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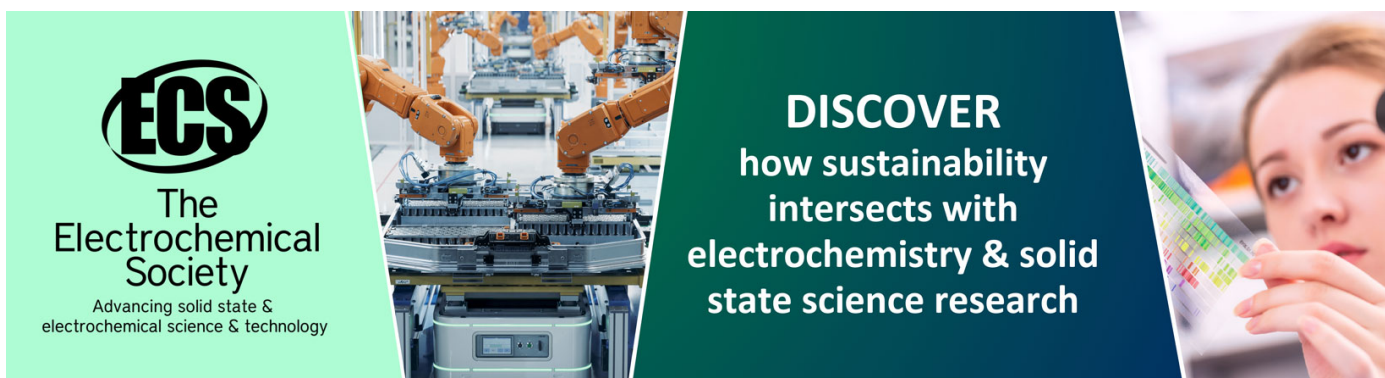
A Critical Review on Triboelectric Nanogenerator

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A Critical Review on Triboelectric Nanogenerator

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Abstract. With the modernization of the technology with time, the demand for energy is increasing day by day, it is necessary to find out the new sources of renewable energy. The fossil fuels upon which the maximum energy has been produced till date are going to be depleted soon. A triboelectric nanogenerator (TENG) is new source of energy firstly demonstrated by Wang et al. in 2012, working basically on the principles of triboelectric effect and electrostatic induction. A triboelectric nanogenerator (TENG) can be used to harvest many forms of energy from the environment which is generally wasted. It has a very simple working mechanism and easy design and can be used to power many small wearable electronics. Many properties of the TENG make it capable of producing large power, and to be used in future for large power generation.

1. Introduction

Energy is one of the most important needs of the society, with the time day by day non-renewable resources such as fossil fuels are getting depleted which is a serious issue with respect to the environmental conditions. The threat of energy scarcity and environmental pollution is increasing day by day, it is necessary to develop new and highly efficient technologies for harvesting energy from the environment and to be used for the welfare of the society. Many forms of different mechanical energy resources are present in our surroundings such as human walking energy, water flow energy, wind energy etc. which are getting wasted and can be efficiently converted into electrical energy to drive various practical and functional devices. Triboelectric Nanogenerators (TENGs) are a new source of energy harvesting technology, having high efficiency, easy working mechanism and capable of harvesting Energy from different sources under different conditions.

TENG has been invented as a new source of energy harvesting device which basically works on the principle of triboelectric effect and electrostatic effect [1]. The TENG follows a mechanism in which, two different triboelectric materials (having opposite polarities) come in contact and then separated or slid against each other. Electron transfer takes place between the materials and electrostatic charges of opposite polarities are developed on the surfaces of the triboelectric materials. Basically, there are two main motions that can be used in a TENG to convert the energy i.e. sliding motion and vertical contact-separation motion. In sliding type TENG rotating and freestanding designs are generally used, whereas in vertical contact separation generally, pressure and vibrations are converted into electricity [2]. The lifespan of vertical contact separation TENG is generally longer than sliding type due to lesser friction damage [3].

In the recent years, many different mechanisms have been developed for the extraction of energy from the environment using TENGs. A number of researches have been carried out to produce portable TENG to run different small-sized portable electronic devices. Present work is an overview



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on TENG which include different sources of energy harvesting in TENG, factors affecting the efficiency of TENG, different mechanism used in TENG and its applications in the real world.

2. Triboelectric Nanogenerator (TENG)

2.1 Different sources of energy harvesting

2.1.1 Wastewater flow energy harvesting method

The wastewater flow energy of the flowing water can be efficiently harvested by a TENG in which Polytetrafluorethylene (PTFE) and Nylon 6.6 are used as the triboelectric materials. Energy is harvested by triboelectric effect and electrostatic induction effect, achieved by contact and sliding modes. The maximum output was achieved using four Nylon plates and one PTFE plate with a maximum discharge of 44 L/min. The device was efficiently able to light up 50 serially connected LEDs [1].

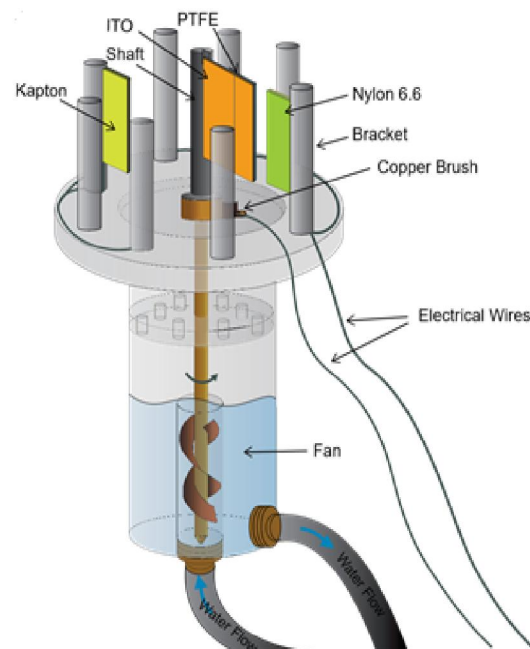


Figure 1. Schematic diagram of a rotatory TENG [1]

