PAPER-BASED TRIBOELECTRIC NANOGENERATORS (TENGS)

BY

MUHAMMAD ASIF NOOR

01-244181-011

SUPERVISED BY

DR. AZHAR UL HAQ

Session- 2018-2020

A Report submitted to the Department of Electrical Engineering

Bahria University, Islamabad

in partial fulfillment of the requirement for the degree of MS(EE)

CERTIFICATE

We accept the work contained in this report as a confirmation to the required standard for the partial fulfillment of the degree of MS(EE).

Head of Department	Supervisor
Internal Examiner	External Examiner

DECLARATION OF AUTHORSHIP

I **MUHAMMAD ASIF NOOR,** Registration No. 56213, hereby declare that I have produced the work presented in this thesis, during the period of registration. I also declare that I have not taken any material from any source except referred to wherever due that amount of plagiarism is within the acceptable range. If a violation of HEC rules on research has occurred in this thesis, I shall be liable to punishment action under the plagiarism action under the plagiarism rules of HEC.

Dated: ________________ Signature: ________________

ACKNOWLEDGEMENTS

First and foremost, I am highly grateful to Almighty Allah, the Creator and the Guardian of the universe, to whom I owe my very existence. I owe my deepest gratitude to my supervisor **Dr. Azhar Ul Haq** and co-supervisor **Shahab Shahid** for mentoring and supporting me throughout my thesis work. I would also like to present my sincere gratitude for their patience, motivation, enthusiasm, and immense guidance during my entire research work.

I am grateful to my parents for giving me continuous inspiration throughout my life and fully supporting my entire education.

I am also thankful to all my friends who were standing with me in every hardship I had to face. Last but not the least; I would like to thank the faculty and staff of Bahria Islamabad for their support and help throughout my master's studies.

ABSTRACT

The triboelectric effect is a type of contact charging effect in which certain materials become electrically charged after they come into contact with other materials. A nanogenerator is a device that coverts mechanical energy into electricity which demonstrates a self-power device driven by electrodes of different materials. In addition, the complex preparation process requires coating with a non-conductive layer, which limits their practical applications, but the output current of a TENG is mainly determined by the quantity of triboelectric charge carried on the friction layer. The triboelectric charge capacity and the charge driving ability of the friction layer are the key parameters for enhancing the output performance of Triboelectric Nanogenerator (TENG)

As first reported in 2006, various nanogenerators (NGs) have been demonstrated using piezoelectric, triboelectric and pyroelectric effects. By using the effect of triboelectric, our goal is to make self-powered system. This research shows the combination of higher ranked triboelectric material and size optimization which ensures the high power generation. This research demonstrates a new type triboelectric nanogenerator which is fabricated using copper tape coated with polyethylene $(C_2H_4)_n$ as the non-conduct layer. Paper is used to separate conducting and non-conducting material. To further enhance the output of the paper-based TENG, a number of polyethylene coated surfaces which is non-conducting and conducting surfaces which is copper tape are combined together for output power. As surface area of conducting and non-conducting material is increased the output power increased. Moreover if number of papers increases, output power also increases.

TABLE OF CONTENTS

List of Figures

LIST OF TABLES

ABBREVIATIONS

TENG	Triboelectric nanogenerators
PI	Polyimide
PTEF	Polytetrafluoroethylene
NGs	Nanogenerators
CNT	Carbon nano tube
PDMS	Polydimethylsiloxane
PVDF	Polyvinylidene
MOSFET	Metal Oxide Silicon Field-effect Transition
PCRET	Pakistan Council of Renewable Energy Technology, Islamabad.
AF	Aluminium foil

Chapter 1

Introduction

CHAPTER 1. INTRODUCTION

1.1. Introduction

Many forms of power generations are available in the world but the most favoured are those in which involvement of human activities is mandatory such as fossil and mineral fuels, nuclear and hydro-electric sources. The main demerit of these sources is global warming. Research shows that around 80% of carbon dioxide on earth is just because of energy production industry and transportation system (local transport system including buses, vans, motorcycles and trains etc.)[1]. There are many other options which are available to fulfil the demand of energy as clean sources of energy production. Renewable energy sources generates power from different sources which are considered as environmental friendly. These sources are wind, geothermal, ocean thermal (tidal energy) and solar[2].

The surface on which two different materials are coated as a layer (by spinning or through coating) is used to produce electrostatic charges when the different sides of coated materials come in contact with each other. The triboelectric charges are developed and also a potential difference when these materials (coated layers) separated by mechanical force. This whole can set-up movement of electrons between two electrodes (positive and negative electrodes) on both sides of the surface. This process is known as “triboelectric nanogenerators” or TENGs. This is a technique where efficiency can be obtained up to 85%. Since 2012, many techniques have been developed but this thesis will demonstrate a new approach towards triboelectric nanotechnology including modelling, material coating on paper (spinning and layer deposit), experimental set-up, different folding patterns and I-V graph of the experiment. This chapter only will include the introduction of triboelectric nanotechnology, approach adopted in thesis and aim and objectives of this proposed work.

Tribo electricity nano generator (TENG) was firstly invented by Wang group in 2012 to track excellently connect ambient mechanical energy that is over present but normally unused in our day to day life routine[3]. The key points of TENG is listed in the following Figure 1.1.

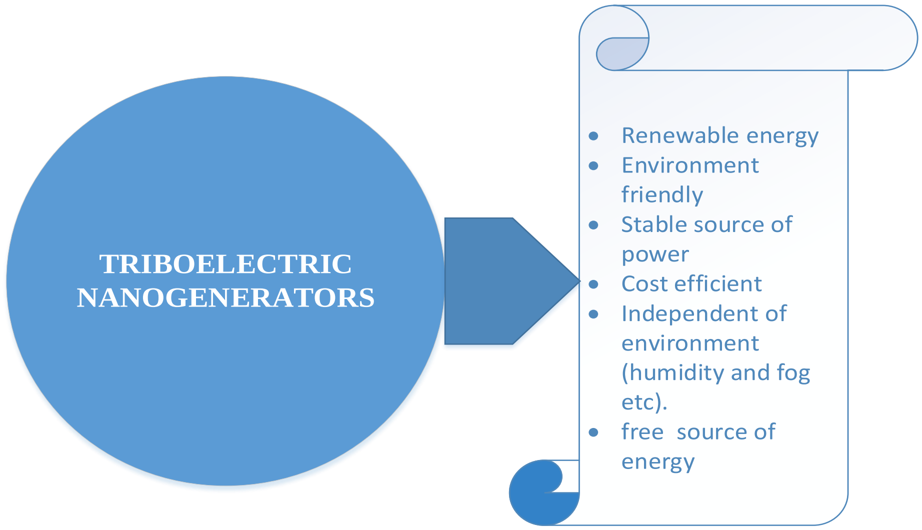


Figure 1.1.1 Key point of Triboelectric nanogenerators.

It is the revolution in the field of nanotechnology having more benefits than above mentioned in the Figure 1.1 but during his early research there were many complication that were hurdles in the progressive research of this field but later on with the development of concepts and understanding of this new theory/mode of power production to the researchers, new doors of research and innovations opened.

From 2012 to 2019, over the span of past 7 years, triboelectric nanogenerators notion has been developed in various modes of applications regarding to the demand of the application[4, 5]. Such Triboelectric nanogenerators used in different modes as mechanical vibration, human motion, wind and water waves[6]. In 20th century, nanotechnology witnessed expectations from industry as well as academic communities. Governments as well as investors put a huge amount of money in this field to open new doors of research in the field of generation[6, 7].

Turbo electricity nano generator can be modeled/manufactured by using materials having diverse charge affinity which is capable of significant performance. Materials which are commonly used for TENG are PTEF (polytetrafluoroethylene), silicon, nylon and metals. Positive and negative charge ends are required for this purpose and which are made by above mentioned materials.

First practical use of TENG was in the numerous mechanical motions as an effective energy harvester. Now, modern research revolutionized the concept of TENG as its weight is reduced (less weight) and performance (output) is increased. They are also known as “Green batteries” in power generation field as less harmful in comparison with the conventional batteries used in power system[8]. Firstly, TENG was based on vertical separation but during its second wave of progress, its preparation is proposed without depositing metal electrodes. This thesis is based on spinning and coating of copper and polyethylene to form negative and positive electrodes respectively.

Previous work shows some trembling energy harvesters which were based on piezoelectric concept for power generation and electromagnetic effects were also used as power supply. This statement justifies by an example of frequency vibration energy harvester. Because of its size and shape, they are broadly accepted in electronic applications and there adoptability is increased day by day. Some difficult concepts for conversion of energy from heat i.e. conversion of human body heat into electrical energy also targeted in previous research but as nanotechnology was not enough matured, so these concepts were not practically implemented but now energy from body heat is obtained in many applications i.e. smart watches. The main hurdle in the field of nanotechnology, to be more precise in TENG was its efficiency and reliability[9].

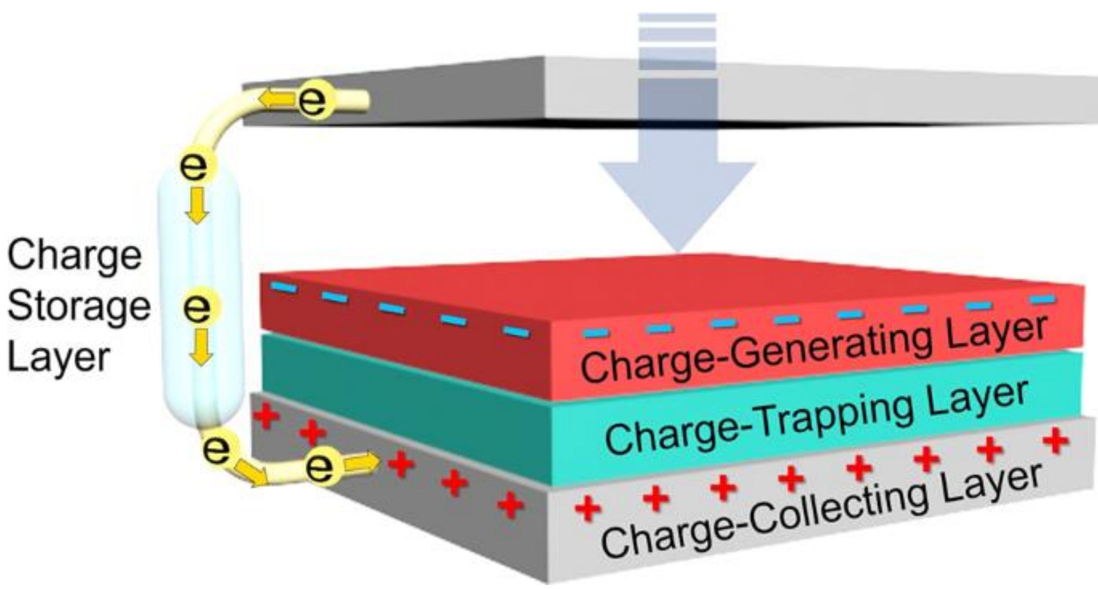


Figure 1.1.2 Paper-based triboelectric nanogenerators set-up

In this thesis, a layer of copper at one side of paper and a layer of polyethylene on the other side of paper is established. These two layers acts as a negative and positive electrodes respectively, with low resistance wires the output is observed through digital multi meter. 55 Celsius was set as the standard temperature of oven for 60 minutes (approx. 1 hour). All the procedure will be discussed in detail in 3rd chapter.

