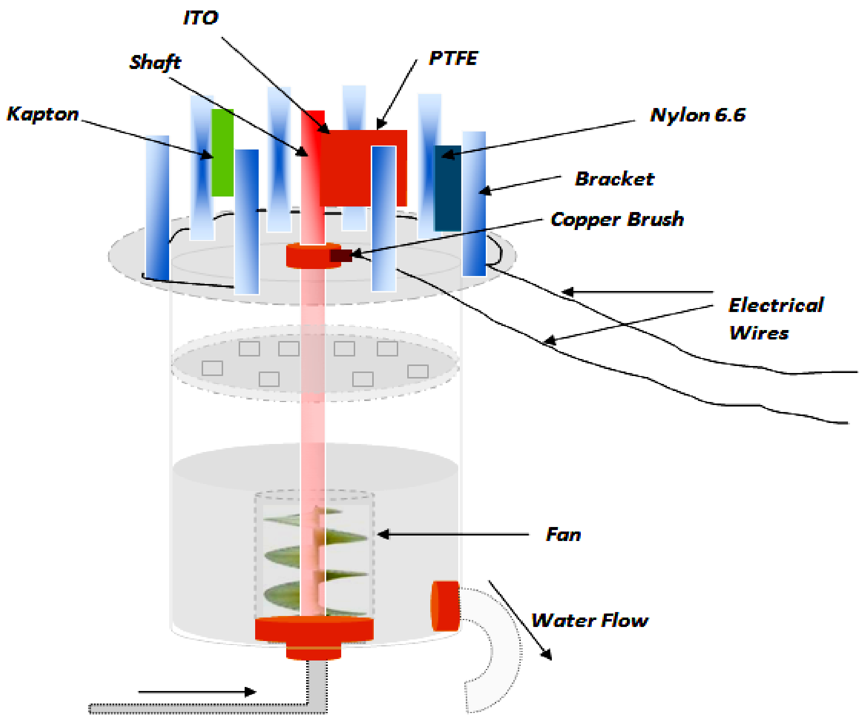


Fig. 6 Schematic diagram of a Rotatory TENG [46]

3.2. Energy harvesting from triboelectric textile

One of the unique sources of energy harvesting takes place through human motion using TET (triboelectric textile). Because of triboelectric effect, the transfer of charge takes place between the skin and the triboelectric textile. In order to obtain a voltage ~ 500 V and a short circuit current of 600 mA, silicon and NI-coated polyester had been used as triboelectric materials as single layer triboelectric textile (STET). On the other hand, for a voltage of ~ 540V and a short circuit current of 140 mA was obtained for a 5x5cm square sized double layer triboelectric textile which is capable of illuminating 100 LEDs connected in series [49] with stretching, rubbing and pressing using folded TET. On stretching, the layer of materials comes in contact with each other and they retain the original shape by removing the external forces. Silk and Si-rubber, when comes in contact with each other on stretching results in the generation of electricity due to the transfer of charge between the two layers as depicted in Figure 7. This type of TET is capable of producing electricity that can light 54 LED bulbs [50].