Figure 1 shows the schematic diagram of a rotatory TENG. When water is allowed to flow through the tube, it forces the fan to rotate which is connected to the shaft. A triboelectric material is attached to the shaft, which rotates with the shaft due to the water flow. On the frame different triboelectric materials are placed at 8 different poles. When the shaft rotates the materials come in full contact and opposite tribocharges are generated on both the surfaces which results in the flow of current [1]. Jiang et al. designed a spring assisted TENG and investigated on harvesting energy from the water waves. Spring was used to store the potential energy of the water waves. The energy stored can again be used to produce energy via translating low frequency water wave motion energy into high frequency kinetic energy through the spring. The results showed that there should be a specific spring rigidity and specific spring length to be used to achieve highest efficiency [5]. Zhang et al. designed a TENG that can harvest the water wave energy. The authors introduced a dodecahedron (12 faced structure) enclosed device consisting of 12 sets of multi-layered wavy structured TENG, having a hard ball in the polyhedron. Each TENG consisted of Cu-Kapton-Cu film and two FEP films. The collision of ball with the TENG due to the kinetic energy of water produced electrical output [2]. Kim et al. developed a water driven TENG based on water electrification by using rotating fluid inertia. Observations showed that liquid-solid contact TENG is slightly affected by humidity and friction, and are capable of

producing energy under harsh environmental conditions. They prepared a hand driven device attached with gear train that can power 30 LEDs at a time, working on the contact-separation mode [4].

2.1.2 Textile energy harvesting method

A triboelectric textile (TET) can be a unique source of energy in which the energy can be harvested from human motions. The charge transfer takes place between the skin and the triboelectric textile, due to the triboelectric effect. NI-coated polyester and silicon were used as a pair of triboelectric material to obtain the output voltage of 500 V and a short-circuit current of 60 μA using the single-layer triboelectric textile (STET). In double layered TET maximum output was obtained with the size of $5 \times 5 \text{ cm}^2$, producing a voltage of 540 V and short-circuit current of 140 μA . The device was able to light up 100 commercial light-emitting diodes (LEDs) connected serially [6]. A corrugated textile based TENG can be fabricated capable of producing energy by stretching, rubbing and pressing motions of the triboelectric materials. When the material is stretched the layers of material come into complete contact and on removal of force it comes back to the original state. When the stretching force is applied, the silk and Si-rubber come in complete contact and electron transfer takes place which results the production of electricity. The schematic diagram of this method is shown in figure 2 and by using this method 54 LED bulbs can be lighted up [7].

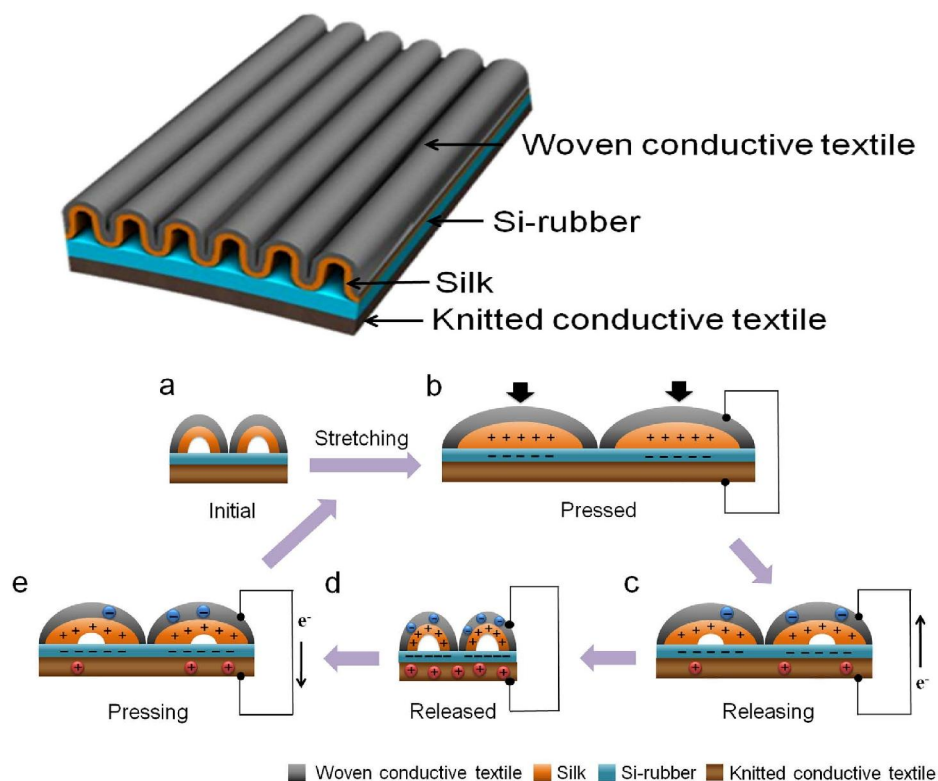


Figure 2. Schematic illustration of working principle of the TENG. (a) Initial state without mechanical force. (b) Triboelectric charge distribution at full-contact state and (c) releasing state. (d) Triboelectric potential at full-separation state and (e) pressing state. [7]