1.2. Problem statement.

As first reported in 2006, various nanogenerators (NGs) have been demonstrated using piezoelectric, triboelectric and pyroelectric effects. The self-powering approaches developed here are a new paradigm in nanotechnology and green energy for truly achieving sustainable self-sufficient micro/nano-systems, which are of critical importance for sensing, medical science, infrastructure/environmental monitoring, defense technology and personal electronics. This work is paper based triboelectric NGs, in which we increase efficiency in output power. By using triboelectric effect on paper we get more efficient power as compared to other effect like piezoelectric and pyroelectric effect. By contacting conducting and non-conducting material by nano wires we decrease loses in output power. Triboelectric nanogenerator & piezoelectric nanogenerators for self-powered with other material were made but self-power triboelectric nanogenerators by using paper put more value on I-V graph with as it is pressed for more time. In this process by using resistor of 1mΩ we got more efficient power.

1.3. Aims and Objectives

The objectives of this research are:

1. Paper-based triboelectric (TENG) arrangements in terms of folding combinations of proposed theory.
2. Positive and negative electrodes preparation by using different materials having sufficient power production capability.
3. Preparation of copper taped paper one end as positive side.
4. Coating of polyethylene layer on the other side of paper as negative side.
5. Patterns of folding which are under-considered are 2*2, 4*4 and 6*6.
6. Different values of I-V graph for different pattern are observed and analysed.

1.4. Thesis Organization

Organization of this thesis is as under:

Chapter 1 In this chapter introduction related to the problem and problem statement with aims and objective is provided.

Chapter 2 This section will cover the introduction of nanotechnology and triboelectric nanogenerators (TENGs) and the challenges in using this technology. The history and present research work in the field of TENG especially on the paper-based triboelectric nanogenerators will be explained and challenges according to their integration will be determined. Than a summary of all the papers which has been studied during this thesis will be given literature review of paper-based TENG.

Chapter 3 This chapter contains all the proposed system and details of all the components used in the system which may be copper, polyethylene, low resistance wire, combination of paper folding pattern i.e. 2*2, 4*4 and 6*6 and I-V graph.

Chapter 4 Presents the case studies and results analysis using the method proposed in the thesis.

Chapter 5 Presents conclusion and future work of the research.

Chapter 2

Literature Review

CHAPTER 2. LITERATURE REVIEW

2.1. Overview

Many forms of power generations are available in the world but the most favoured are those in which involvement of human activities is mandatory such as fossil and mineral fuels, nuclear and hydro-electric sources. The main demerit of these sources is global warming. For power generation, many factors should be considered such as environment pollution, emission of hazardous gases (carbon oxides and nitrogen oxide), geosphere deterioration, fuel consumption rate, economy, stability of the system, distribution network and maintenance of the overall system etc. research shows that around 80% of carbon dioxide on earth is just because of energy production industry. There are many other options available to fulfil the demand of energy as clean sources of energy are still available. Renewable energy sources generates power from different sources which are considered as environmental friendly. These sources are solar, wind, geothermal, ocean thermal[2].

Power generation from renewable energy sources in United States of America is 7% in comparison with the generation of power from nuclear energy which is 8%. Conventional methods to generate electricity is still popular there as the produce energy more than 80% with fossil fuels. In Germany, power production from nuclear energy and fossil fuel covers around 57% of its power demand. More than 12% of energy is produced by the usage of renewable energy sources. These examples clarifies the importance of renewable energy sources for production of energy as it is a clean source of energy. By using these sources, we can save environment and sources of fossil fuels for our next generation.

Tribo electricity nano generator (TENG) was firstly invented by Wang group in 2012 to track excellently connect ambient mechanical energy that is over present but normally unused in our day to day life routine[3]. Illustration of the first tribo electricity nano generators (TENG) and its process cycle is presented in the figure 2.1. In addition electrification offers static polarized controls on material faces which is in contact. Moreover, electrostatic induction drives the alteration of mechanical energy to electricity through the change in electrical potential tempted by mechanically frantic apart. Figure 2.2 and figure 2.3 shows the separation model and electric circuit model respectively.

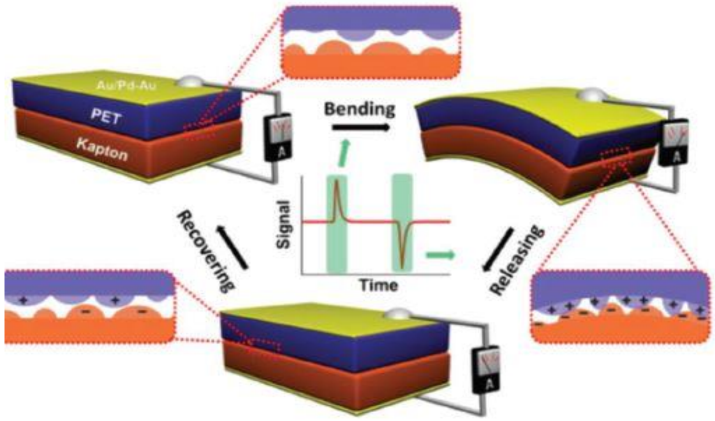


Figure 2.1 First triboelectric nanogenerators and its process cycle.

From 2012 to 2019, over the span of past 7 years, tribo electricity nano generator notion has been developed in various modes of applications regarding to the demand of the application[4]. Such Tribo electricity nano generator is used in different modes such as as mechanical vibration, human motion, wind, and water waves[6,7].

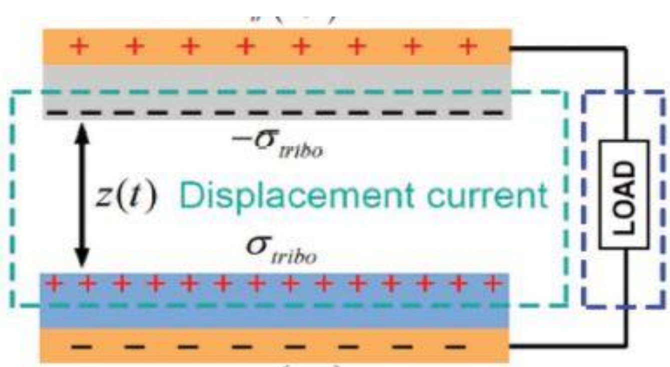


Figure 2.2 Separation model of TENG.

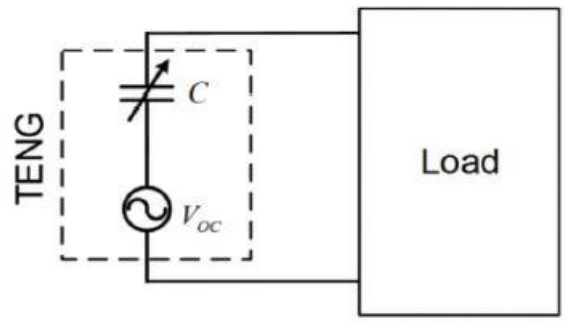


Figure 2.3 Electric circuit model of TENG.

Because of this rapid increase of power, nanotechnology is one the main stream of power generation which gained a lot attention over other steams of electricity generation because of its vast advantages. In 20th century, nanotechnology witnessed expectations from industry as well as academic communities. Governments as well as investors put a huge amount of money in this field to open new doors of research in the field of generation. It is not a particular field of power generation but having its roots in other fields as well. It is capable to fabricate new materials by different process which plays a vulnerable role in the applications of wide number of fields. Great achievements are grasped in the field of power generation. By taking advantages from this fruitful technology, demand per capita can be decreased which depends on conventional power system. Power generation from nanotechnology is considered as green power generation.

Nano technology refers to those materials which are nanoscale (on the gage of 1 billionth to few tens of billionths of a beat). It is elucidated in figure 2.4[9].

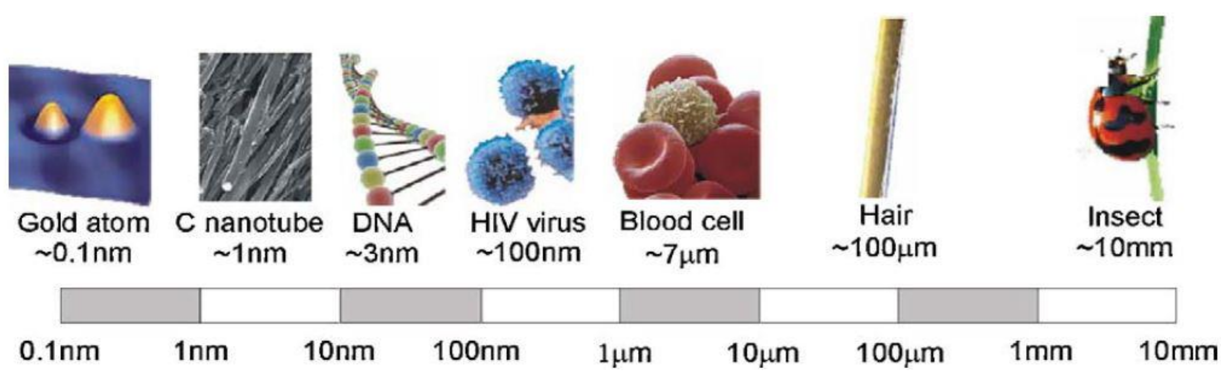


Figure 2.4 Nanotechnology and wavelength of different materials.