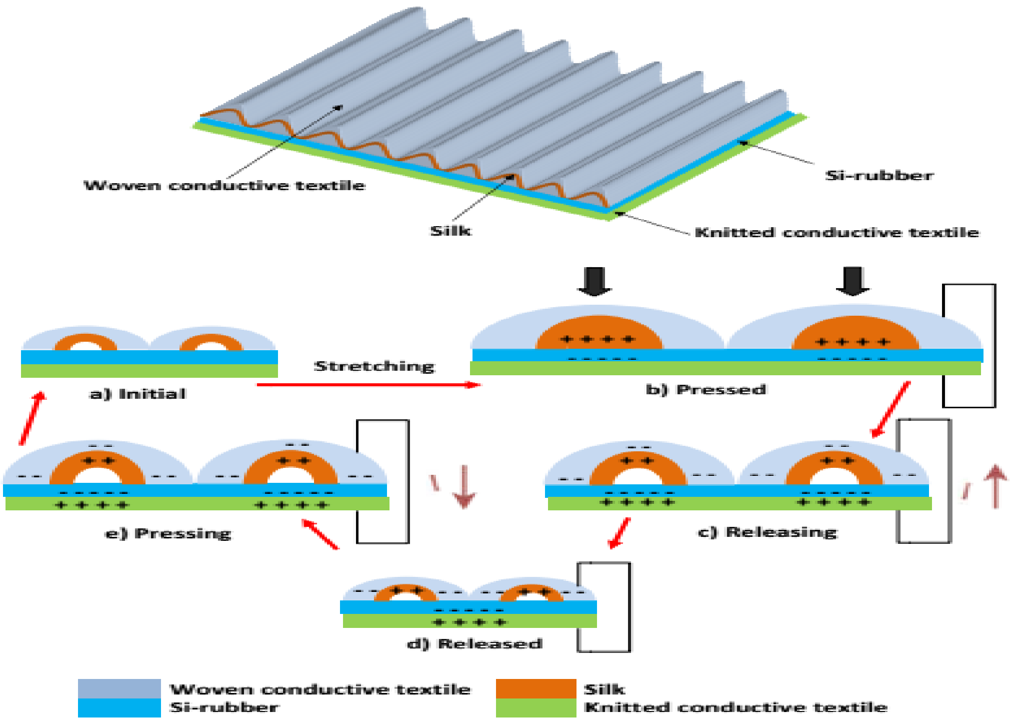


Fig. 7 Working principle of TET

3.3. Energy harvesting from human walking

The energy harvesting from a foot-fall was analyzed and demonstrated by Te-Chien Hou and others experimentally [51] in the year 2013. The fabrication of shoes soles using triboelectric materials with proper use of spacers has been done by using elastic sponge as a spacer. The variations in the size and thickness of the spacer varied the output so generated. The energy converted from human walking into electricity has generated an electrical output which is capable of illuminating 30 LEDs connected in series. It has also been observed that an increase in the number of spacer reduces the output voltage because of a decrease in the effective area of contact.

3.4. Magnetic force and finger tip pressure driven TENG

The TENG driven by magnetic force and finger tip pressure was designed by Taghavi et al [52] as shown in the Figure 8. With the application of pressure on the upper part, the upper pair of materials comes in contact with each other, whereas when the pressure is removed the lower part is pushed in upward causing the lower pair of materials to come in contact with each other due to magnetic force. This contact and separation causes the transfer of charge between the materials resulting in the flow of electric-current.