2.1.3 Energy harvesting from walking

An experiment can be performed in which electrostatic charging occurs when two different materials come in contact and are then separated. According to the results, material selection of the footwear and the flooring surface is the decisive factor for the polarity and the amount of charge build-up while walking on the floor. For humans, the threshold of sensing an electrical discharge is about 2 kV of body voltage and from 4 to 6 kV above it gives pain. The maximum output voltage measured during walking test on the laminate floorings is found to be 12 kV. Adding antistatic additives to cleaning liquids can eliminate the problem of static electricity [8]. Hou et al. experimentally analyzed and optimised the energy generation through the foot-fall energy. A shoe sole can be fabricated using the triboelectric materials where spacers can be placed between them. Elastic sponge is used as the spacer, where the size and the thickness of the spacer effectively affected the output. The device was capable of converting the human walking energy to electrical energy and can light up 30 LEDs in serial connection. From the results it was observed that with the increase in the number of spacers the voltage and the current density decreases due to small effective contact area [9]. A large area intelligent power floor (LIPF) can be prepared on the concept of single electrode TENG. When two surfaces come in close contact and are separated, then negative charges are produced on the PVC surface and positive charges are induced on the copper film, resulting in power generation. With the increase in impact force between the triboelectric materials there is a significant increase in the efficiency of the TENG. Another observation was made by keeping the PVC flooring and TENG in the indoor air for ten days and noticed a significant increase in proportion of dust collection for the TENG as compared to blank floor. This proves the capability of the TENG to be used for dust removal and air purification [10].

2.1.4 TENG driven by Magnetic force and fingertip pressure

Taghavi et al. designed a typical contact key based TENG, driven by the magnetic force and fingertip pressure mechanism which is shown in figure 3.

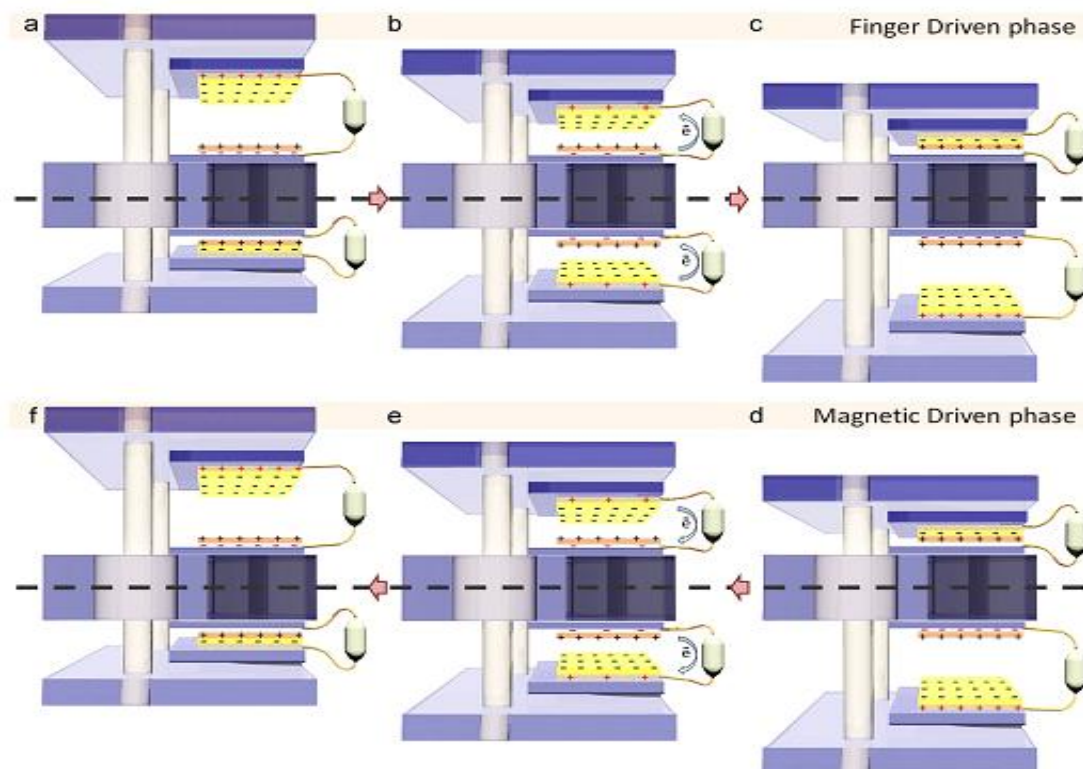


Figure 3. Mechanical functioning and electricity production mechanism of the contact-keys driven by fingertip and then magnetic force; the dashed line shown here represents a fixed plane which stands on plastic pillars. [11].

when finger pressure is applied on the upper part, causing the upper pair of materials to come in contact. When the pressure is removed, due to magnetic force the lower part is pushed upwards causing the contact of the lower pair of materials. Hence the contact and separation leads to charge transfer between the materials, resulting in the flow of current [11]. A seesaw structured TENG can be operated under different speeds and magnetic force. Magnetically coupled contact mechanism is used to reduce the wear of the material. Rubber sponges were used for long-term stability of the TENG electrodes. High-density sponges provided a better shock resistance, resilience, elasticity and tolerance to the seesaw structure at high speeds. The discs were provided with the permanent magnets on the side of each disc due to which a non-contact magnetic force acts between the discs [12].

2.1.5 TENG from a self-retracting dielectric sheet

A portable self-retracting TENG (PSR-TENG) can be fabricated in which a flat sheet dielectric is used and rolled in the cylinder casing. The end of the dielectric sheet is attached to the inner cylinder of a spiral spring. When a user pulls the sheet, the dielectric sheet gets uncoiled into a flat sheet and a restoring force acts on the sheet due to the spiral spring which causes the sheet to roll back when the force is removed. Power is generated due to the stacking and fluttering process during the extraction and retraction phases of the sheet as shown in figure 4. The output power can be maximized by regulating the dimensions of the casing material. The output power increased with the number of dielectric sheets and the rotation speed. A pen-type TENG can light-up a LED array and a segment of LCD screen using hand-driven input [13].