Management of atoms, contraction and control the properties of nanosystems or nanomaterials suggest in this pattern. These characteristics are absolutely unlike than those controlled by the constituent materials, generating custom-made expedients with abilities which are not present in the nature of constituent materials.

Turbo electricity nano generator can be modeled/manufactured by using materials having diverse charge affinity which is capable of significant performance. Materials which are commonly used for TENG are PTEF (polytetrafluoroethylene), silicon, nylon and metals. Positive and negative charge ends are required for this purpose and which are made by above mentioned materials. Positive charge end is made by nylon and metals, in contrast negative charge end is obtained with the help of PTEF and silicon coating. Numerous characteristics which make TENGs vulnerable than other electric generation methods are the flexibility and cost effectiveness. TENGs are also suitable for severe conditions where ceramics materials are used to build TENGs[10, 11]. Two influencers device design and active material effects the power density of turbo electricity nano generator to the limit of 550W[12]. To operate many small electronic gadgets, energy from harvesting sources by turbo electricity nano generators is sufficient. Because of its numerous significant applications in power related field, it is declared as "Energy of new era[13].

2.2. Current Status around the Globe

With the invention of PENGs (Piezoelectric nano generator) in 2006 by "Wang group", it revolutionized the nanotechnology which was not up to the marked before 2006 as their applications were limited. After PENGs, more than 195 patents were in the field of nanotechnology were discussed across globe[13]. Its developments, controls, and approaches in the direction of large-scale commercialization have been considered using several procedures[13-16]. including bibliometric, patent scrutiny, in mining, techno-economic generation valuation, and technology road-mapping, with the results showing that nano generator expansion is pleasant in more interdisciplinary and calls for labors not only from materials science and nanotechnology, but also from computer science and many others forms of science. As nanotechnology is flourishing by leaps and bounds, it was decided that regular conferences would be held in future from 2012 to onward after every two year. The first international conference was held in North America in which total participants were around 50 in 2012 but it were expanded in 2018 where total number of participants exceeded 400 and this was held in Asia. Now, the next conference will be held in Europe in 2020. A particular journal named "Nano Energy" is especially assigned for NGPT by founder of TENG Prof. Z. L. Wang in 2012. The main purpose of this journal is to promote the solutions of problems regarding energy and nanotechnology. In this journal, number of publications were just 40 when it started in 2012 but in 2018 total publication were 400. These figures shows the development and growth rate in nanotechnology especially in TENGs. In these conferences, suggestions regarding face masks[17] and air filter[18] were discussed and after that these two products were launched in China. The concept of air filter and face mask is shown in figure 2.5.

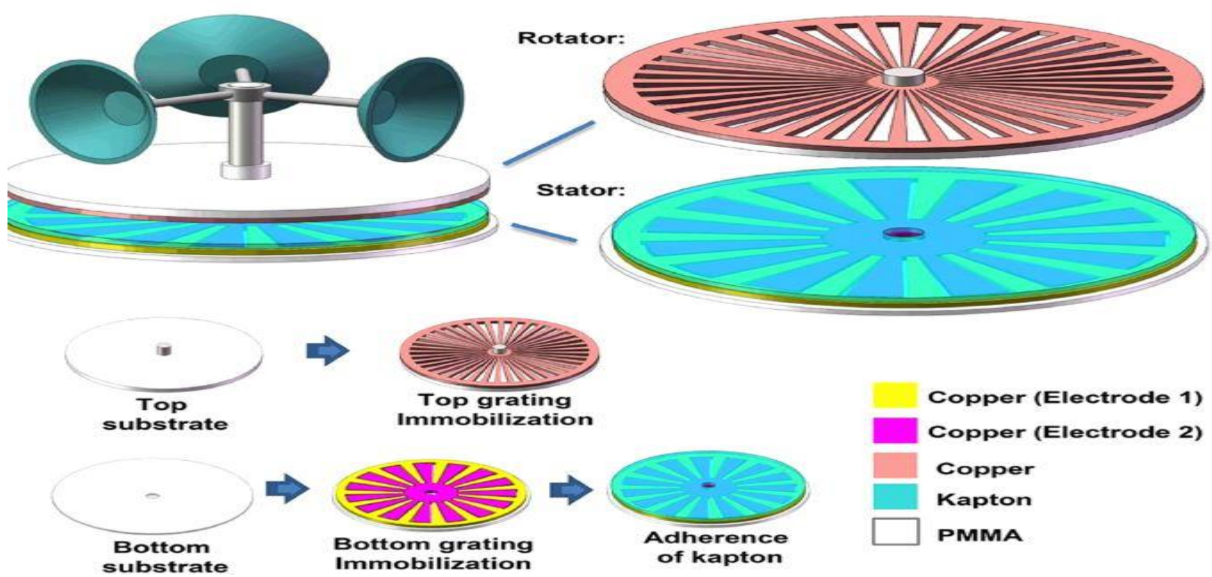


Figure 2.5 Air filter and face mask.

2.2.1. Principle to remove Sulphur dioxide and dust from air.

Oxidation of SO2 at anode and cathode is presented in following equations:

$$\mathrm{SO2} + 2\mathrm{HO2} \rightarrow +\mathrm{SO}^{2-} + 4\mathrm{H}^{+} + 2\mathrm{e}^{-} \tag{2.1}$$

$$2\mathrm{H}^{+} + \frac{1}{2}\mathrm{O2} + 2\mathrm{e}^{-} \rightarrow \mathrm{HO2} \tag{2.2}$$

The complete reaction is

$$SO2 + HO2 + \frac{1}{2}O2 \longrightarrow H2SO2 \tag{2.3}$$

Switching of electrons from anode to cathode during this process mentioned in above equations. At anode, Sulphur dioxide is detected and sulphuric oxide is detected by the thin coating of copper.

Removal of dust and Sulphur dioxide is explained in figure 2.6. The official name of this filter is "R-TENG" which is the initiative of nanotechnology towards the pollutants control and formaldehyde removal in near future[19].

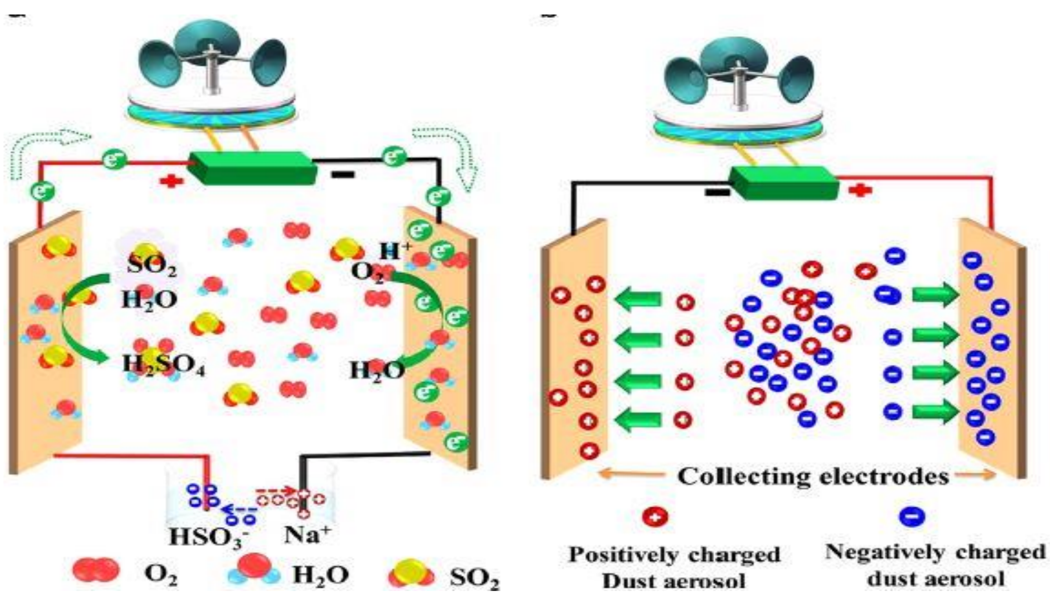


Figure 2.6 Removal of dust and sulphur dioxide

2.2.2. Operations:

"Electrostatic precipitation" is the principle for the removal of dust in above mentioned face mask related to the innovation of nanotechnology. Following equation will justify the mechanism;

$$E = \frac{\Delta\varphi}{d} \tag{2.4}$$

$$F = Eq \tag{2.5}$$

Between two plates, electrostatic field is represented by E while Δφ and d is for potential difference between plates and horizontal distance respectively[19].

The generated dust aerosol may be positive or negative because of the triboelectric. The charged aerosol is injected into chamber with the help of an inlet by pump of air, two electrodes are responsible for the attraction of dust particles which are charged because of attraction and repulsion forces. All the procedure is illustrated in above figure. Opposite charged particles are pulled out opposite electrodes (positive charged particles of dust are eliminated by and negative electrodes and vice versa). All these factors are key influencers to gain weight of copper mesh. The important thing in whole procedure is that all energy required to perform these operation of dust removal is carried out by wind which is the best example of TENGs technology.

2.3. Self-powered adsorption of dust:

Self-powered absorption of dust, electrode components and circuit for the supply of electricity is demonstrated in the figure 2.7[20].

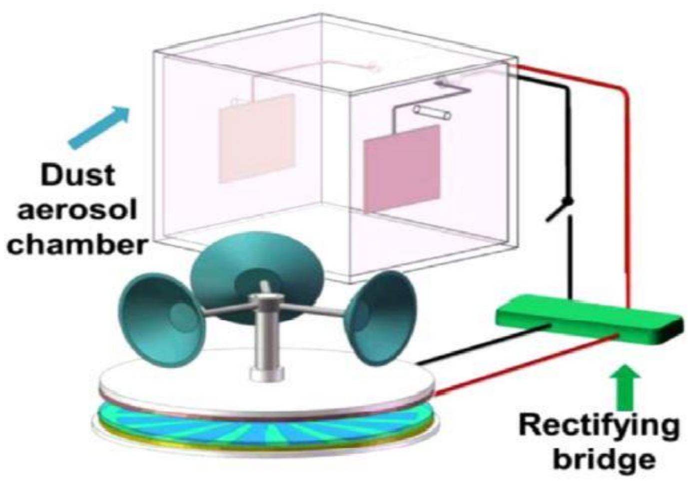


Figure 2.7 Self-powered absorption of dust.