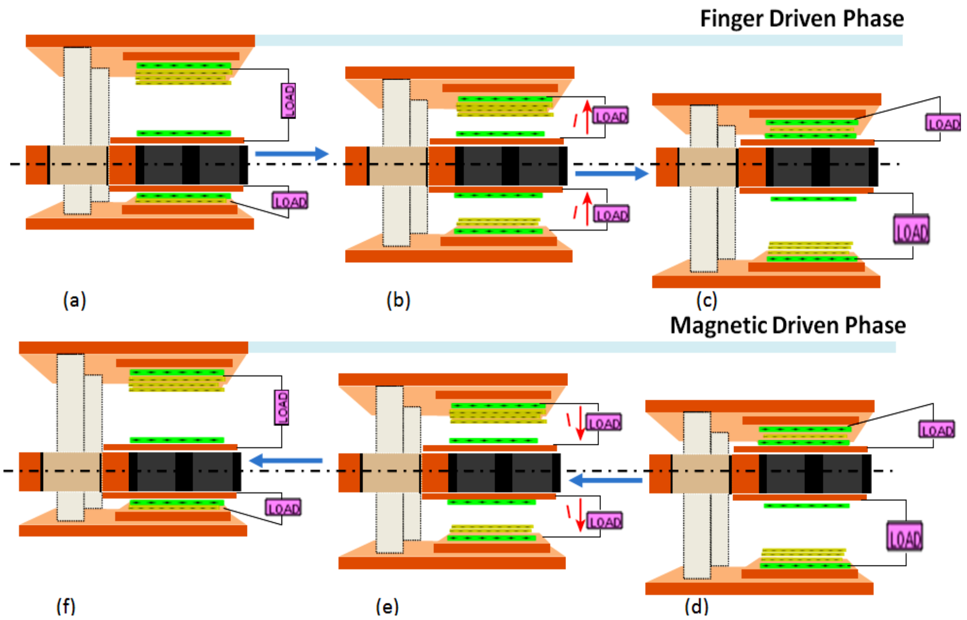


Fig. 8 Mechanism of contact keys driven by finger tips and then by magnetic-force [52]

3.5. Pendulum and comb shaped electrodes based TENG

Another triboelectric nanogenerator that can be fabricated using contact electrification and electrostatic induction is using by a comb-shaped electrode for harvesting energy. More the number of comb electrode arms, the more will be the production of energy. Even the rougher surface shows higher output as compared to the flat surface [53]. The working of this TENG is basically based on the oscillations of a pendulum. With the application of force to the pendulum, a to and fro motion is generated which produces multiple output for a single input. Many setups were created based on the surface roughness and nanowires showing maximum efficiency. The efficiency of TENG increases with an increase in the surface roughness because the surface roughness ultimately increases the area of contact [54]. As shown in figure 9, when one material is placed on the top of pendulum and the other material is placed

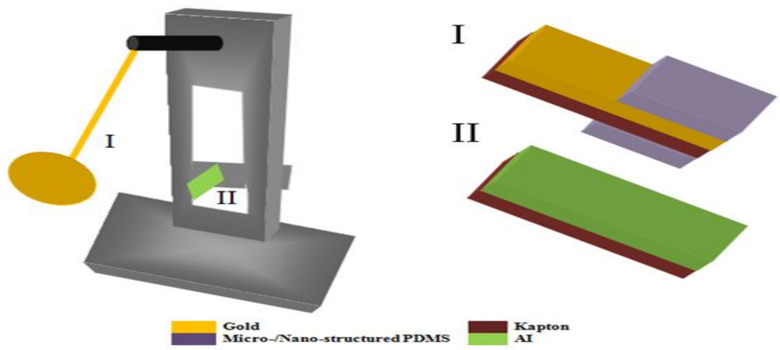


Fig. 9 TENG consisting of two parts I and II (I is movable and II is fixed)

on the frame, with the starting of oscillations, the contact and separation take place between the two materials resulting in charge unbalancing thereby producing the flow of electric-current [54].

4. Effect of Various Factors on the Efficiency of TENG

4.1. Effect of humidity

The generation of charge is greatly influenced by humidity as well as temperature. It has been noticed that the generation of charge between various triboelectric materials increased up to 20% with the decrease in the relative humidity whereas increase in the humidity has adverse effect on the efficiency of triboelectric materials and on the triboelectric effect [55]. A triboelectric nanogenerator can also be fabricated which works on a wide range of humidity without causing change in its electrical output. Such a TENG is consists of triboelectric materials which are water reluctant and hence can be utilized for low and high humidity pendulum conditions [56].

4.2. Effect of temperature

Temperature also has an impact on the output of triboelectric nanogenerator as observed by various researchers. It has been observed that with an increase in temperature, the ductility of triboelectric material increases while the stiffness decreases whereas on decreasing temperature reverse process is observed. From the graph shown below in Figure 10, it is observed that the output voltage decreases beyond a temperature of 300^0K and the output also varies over a wide range of temperature. U+ denotes average positive peak voltage and U^- denotes the average negative peak voltage respectively [57].