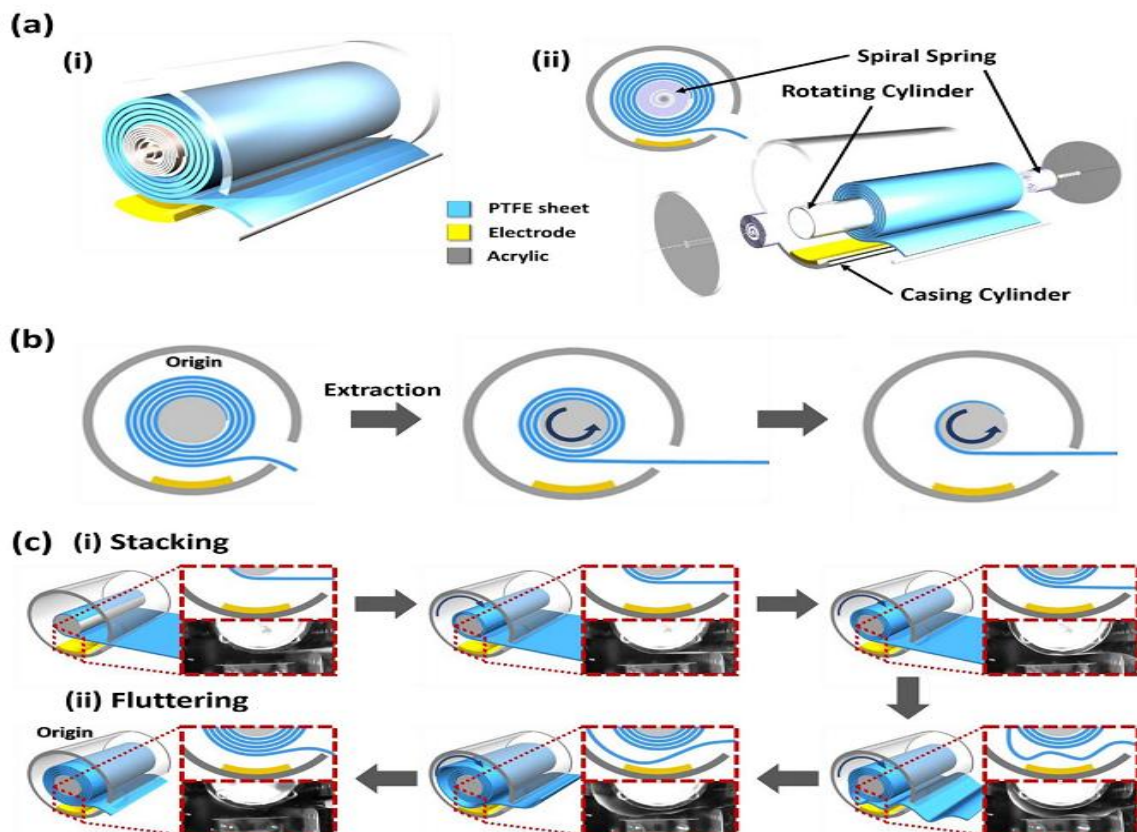


Figure 4. Portable self-retracting TENG, (a) schematic representation of PSR-TENG, (b) schematic representation of extraction process of the dielectric sheet, (c) schematic representation of stacking and fluttering processes. [13]

2.1.6 TENG from a comb shaped electrode and a pendulum

A simple design and highly accessible TENG can be fabricated by using a comb-shaped electrode. Its working mechanism is on contact electrification and electrostatic induction effect for harvesting energy. The larger the number of comb electrode arms used, larger will be the energy produced. Rough surfaces produce more energy as compared to flat surfaces [14]. By using the oscillations of a pendulum a TENG can be prepared. When the force is applied on the pendulum, the gravity force helps the pendulum to sustain to and fro motion, producing multiple outputs for a single input. Four setups were prepared among which materials having micro roughness and nanowires showed the maximum efficiency. With the increase in surface roughness, the efficiency increased due to the increased contact area. [15]

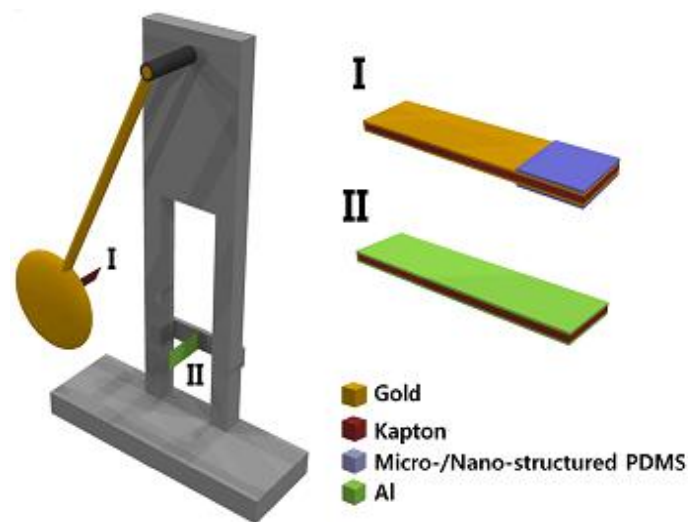


Figure 5. Schematic diagram of TENG and the pendulum of the clock, having two parts (I and II) among which I movable and II fixed. When I and II come in contact charge generation takes place, hence electricity. [15]

In figure 5 shown above, one material is placed on the frame and another material is attached with the bob of the pendulum. When the pendulum is set into oscillations, both the materials come in contact and charge transfer takes place due to the unbalancing of the charges that leads to the flow of current [15].

2.2. Performance on the basis of the type of contact:

2.2.1 Contact-separation mechanism

A vertically stacked TENG consisting of two outer electrodes and a vibrating membrane between them was fabricated for harvesting the bi-directional wind energy. To prevent sticking of the electrodes due to vibrations a pyramid microstructure was engraved on the electrodes. It enhanced the contact area and resulted in more charge density. The output power increased proportionally with the number of stacking layers [16]. Elastic bellows can be utilized as a packaging part and elastic component in the fabrication of a TENG. The bellows are elastic in nature when pressed they naturally attain their original shape after the removal of the force. The device works on the vertical contact-separation

mechanism and produces output with the help of external pressure. When external pressure is applied, the electrodes come in contact and transfer of electrons takes place i.e. electricity flow takes place which is shown by the schematic diagram in figure 6 [17].