R-TENG voltages remained saturated having value of 300V which is connected with the copper. Two important factors must be discussed here[21],

- The tribo electrification area is not affected by the increase of wind speed which assures that the voltage remains stable at any cost.
- Output voltage of R-TENG and the voltage between copper plates are equal during the process of dust absorption.

2.4. Electrostatic energy from daily activities.

Electrostatic energy can be harvested from our daily routine life. Energy from the bottom of shoes can be generated because of pressure is best example in this regard. Other example is to harvest energy from the motions of our body such as stretching and bending. It is also claimed and proved with experiment that energy production from human skin and clothes is also possible as human skin is always at the positive end of triboelectric series[22, 23]. So, sufficient amount of micro-electric energy can be produced which will be enough for the operations of small electronic gadgets.

2.5. Tribo electric nano generator (TENG) with coplanar electrode for energy Harvesting.

Two electrodes (positive electrode and negative electrode) are formed when coating on two different material is done. These two electrodes are placed in such a way that attachment of the electrodes with skin is mandatory in every aspect. Magnitude and energy efficiency are considered important in nanotechnology but in this set-up discomfort of human body because of the presence of electrons is also unconsidered.

An international report shows the negative impact of electrostatic charges on human skin can causes many infectious as well as hazardous diseases[24]. To eliminate the negative impact of charges on skin, one patch must absorb/collect electrons from the entire human body to balance the electrons as zero. The circuit diagram of tribo electricity nano generator with coplanar electrodes for energy harvesting is shown in following figure 2.8.

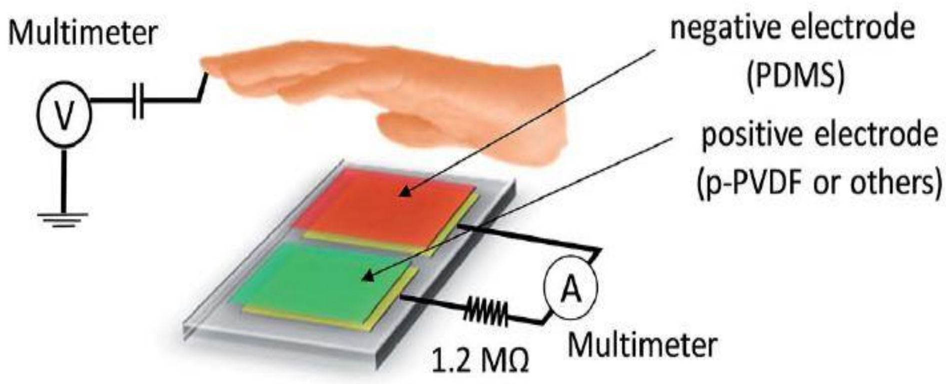


Figure 2.8 Electric circuit of TENG with coplanar electrodes for energy harvesting.

With skin, cotton and Butyronitrite when device was brought into connect, its production of energy in these three medium is in the following order,

Cotton > Skin > Butyronitrite

The least amount of energy was obtained when this device came into contact with Butyronitrite, intermediate production of energy with skin and maximum amount of of energy is obtained by cotton. On the basis of this result, the skin is at the intermediate position in the triboelectric series, although skin is capable to loss more electrons in comparison with cotton and Butyronitrite[24]. CNT (carbon nano tube) coating on sticky tape and Butyronitrite is obtained from domestic glove. In this experiment of energy production, the triboelectric order is

CNT < Cotton < Skin

The size of each electrode was 4*4 cm2 and a coating of PDMS (polydimethylsiloxane) is used. The figure 2.9 shows the energy per touch by various material on positive electrode[25].

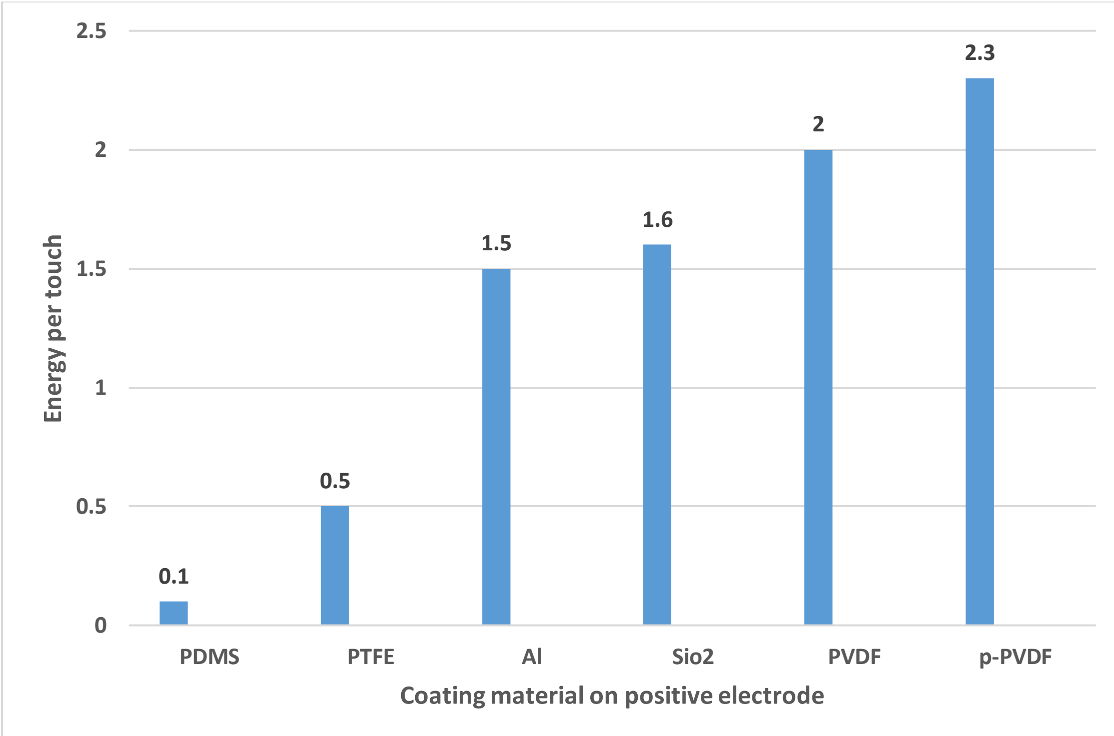


Figure 2.9 energy per touch by various material on positive electrode.

The figure 2.10 shows the electrostatic potential left on the skin after 25 touch iterations.

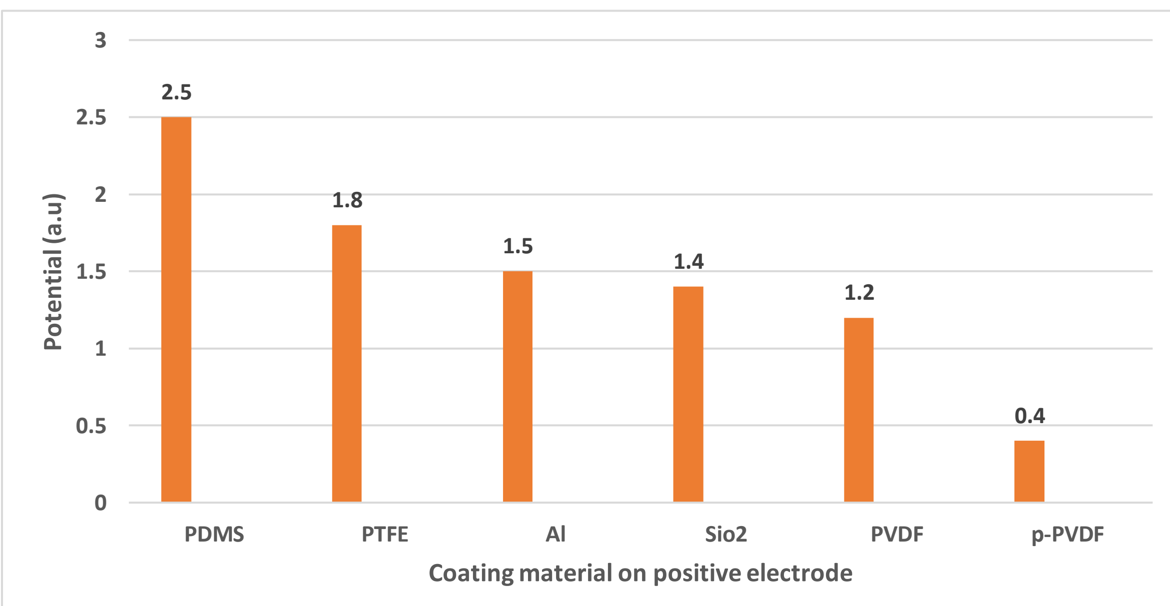


Figure 2.10 the electrostatic potential left on the skin after 25 touch iterations.

In term for polarity of charges, PDMS is ranked in the lowest order in triboelectric series. Materials including PMDS, PTEF (polytetrafluoroethylene), PVDF and some others are tested as positive electrode and results is shown in above fig 8. 10.2% of energy density is improved in p-PVDF as compared to untreated PVDF.

Power efficiency trend is in opposite to that of electrostatic potential of skin which is demonstrated in fig 9. There is more than 40% difference of electrostatic potential when PVDF (untreated) and PDMS separately used as positive electrode. Electrostatic potential is reduced by 10% when p-PVDF is used. To gain more electrostatic charge, size of PVDF patch is weighted by factor of 1.78[25].

This research suggested that coplanar triboelectric scheme led the design of an electronic device which is placed on clothes (inner side of clothes) which can make contact with skin easily. In addition, power generation and electrode resolution depend on size of an electrode. Furthermore, research in future will replace these material to the safer ones which will be human friendly.

2.6. Paper based tribo electricity nano generator (TENG).

Cost is a main factor in nano technology as most of the materials used in TENGs are expensive as compared to those which are in in conventional power generation methods. Maximum power density (39.8 $\mu W/cm_2$) is achieved by the paper based tribo electric nano generators with less cost as compared to the other TENGs[26, 27]. For paper based TENG, conductive ink and Teflon was introduced by Xia. This approach was not sufficiently up to the desired of investors as the output of this scheme was low in comparison with other approaches towards nanotechnology. In addition, because of the environment (humidity and fog) further improvements were required in this model.