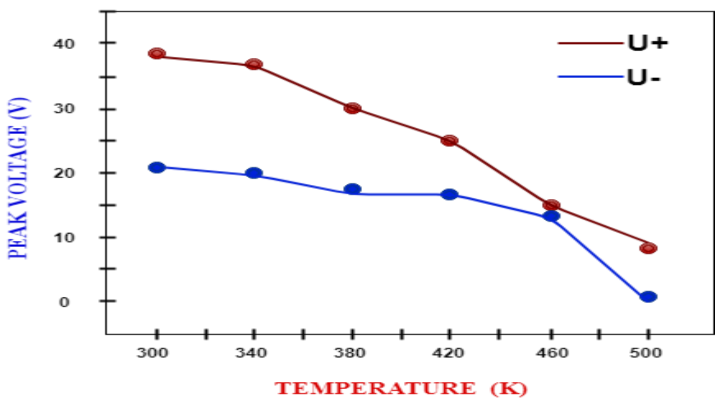


Fig. 10 Variations of peak voltage with temperature [57]

4.3. Effect of surface structure patterning

Various triboelectric materials like PDMS (polydimethyl siloxane) and PMMA (polymethyl methacrylate) can be used for the fabrication of TENG with nanopatterns fabricated on their surface using photolithography. Different types of patterns like hexagonal, pillar, and line can be printed and it has been observed that hexagonal patterns show maximum output voltage as compared to the other patterns. Triboelectric materials with smaller width pillars show higher output as compared with the large width pillar shaped patterns [58]. Seol et al [59] has demonstrated that the effect of pressure on the surface of triboelectric materials result in deformation which has an impact on the output of the TENG devices. It has been observed that high pressure applications result in increased output because of the increase in contact surface thereby causing an increase in the maximum charge density.

5. Applications of TENG

5.1. TENG as a micro-scale power source

The main and most important purpose for developing TENG is to act as a power source for small scale electronic devices and sensors applications. Energy harvesting by using its various modes of operation has been demonstrated for body motion [60] vibrations produced by human walking [61], pressing of hand [62-63], insole of shoes [64-65], sound waves present in air [66] and in water [67]. In its sliding mode of operation, approximately a conversion efficiency of 50% has been observed [68] whereas it is about 24% in the case of rotation based TENG [69]. It has been demonstrated that the output power reaches to a maximum value of 1200 W/m square which is quite sufficient for powering the small device applications in wearable electronics. Energy harvesting has also been demonstrated from flowing river water [70], rain drops [71] by using contact-electrification between solid surface and liquid as applicable in parallel TENG [72]. The energy can be harvested using the fluctuations in the water surface [73], water wave, and water stream [74]. Energy harvesting can be easily done without constructing huge dams. It has been predicted that in the near future a 1MW of power can be generated from 1km square of surface in ocean if the output of each unit will be 1mw on an average by constructing a 3-D network of TENG [75-76]. This will be a big source of blue energy for fulfilling large scale applications/requirements of the world's energy needs.

5.2. TENG as self –powered sensor

Triboelectric nanogenerators can also be used as self-powered sensors without applying any external power source just by sensing dynamic mechanical action. A large number of sensing applications are available which includes finger touching [77-79], detection of vibration [80], rotation and chemical sensor [81-82].

6. Conclusion

In this review paper, a study of triboelectric nanogenerator (TENG) has been made on the basis of its fundamental modes of operation, harvesting energy from various sources, along with various factors affecting its efficiency and applications in the real world. Its simple mechanism of working, compact size, light weight and innovative design makes this device applicable in small and large power generating fields. The output of theTENG depends upon various factors like effective area of contact, amount of force/pressure applied, and morphology of the surface in contact, temperature and humidity. Triboelectric nanogenerators are capable of working over a wide range of temperatures and variable humidity conditions. All the energy which otherwise goes waste in the environment can be utilized by such devices. For achieving sustainable and self-powered systems, TENG devices will soon be available in the form of various products in the wearable electronics, mobile and healthcare monitory systems along with many other relevant applications.

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