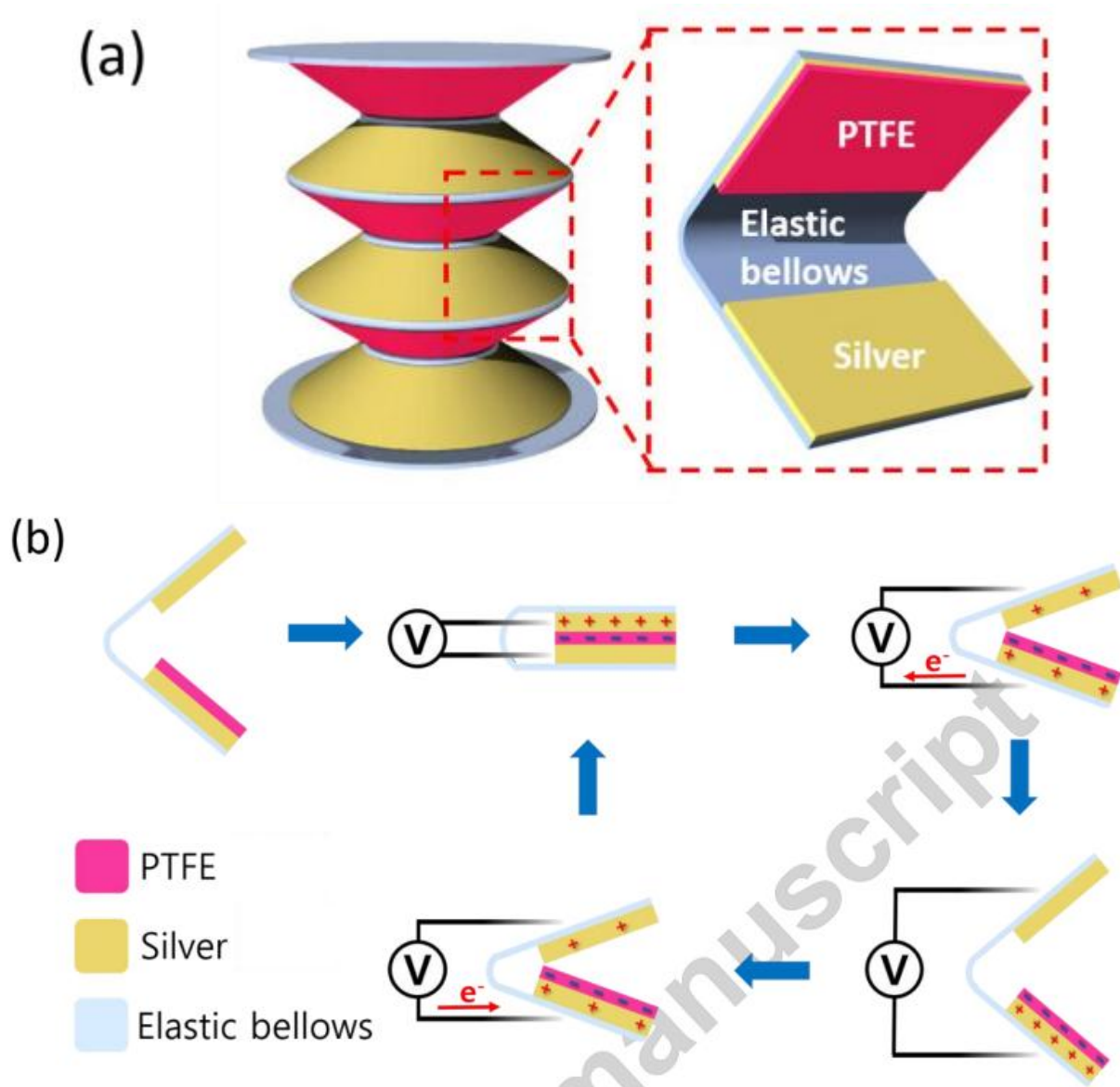


Figure 6. (a) Schematic diagram representing the elastic bellows-type TENG, (b) working mechanism of bellows-type TENG [17]

Jin et al. mathematically described the effect of surface distortions and the adhesive interactions in vertical contact-separation mode TENG. The results of the mathematical simulations showed that the surface structures directly affect the output. Nano-/micro- structures are always designed to increase the effective contact surface area. In the simulations, adhesive interactions were in the terms of interaction potential and the deformations on the surfaces [18]. Xie et al. developed a TENG by using multi-layered integration of the disk of triboelectric materials. The device worked on contact-separation method. In it, a D-shaped shaft was used to transmit rotational power to each triboelectric layer. The device was run by the water flow energy and was capable of lighting hundreds of serially

connected LEDs. To maintain intimate surface of contact between the plates low stiffness springs were used [19].

2.2.2 Sliding mechanism

In the sliding mechanism, two different materials slide with respect to each other and electron transfer takes place between the materials. Yao et al. investigated about the electrostatic charge generation for the granules in the process of achieving equilibrium. The process of achieving equilibrium depends upon granule length ratio, sliding face shape, number of times the sliding occurs, the ratio of sliding area, relative sliding velocity, front facing edge and the sliding plate inclination angle. It was noted that semi-cylindrical granule generates more charge as compared to the rectangular granule [20]. A pendulum can be used to fabricate a TENG in which one triboelectric material is placed on the bob and another on the frame. When the bob is set into oscillations the materials slide with respect to each other and charge transfer takes place i.e. flow of current [15].