This proposed approach consist of silicon paper, Teflon and copper foil. Bottom part of paper is coated by silicon while silicon oil acts as supporting part. Because of this approach, environment factors such as humidity and fog which were hurdles in previous research can be eliminated. Triboelectric pair is formed by conductive copper foil. This techniques reduced the process of precipitation. Experiment results showed that this orthodox approach can easily illuminate more than 27 LEDs (Light emitting diodes). Such devices can be used in many domestic as well as commercial applications[27].

2.6.1. Experimental set-up.

Layer of Teflon tape is placed on the conductive copper foil (conductive electrode). Figure 2.11 demonstrated the construction process of paper based TENG. Output is observed with the help of digital oscilloscope. A precision unit called “Keysight B2902A” is used to verify the output results of paper based TENG[28].

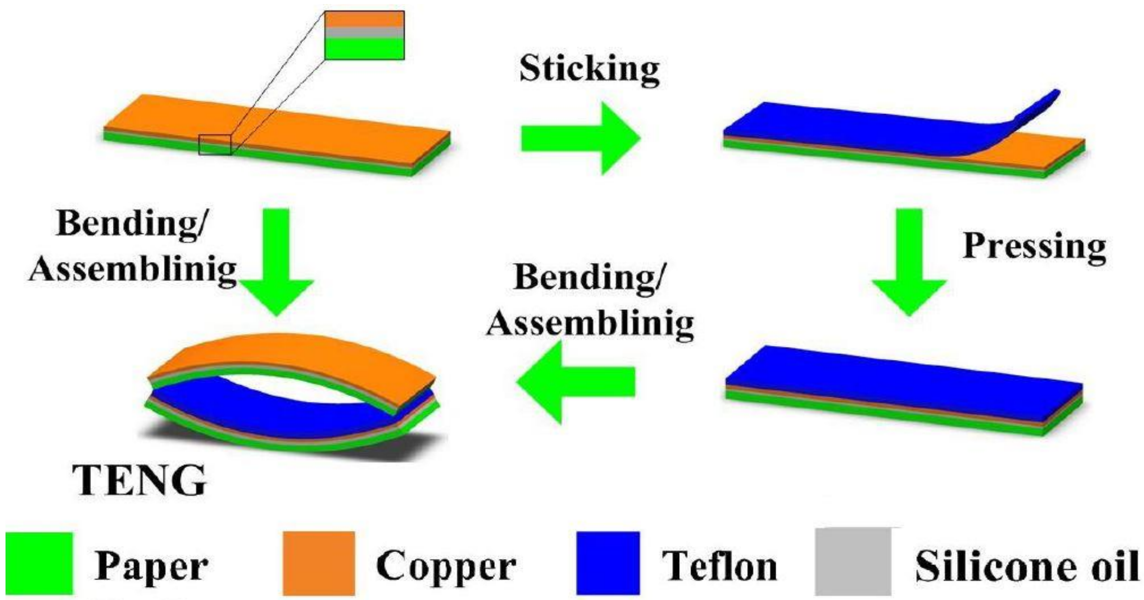


Figure 2.11 Electrode layers of different materials.

When triboelectric contact pairs (silicon paper and Teflon tape) come to contact with each other, electrification happens. Positive charge is carried by silicon paper, at the same time negative charge is carried by Teflon tape. Potential difference occurs as the Teflon and silicon paper are segregated. The mentioned setup is capable to produce the output voltage up to the value of 295V and current 120μA. Operating mechanism is shown in the following figure 2.12[28].

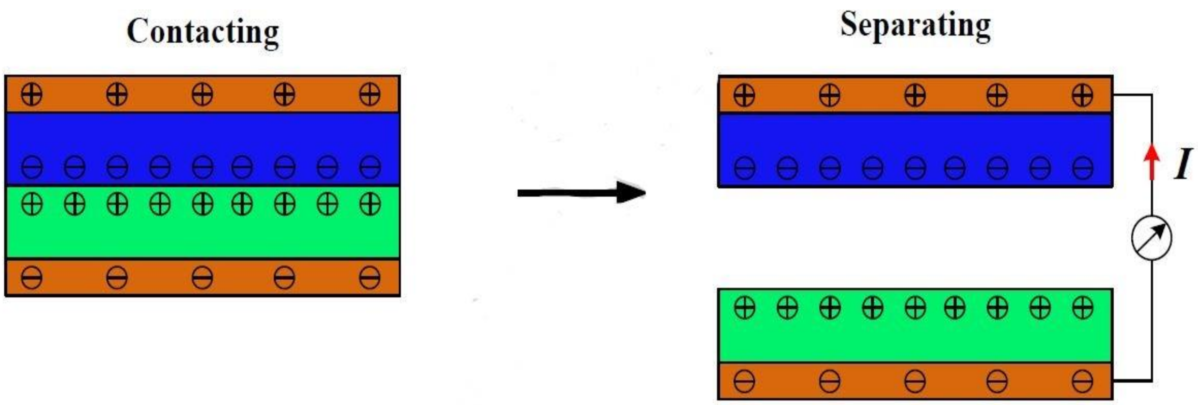


Figure 2.12 Operation and mechanism.

When teflon and silicon paper comes close to each other, inductive charges relocates in reversal order because of the opposite potential differences.

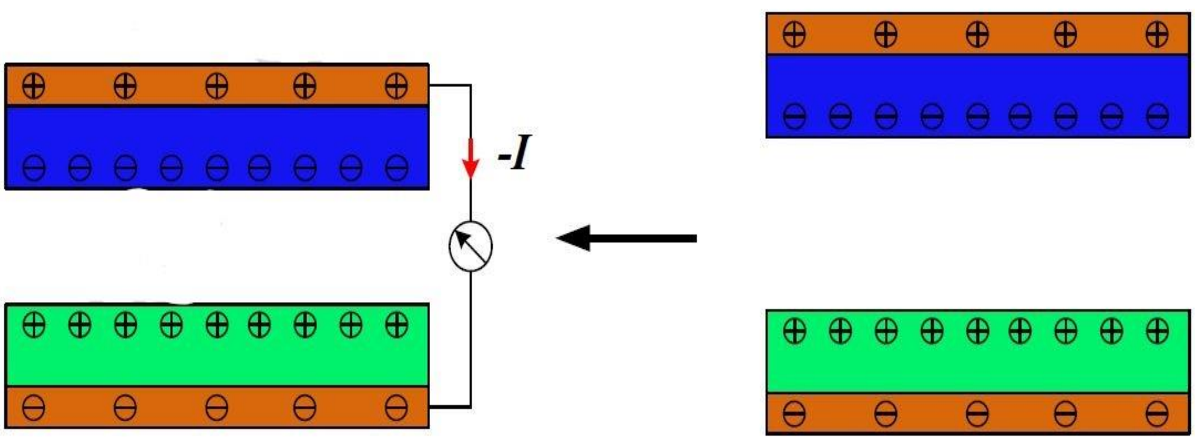


Figure 2.13 Reversal potential differences.

Electronic performance with the help of potentiometer which is associated to electrodes is measured. It is elucidated in fig when value of load resistance is increased from 100 KΩ to 50 MΩ, the output voltage rises continuously. When the resistance of the load is 0.9 MΩ, the device reaches to its peak power which states that the TENG has internal resistance is 0.9 MΩ. The outcome of this paper based TENG is mentioned in the following table.

Table 2.1 Paper-based TENG materials and its value.

Sr. No	Components	Value
1	Internal resistance	0.9 MΩ
2	Output Voltage	75V
3	Output Current	83 μA
4	Power Density	1038 μW/cm2
5	TENG Size	2cm*3cm
6	Output Voltage when R=50MΩ	295V
7	Output Current when R=100KΩ	120 μA

The device set-up is shown in the following figure 2.14.

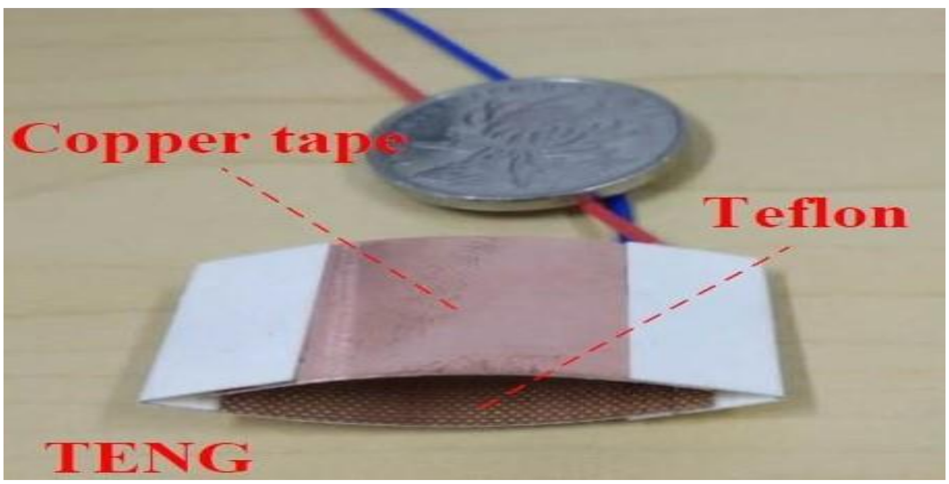


Figure 2.14 Copper-Teflon paper-based TENG.

As the main focus of this research was on the production without any effect on humidity which is achieved and is shown in the following graph. There is negligible/minor drop of voltages with respect to the humidity. Humidity by controlling the temperature is increased from 50% to 90%. Voltage was 295V when humidity is 50% and its value is 288V when humidity increased up to 90%. It is clear from the following graph that the total voltage drop is 7V while humidity was increased two folds.