2.3. Factor affecting the efficiency of TENG:

2.3.1 Impact of contact forces

It was analysed that how the output efficiency of the TENG changes with respect to the change in the contact forces. When the contact force between the electrodes or the materials is less, a lesser area is in contact, hence less triboelectric charge density is produced. When the contact force is more, a larger area of contact takes place between the materials, the triboelectric charge density reaches to maximum and saturated, showing the hysteretic behaviour of the contact force response in TENG [21].

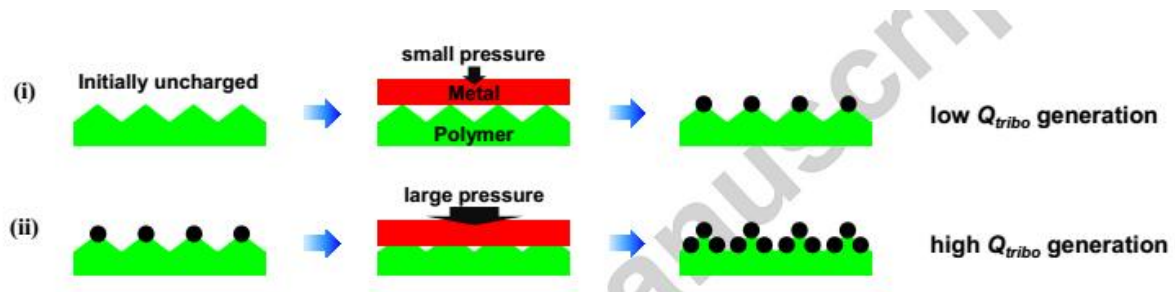


Figure 7. Response of the TENG to the pressure applied. [21]

As shown in figure 7 when a small pressure is applied between the triboelectric materials, lesser charge density is produced due to less contact area while in the second case due to large pressure there is larger contact surface area resulting in more charge generation. Strain in a material can strongly affect the charge transfer between the triboelectric materials. Strain affects the physiochemical properties of the surface which affect the charge transfer [21]. In case of elastic materials when one surface of the material get in contact with the surface of other material strain is produced. Increasing the contact area increases the charge transfer. Greater forces during the contact resulted in the reverse of the direction of charge transfer and cause material strain [22].

2.3.2 Effects of temperature and humidity

The effect of humidity and pressure on the efficiency of the TENG can be optimised. The charge generation between the triboelectric materials increased by more than 20% when the relative humidity is decreased and when the atmospheric pressure decreases to 50 torr. High humidity is not efficient for triboelectric effect and is efficient at lower pressure [23]. A humidity resisting triboelectric generator

can be fabricated in which human biomechanical movements produce energy for small wearable electronic devices working under high humidity. Layers of the material surfaces were chemically modified for enhancing the surface charge density. The materials chosen were having strong hydrophobicity (water reluctant) so that the device can work under a wide range of humidity with same output producing capability [24]. The effects on the performance of a TENG over a wide range of temperature were studied by some researchers. The material properties change with respect to the temperature. With the increase in temperature material gets less ductile and at higher temperatures, the material gets more ductile and lesser stiffer. In experiments, the efficiency increased from 77K to near about 260K and then decreased unvaryingly [25].

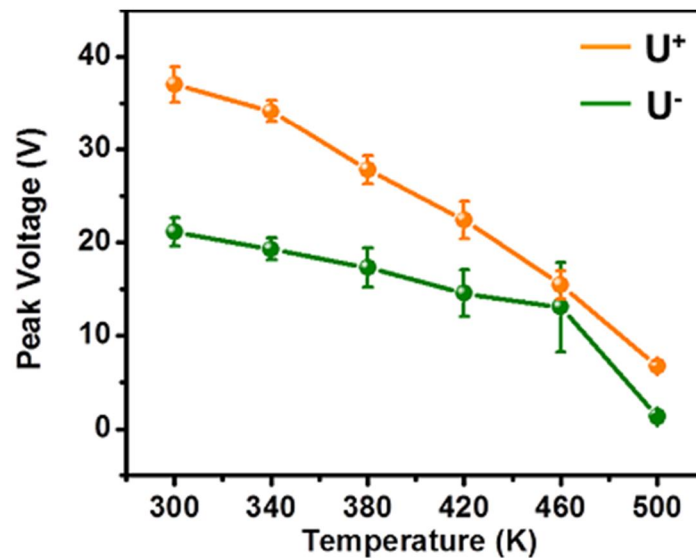


Figure 8. Dependence of peak voltage upon temperature. [25]

The graph shows that with the increase in temperature the output voltage is continuously decreasing but also depicts that the TENG is capable of producing output in a wide range of temperatures. Here U^+ denotes average positive peak voltage and U^- denotes average negative peak voltage [25].

2.3.3 Effects of surface structures

Polydimethylsiloxane (PDMS) and Polymethylmethacrylate (PMMA) were used as the triboelectric materials and nanopatterns were imprinted on the surfaces using thermal nano imprint lithography. Different patterns were printed such as line, hexagonal cone and pillar-shaped and maximum output was achieved with the hexagonal cone pattern. Pillars with the smallest width produced the maximum output as compared to the larger width pillars [26]. Seol et al. presented the effects of the interfacial surface deformations on the charge density of a TENG in contact-separation mode. The results of the simulation showed that maximum pressure should be applied between the triboelectric layers, Due to higher pressure, the maximum surface area will be in contact hence maximum charge density will be obtained [27].

2.3.4 Other Parameters

A kinematic design of TENG can be prepared for enhancing the power conversion efficiency. Gear train mechanism is used in the setup to achieve high output frequency at the lower input by using the gear. The contact type TENG is fabricated using slider crank mechanism from a rotating input source. It was noted that it was much more effective at lower frequency [28]. A prototype can be prepared in

which rotational mechanical energy can be converted into electrical energy. When the two triboelectric materials rub each other, electron transfer takes place between the surfaces of high to low electrochemical potential energy so as to reach an equilibrium condition. The current generated enhanced with the increase in angular frequency and the rotation speed [29]. Cheng et al. proposed a strategy for extracting maximum energy from the TENG. They designed an appropriate power management strategy to power small energy storage units (battery). For maximum output of the system, the resultant output energy of the TENG should be maximized and transfer of output energy to the storage unit should be done with minimum loss using smaller resistances [30].

2.4. Different methods for surface charge density enhancement

2.4.1 Enhancement of surface charge density by heating

Different methods can be used to improve the output power with the help of Nano to micro morphology by using simple glass transition of polystyrene. In this method heating is done which results in shrinkage. The longer is the heating better shrinkage occurs which implies an efficient Nano to microscale morphology. Thus the output is improved without any complex or tricky manufacturing process [31].

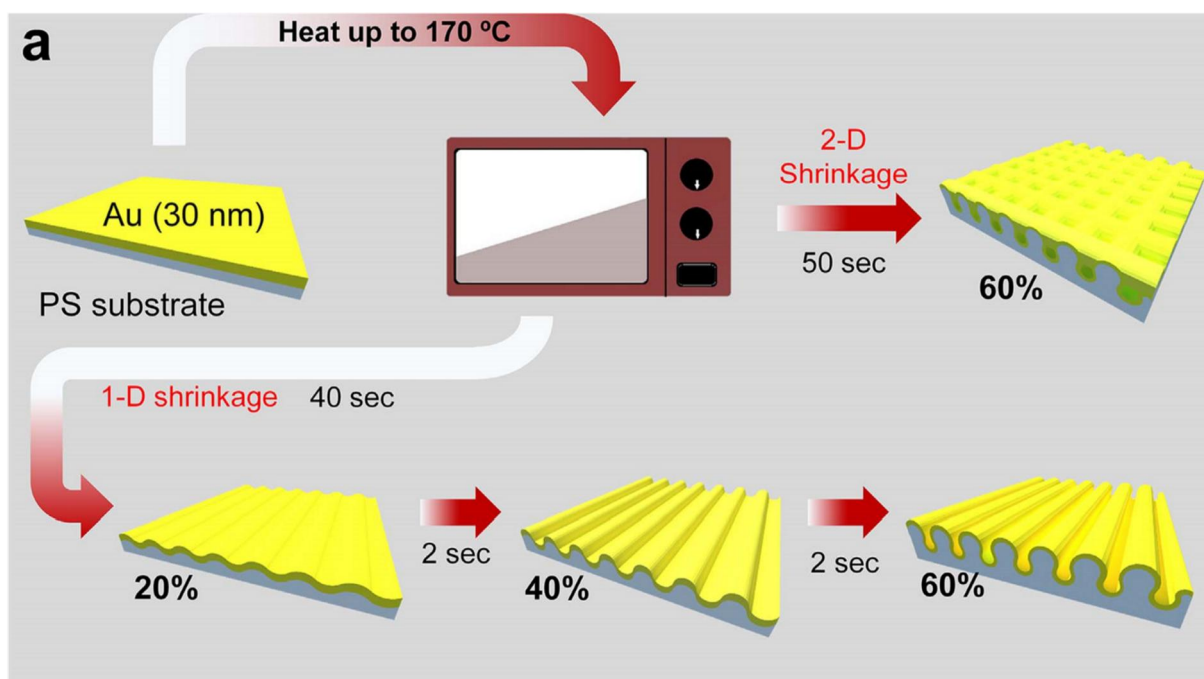


Figure 9. Schematic diagram of the crumpled Au/PS contact electrode. [31]

Here the material was heated to improve the surface morphology which directly enhances the charge generation. Due to the shrinkage, more charge was produced resulting in better efficiency [31].

2.4.2 Enhancement of surface charge density by plasma treatment

Plasma treatment can be done on the surface of PDMS film by chemically treating with argon plasma before the experiment. Smooth and micropillar arrays are engraved on the surface films by using plasma treatment. Some parameters such as treating time, plasma power and the roughness of the films are altered, as the treatment time is increased, the roughness of the films increases first and then decreases with time. Due to plasma treatment, a small column-like structure is distributed on the surface resulting in increase of roughness of the surface and a larger contact area, leading to more

charge transfer. The plasma placed between the two metal plates acted as a parallel plate capacitor, which helped in more charge storage. Hence the output efficiency is increased [32].

Table 1: The average surface roughness of PDMS films after the plasma treatment [32]

Power (W)	Average Roughness (nm) , t=5 mins	Average Roughness (nm) , t=10 mins	Average Roughness (nm) , t=15 mins
0	65.47	--	--
60	141.10	142.18	150.06
90	150.94	144.65	141.53
120	141.38	142.22	140.40

Table 2: The transferred charge for each specimen in one contact-separate cycle

Plasma power (W)	Transferred Charge (nC) t=5 mins	Transferred Charge (nC) t=10 mins	Transferred Charge (nC) t=15 mins
0	3.6	-	-
60	4.7	6.2	7.7
90	9.8	7.1	7.2
120	6	7.3	6.8

The table 1 shows the average surface roughness of PDMS films after the plasma treatment which is used to enhance the surface morphology, with less power and more time duration of treatment better surface roughness can be achieved. Table 2 shows the transferred charge for each specimen in one contact-separate cycle which reveals for less power treated surface there is the maximum charge transfer due to maximum surface roughness [32].