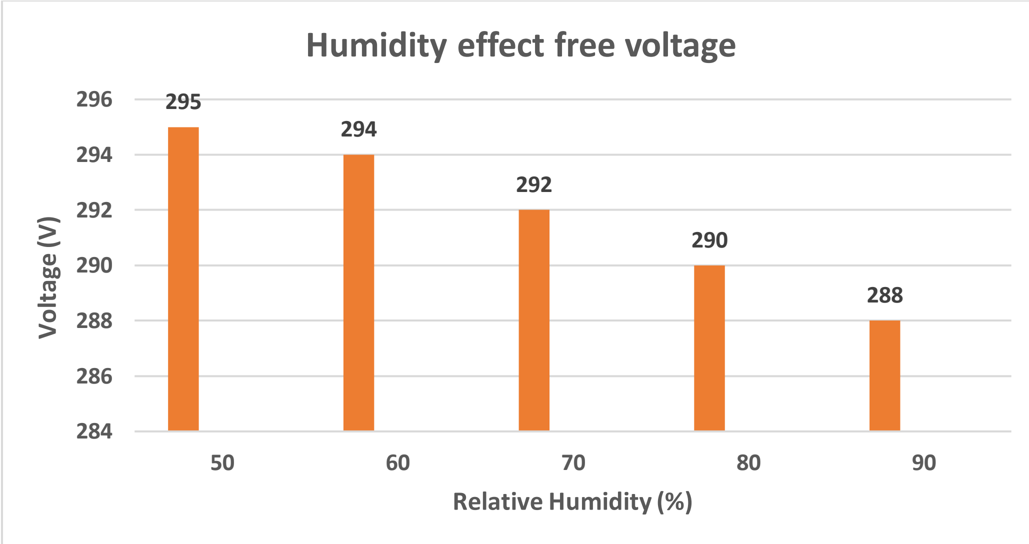


Figure 2.15 Humidity effect free voltage.

2.7. Additional research.

Naturally, micro-fibers and nano-fibers are composed by various materials which are bio-degradable, paper is one of them which is commonly available and cheap as well. Its main characteristics which declares it as a environmental friendly and green-electronics are polarity, easily accessible, easy to dispose and non-polluting behavior[29-31]. To form paper-based TENG, many materials are embedded into paper such as micro-fiber, nano-fiber and nanocluster to make it flexible and to bear resistant of electronics.

Friction layer polarity is an important factor which plays vulnerable role in the performance of TENG. Paper has property to lose as well as gain electrons when rubbed with any sort of material[1, 32]. In addition polarity can be increased by high polar agents. Recycling process of paper is easy as compared to other materials.

Paper based TENG can be designed by the use of Al layer (coated on paper). The paper is used for TENG is gum paper because of three main reasons,

1. Polarity and structure of gum paper is suitable for TENG.
2. No further additional process required as back of the gum paper is already coated by Al foil.
3. Because gum paper is common and can be easily obtained without any difficulty.

PVDF (polyvinylidene) has capability to gain electrons, therefore it is chosen as 2nd material. The other reason in selection of PVDF is that it can easily dissolved into organic solvent and its preparation is common[33].

Polydopamine is used for "self-polymerization method" to increase the output of paper based TENG. In this method, loose of electrons is easy when attached and rubbed by Polyvinylidene layer. Previous research was only capable to light up 27 LEDs but by using this approach 100 of LEDs can be illuminated and this mechanism is free from corrosion.

Table 2.2 material used and its values

Sr.NO	Material name	value
1	Gum paper size	4cm*4cm
2	Product name	Yida Gum
3	Product country	China
4	Thickness of Al layer	100nm
5	PVDF	3.75g
6	N	8.5g
7	Acetone	12.75g
8	Distance B/W needle and collector	16cm
9	Oven temperature	80C

The gum used for this experiment is obtained from China "Yida gum" and its area was 4cm*4cm. The front side of gum paper is coated by Al while as back side of the paper is also coated by the same material as coated on front side but an extra layer on the back end is placed over the Al layer which is Copper lead layer. For protection purposes, a PET sheet is used. PVDF layer is generated by the electrospinning technique which is discussed above. A Silver (Ag) layer having thickness is placed over kapton layer. A mixture is prepared by using different material. Materials with their corresponding values used in mixture are mentioned in above table. These materials are PVDF, N, NMAc (N-dimethylacetamide) and acetone. The experimental setup is shown in following figure 2.16[34].

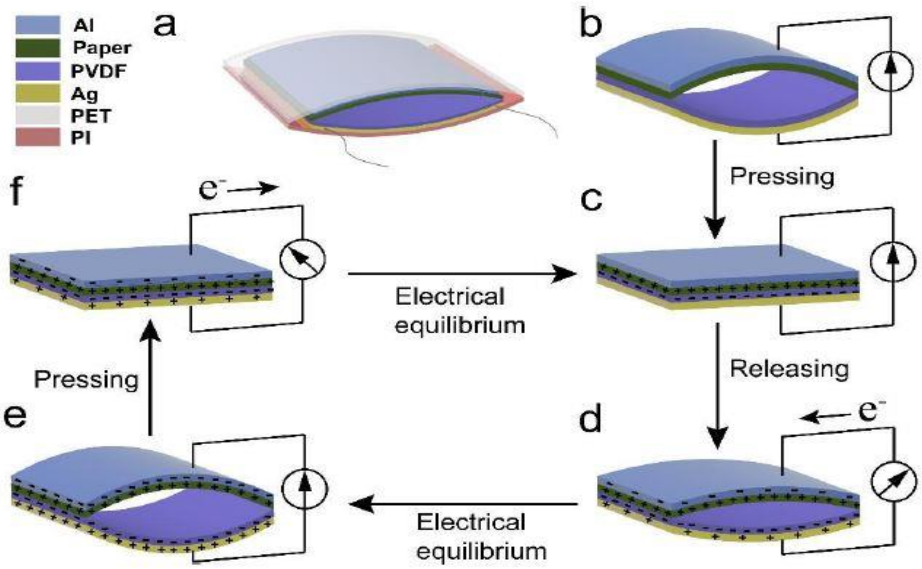


Figure 2.16 Gum paper-based TENG.

The scheme in part (a) elucidates the power generation process of paper based TENG. In part (b) and part (c), the before and after contact scenarios are discussed. When it is fully contacted, generation of electric charges starts on paper and PVDF surface. Part (d) shows the releasing, electrons flow from PVDF electrode to paper electrode. Part (e) and part (f) demonstrates the electrical equilibrium, no current flow and electrons flow from paper electrode to PVDF electrode respectively.

This setup is a new approach towards TENG paper based power generation. A layer of Polydopamine is used to obtain the output power density higher than the previous proposed methods. The output voltage and current is 3 to 4 times higher than the previous research history in the proposed field of TENG. The output voltage and current is 1000V and 30A respectively. From this setup, more than 496 light emitted diodes (LEDs) were illuminated simultaneously[35]. To protect it from corrosion, self-power cathode system is designed.

Briefly speaking, this revolution in the field of nanotechnology especially TENG will open many doors of new research and innovations.

Chapter 3

Methodology

CHAPTER 3.

PROPOSED METHODOLOGY

This chapter deals with the method that we have used in our experimental work. The method is explained in detail. In the end, main points are describes that will be performed by using this method.

Triboelectrification is the method by which current is generated when two tribo-materials come in contact with each other to drive the electrons flow in the external circuit. The effect is known as tribo-electric effect. The method converts mechanical energy into electrical energy on the principle of electrostatic induction. With regular force for contact and de-contact, IV measurements are observed through Digital Multimeter (DMM) as shown in Figure 3.0. The generated current depends on various factors e.g., triboelectric properties of the materials, surface area, applied force etc. This current is generated in milli ampere and micro ampere depending on these factors.

Figure 3.0: Digital Multimeter 2420, Keithley, USA

Multiple working modes can be used to generate power. There are four types of fundamental modes of TENG that are used in experiments. These are vertical contact separation mode, contact sliding mode, single electrode mode and freestanding triboelectric layer mode. Out of all these modes, vertical contact separation mode is commonly used in experiments as maximum power can be produced and high efficiency can be achieved as compared to other modes of TENG. We have also used vertical contact separation mode of TENG in our work. Different methods of TENG (triboelectric nanogenerators) based electricity generation discussed which are broadly used in numerous real life applications. Body based triboelectric nanogenerators and automatic dust removal face mask are example in this best regard. Each and every single proposed method have some limitations. The approach used in this thesis adopted after the careful observation of previous research and limitations. Materials used in previous research can be replaced by other suitable materials which would have better characteristics, by using these materials cost and efficiency can be improved.

The series is a list in which the materials are ranked as per their tendency to gain or lose electrons shown is figure 3.0.1. The material placed at the top of positive side has maximum potential of positive charge generation on contact with other material while material placed at the bottom of negative side has maximum potential of negative charge generation. The materials like paper, wood, cotton can generate neither negative charge nor positive charge so they are placed in neutral charge group.

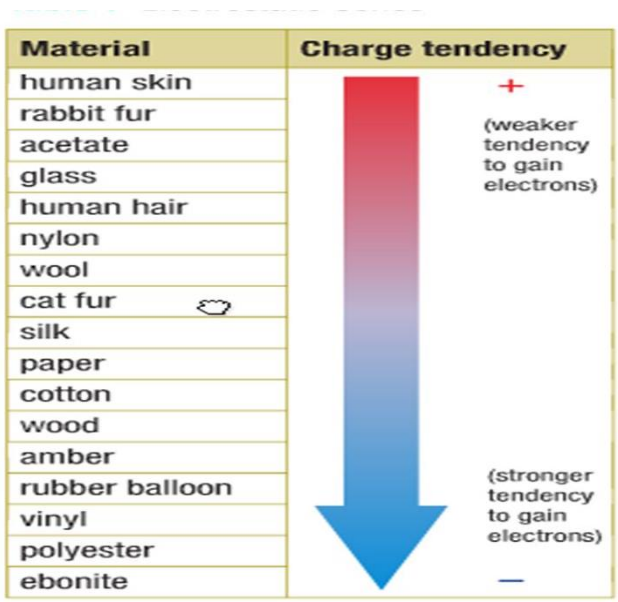


Figure 3.1 Triboelectric Series

Out of all the modes, vertical contact and separation mode is commonly used.

3.1. Copper

Copper is widely used in day to day applications such as roofing, rainwater systems, oil and gas lines, heating systems and in electrical wiring because of its conductivity and other characteristics. More than 23% of copper is used in electronic and electrical applications across the world.

Main applications of copper in electronic and electrical engineering are[36]

- Power transmission lines
- Spark plugs
- Electrical wiring
- cables and bus bars
- High conductivity wires
- Electrodes
- Heat exchangers
- Refrigeration tubing
- Water-cooled copper crucibles

3.1.1. Properties and electrical conductivity of copper.

The properties of copper which makes it suitable in electrical applications are its heat conductivity, electrical conductivity, Good corrosion fight, good biofouling confrontation, good machinability, retaining of mechanical and electrical characteristics at cryogenic temperatures and its non-magnetic behavior[37].