2.4.3 Enhancement of surface charge density by Laser treatment

A femtosecond laser can be used to enable microstructure on the (PDMS) layer. The microstructure pattern on the PDMS surface increases the contact area between the polymer layer and the metal electrode, thereby increasing the output power of the device. As compared to a normal TENG the efficiency of TENG increased with moderate laser power and decreased with large laser power. Due to large laser power, deep surface area patterns are formed which decreases the surface area of contact, resulting in a decrease in charge density hence the efficiency decreases [33]. Yu et al. prepared a TENG using electrospun polymer mats and spongy parenchyma-like structure. Electrospinning method was used to develop nanostructured mats. The benefits of the electrospun mats are large surface area, roughness, and better flexibility. The treatment of the mats resulted in an increase of the output voltage by three times [34]. Park et al. Conducted an experiment and found that surface relief

structures can enhance the effective mechanical surface area between two material and hence the output voltage of the TENG. With time the surface structure gets degraded hence, the output voltage of the TENG decreases continuously [35]. Wang et al. used the most efficient renewable energy resource, the water wave energy. In this review, they focused on the comparison of electromagnetic generator and TENG. The working principles of TENG are triboelectric effect and electrostatic induction effect. Electrostatic charges of opposite polarity are developed after the sliding of the surfaces. The electrostatic field forces the charges to flow through external load [36]. Human skin can be used to generate power by fabricating a TENG on the human skin. For better adhesion with the human skin, the thickness of the TENG is taken less than $2.4\mu\text{m}$. The plasma treatment was done to produce large contact area surface structure. When the TENG come in contact with the human skin electricity is produced with the fabrics [37].

2.5. Applications of triboelectric nanogenerators

2.5.1 Application in automobiles

A single electrode TENG can be used to harvest the braking energy in vehicles. In case of rolling tires on the ground, the maximum energy loss is due to friction and that energy can be harvested by using a TENG. When a triboelectric material (PDMS) comes in contact with the ground, transfer of electrons take place between the PDMS plate and the ground due to triboelectric effect which is shown in figure 9. Due to continuous rotation of the wheel, there is a non-equilibrium of charges on the surface which leads to the generation of current. It is observed that the electric output from the TENG on wheel increased with the increase in rotation speed of the wheel and the load [3].

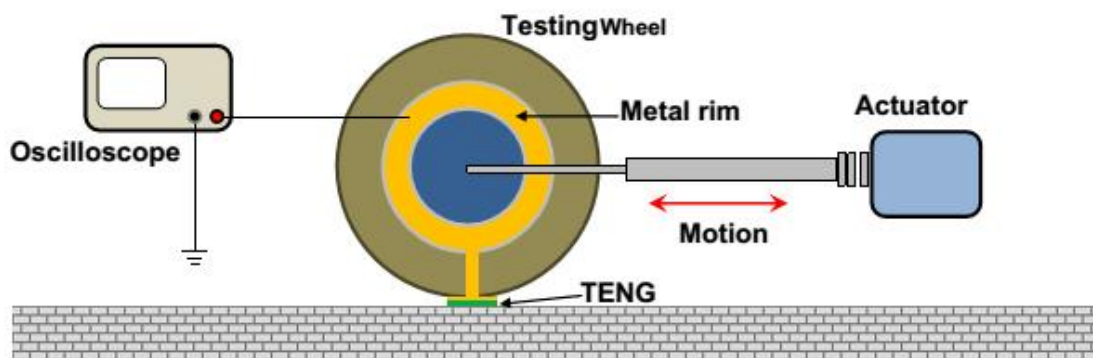


Figure 10. Schematic setup of characterising the friction energy scavenging ability of the TENG from a rolling wheel. [3]

A disc-based design of the braking system can be used in automobiles. Waste energy can be harvested during the braking action of a vehicle using the contact and non-contact modes of braking pads having opposite tribo-polarities. The energy was harvested using the principles of triboelectric effect and electrostatic induction process. Efficiency is high in non-contact mode due to reduced friction. Efficiency was found to be directly proportional to rotational speed and inversely proportional to the distance between the discs [38].

2.5.2 Other different applications

Ahmed et al. conducted an experiment in which they used a rotator, stator and layer of fluorinated ethylene propylene as a dielectric material. Two integrated patterned copper electrodes separated by small gaps having direct contact with copper layers were used. Energy was generated due to the rotation of electrodes, on the principle of triboelectric effect and electrostatic induction. Device was

capable of harvesting energy at all speed ranges [39]. Lee et al. presented newly designed fully-enclosed TENGs, prepared by 3D printing technology. The case of the fabricated TENG was cylindrical in shape having inner surface covered with aluminium film and PDMS balls in the case. When the device was shaken charge transfer took place. Al from the TENG was replaced by the sponge to decrease the noise produced up to the normal level of conversation, without affecting the output efficiency [40]. Kuang et al. presented a two-dimensional rotating type TENG. Its specific design contains coplanar electrodes, capable of producing constantly varying potential that can induce current between the electrodes. TENG can be used to harvest energy from pedalling, pressure due to foot while walking and the too and fro swinging motion of the arm [41]. A simply designed TENG can be used to harvest the unused and waste mechanical energy from the environment. When deformation is caused on the surface of the triboelectric layers, electricity is produced. When two TENGs are connected in antiparallel, the output efficiency decreases, while when in series it increases [42].

3. Conclusion

In this review, TENG has been studied on the basis of its working principles, types of contact, optimization techniques, surface morphology enhancement and its applications in real world. TENG has a very simple and innovative design, easy working mechanism, light in weight and compact in size, makes it applicable to be used in every small to large power generating fields. The charge generation in TENG depends upon the effective contact area, the pressure applied, surface morphology, humidity, temperature, relative speed and frequency of motions. A TENG is capable of working under high humidity and under a wide range of temperature region. A triboelectric nanogenerator (TENG) can be used to harvest many forms of energy from the environment which is generally wasted. It has a very simple working mechanism and easy design and can be used to power many small wearable electronics. Many properties of the TENG make it capable of producing large power, and to be used in future for large power generation. TENG can be used in different sectors like automobile, house flooring, textiles, shoe soles for generating power in an efficient manner.

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