The electrical conductivity of copper is second in the list after silver. Silver is the material whose conductivity is higher than any other material in the world in the world. The conductivity of silver is much higher than copper, but not conductivity which makes it suitable for use but also cost plays a vulnerable role in selection. Because of its abundancy and lower cost which makes it a standard material for electrical applications. In addition, its limitations are its weight and strength. Strength can be improved by adding foreign materials but it reduces its conductivity. For example when only 1% of cadmium is added in copper, it increases its strength more than 55%. Though its strength is increased but its conductivity is reduced 16%[38].

3.2. Polyethylene Characteristics.

Polyethylene is a combination of carbon (C) and hydrogen (H) atoms, having chemical formula $(C_2H_4)_n$. it is may be mixture of homogeneous polymers. Different type of polymers (polyethylene) is available in the market with different values of n i.e. n=1,2,3,4,5…… They are categorized on the basis of their density (high density and low density) and temperature required for extrude. For extruded, high density polyethylene uses low temperature and low density polyethylene by high temperature and vice-versa[39].

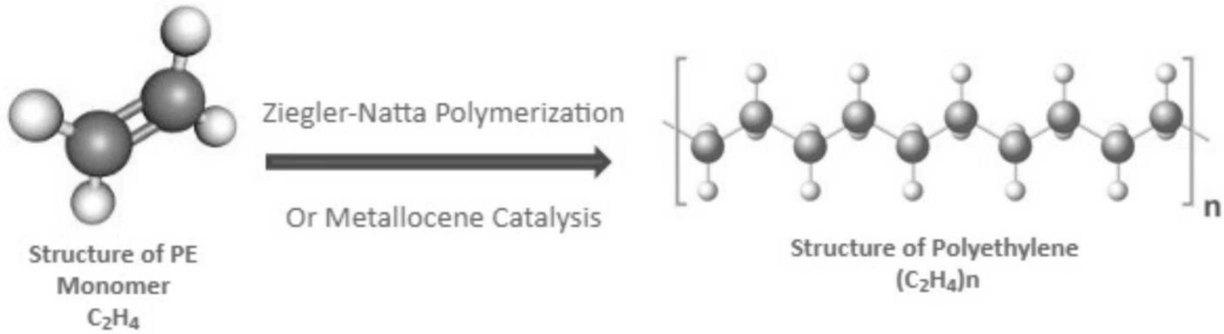


Figure 3.2 Laboratory preparation of Polyethylene[40]

To make triboelectric nanogenerators more efficient, different approached have boon tested. Friction layers material selection for triboelectric nanogenerators is crucial. Many polymers are used in triboelectric nanogenerators because of its negative charge. Materials such as nylon, cotton, copper and aluminium are used as positive electrodes because of its positive charged layers. Polyethylene has highest negative charge nature capability after polyimide (PI). Because of polyimide's cost, it is not commonly practiced in triboelectric nanogenerators but properties like it can be achieved from polyethylene. For this purpose, polyethylene is mixed in toluene. In this thesis, because cost a main issue, polyethylene is mixed in toluene to achieve characteristics like polyimide. 50 ml toluene is mixed in 0.25g of polyethylene. The mixture was ready within 4 hours. To make it more compact and stable, it is placed in oven at 85°C for two hours and at 83°C for ninety minutes (90 mints).

3.3. Toluene

Toluene is also called "toluol". It is a colorless aromatic hydrocarbon. Its smell is much similar to the smell of paint. It is a water soluble liquid. It is mixed in IUPAC (polyethylene) to make it denser and to obtain the properties of polyethylene like polyimide. It enhances the sickness property of polyethylene. In this thesis, a layer of polyethylene is placed on the paper as a negative electrode. So, it must be stacked to the paper firmly. 50ml of toluene is used in this thesis to form polyethylene.

Naturally, toluene can be obtained from crude oil and it is a byproduct during the formation of gasoline. When coke is produced from coal, toluene is also obtained as a byproduct. Through solvent extraction processes, toluene is purified from other chemicals (impurities). Commonly distillation process practiced for purification (benzene isomers, toluene isomers and xylene isomers).

Toluene can be manufactured through artificial manners in laboratory by the chemical reactions of benzene and methyl chloride in the presence of a catalyst aluminum chloride. Though, toluene can be obtained from both industrial and naturally but it is expensive if obtained in laboratory by the chemical reactions of different chemicals.

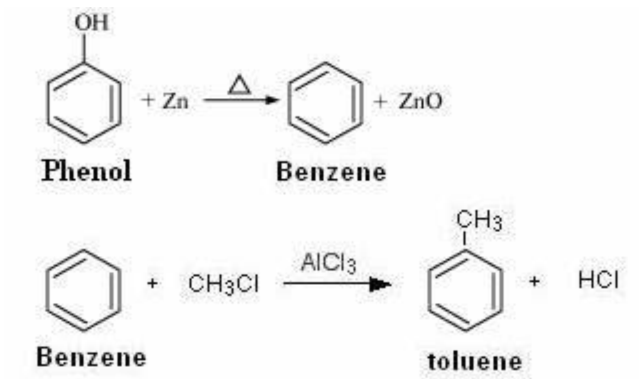


Figure 3.3 Laboratory preparation of Toluene[41].

3.4. Nanowires.

Nanowires are called “nano” because of its diameter is in nanometers (10^{-9} meters). Their ratio of length and width is greater than 1200. These wires are especially designed because of their usage in electronic applications. Many sorts of nanowires are available but the most common nanowires are silicon nanowires, molecular nanowires and metallic nanowires[42]. Silicon nanowires are used in this proposed set-up of paper-based triboelectric nanogenerators.

These are broadly used in metal oxide silicon field-effect transition (MOSFETs). Other applications of nanowires in the field of electrical engineering are the electronic devices configuration, nano lasers, sensing of chemicals, materials and proteins using semiconductor devices.

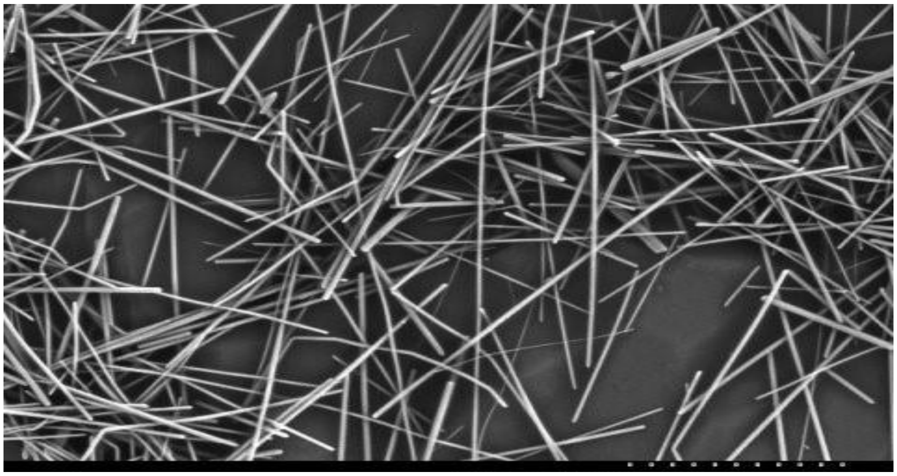


Figure 3.4 Silicon nanowires.

3.5. Paper.

Fine-art paper, cardboard paper, coated paper, paper board, chart paper and newspaper are common types of paper used for triboelectric nanogenerators. A fine, thick and hard surface paper is required to place copper and polyethylene on both sides of paper as positive and negative electrodes respectively. For triboelectric nanogenerators (TENGs), the selection of paper quality is a key factor. Quality must be good because during the coating process, layers of copper and polyethylene should be wrinkle-free. If there are wrinkles, it decreases the efficiency of paper-based triboelectric nanogenerators and also effects the set-up stability (life).
Paper used in this experiment is chart paper having size 6xcm4.6cm.

3.6. Indium tin oxide (ITO)

An optoelectronic material which is used in research as well as industry purposes. It has many industrial applications including flat-panel displays and windows, electronics based on polymers, supermarket freezers glass doors and in architecture.

3.7. Aluminium foil

Extrusion process is done usually AF 1600 (Aluminium foil). In addition, compression modelling and injection is also done with the help of AF. Furthermore, it plays vital role in pipes and fitting, hybrid devices as well as in different industrial and chemical applications. It is an amorphous i-plastic grade. In solid form, its shapes are like bars, rods, tubes and thickened sheets. It has good electrical properties (thermal conductivity and excellent mechanical strength). It also offers clarity of optics, higher stability and resistance against temperature[43].

Aluminium foil has also applications in the food industry especially to preserve and storage of food and meet in order to prevent the loss of moisture as if moisture is lost in food and meat (stored), taste and colour of food and meat changes. It is also used to wrap-up cooked food especially grilled meat and fish.

3.8. Experiment set-up

First of all, temperature in hot plan is set at 85°C by using distilled water. The main purpose to set temperature at particular point is to purpose is to set polyethylene and to dissolve properly in toluene at 85°C. The boiling point for toluene which was set is 110.6 °C. To obtain proper and better disseverment of Polyethylene in toluene, 3 to 4 hours are required. Size of copper tape is 6x4.6cm (6cm long and 4.6cm in width) of each piece and same paper of size is cut for experiment. With full cautions, copper tape is placed and wrapped on paper. During wrapping and tapping, it was assured that the paper surface should be remain wrinkle free. After applying temperature, polyethylene is weighted in electronic digital scale and exact 0.10g of polyethylene is mixed with 50ml toluene for 120 min at 83°C. After 2 hours, 0.15g polyethylene is again added in the mixture for further 120min at 85°C.

After obtaining desired solution, paper slides of copper tape dipped in it for 4 to 5 second of each slide. After dipping in solution, paper slides are kept at room temperature for more than 30 min but less than 45 mints and kept it in oven at 40°C for 70min to get smoothness. Copper was tapped at paper having 6x4.6cm size which is used as positive charge electrode and the other side “dipped slides” are used as a negative charge electrodes. A number of copper tape slides which were dipped and without dipped in polymer was made. All Paper slides are adjusted in a way that the top and bottom side of paper should be arranged in a way that the top must be positive electrodes and bottom side should be negative electrode. The positive and negative sides are connected through nanowires. The length of nanowires were 17.6cm for measurement. Firstly, the measurements of 1x1 paper slides to contact each other by pressing for 30 seconds and this output is obtained at digital multi meter. Resistor of 1mΩ is used to get I-V graph with respect to time. Digital multi meter is used for I-V graph on which values for current and voltages are obtained. The value of current and voltages increased with respect to time as positive and negative slides are pressed each other to get the desired output. The same procedure repeated with all paper slides by connecting each other. Whole procedure repeated with and without resistor. Resistor is used to get output power. Output for all paper slides pattern i.e. 1*1, 2*2, 4*4, 6*6 with and without resistor are obtained.

Figure 3.5 Toluene heating process and mixture of polyethylene.

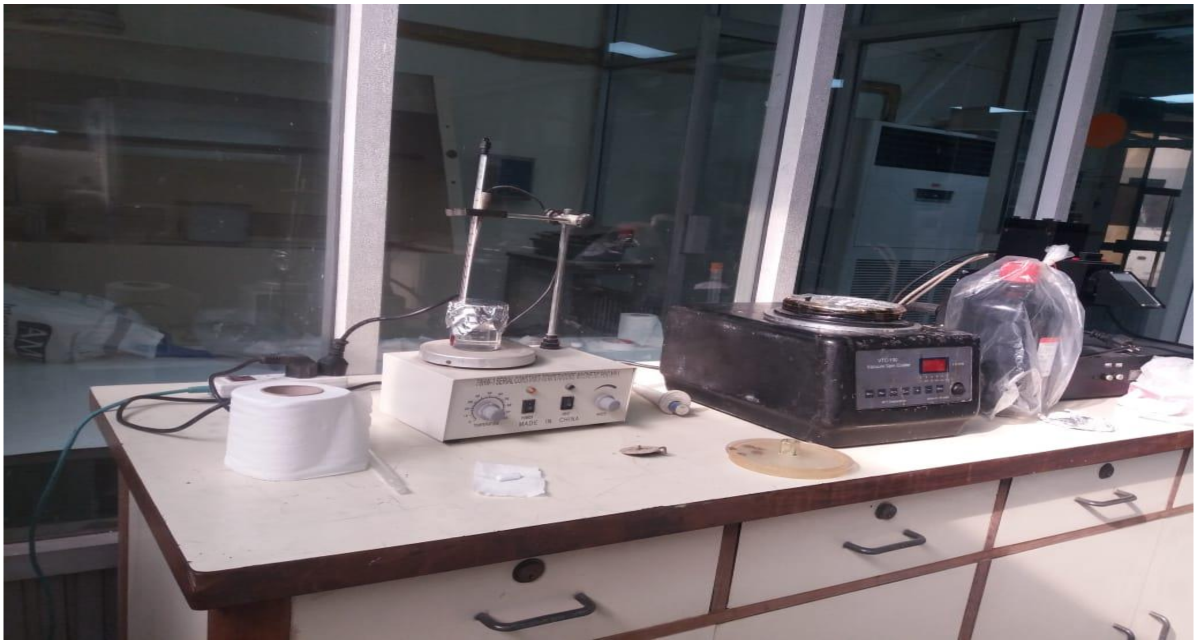


Figure 3.6 Laboratory set-up for paper-based triboelectric nanogenerators.

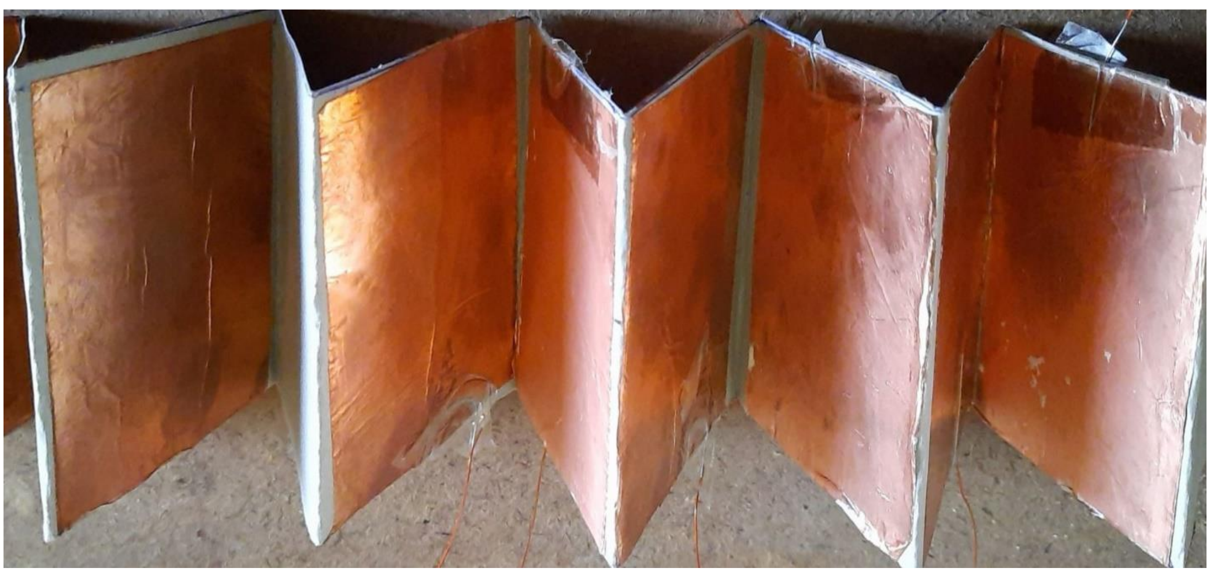


Figure 3.7 paper-based triboelectric nanogenerators.

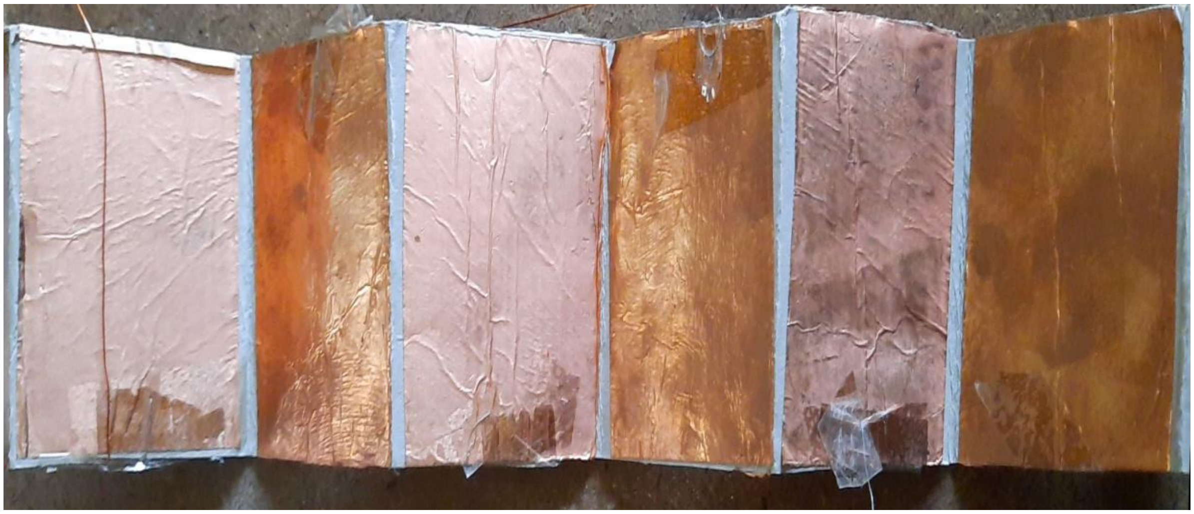


Figure 3.8 Positive and negative electrodes of paper-based TENG.

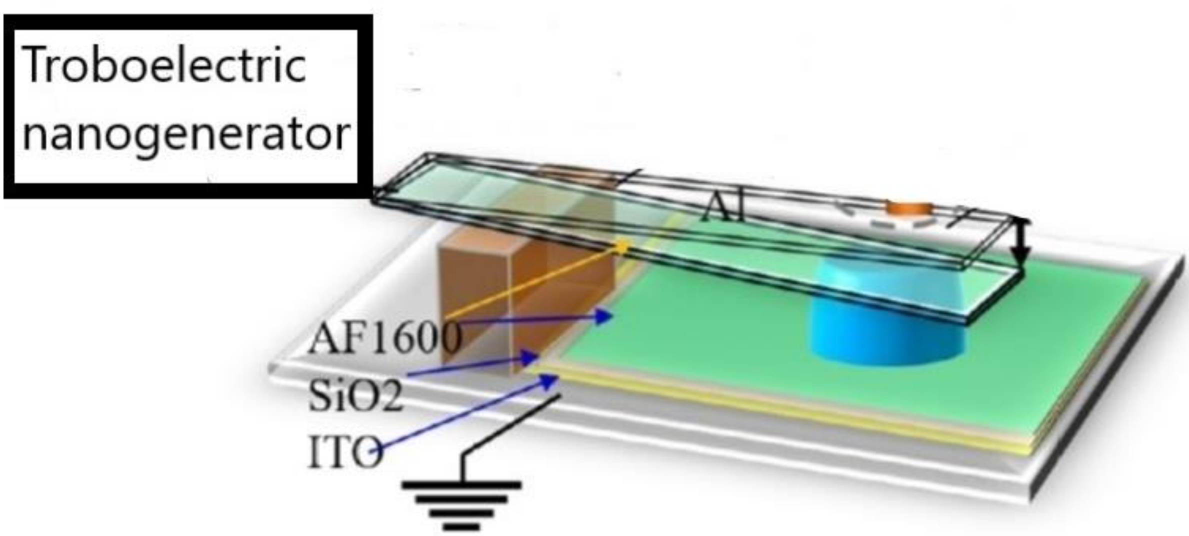


Figure 3.9 Water droplet movement setup connection with TENG.

For practical purpose of moving water droplet on aluminium surface oil with the help of paper-based triboelectric nanogenerator, triboelectric generator (TENG) is synchronized with a function generator. The positive and negative sides of the TENG is connected with the Aluminium foil and ITO respectively.

Chapter 4

Evaluation

CHAPTER 4. EVALUATION

4.1. RESULTS AND SIMULATIONS:

4.1.1. Laboratory:

Experiment done at Pakistan Council of Renewable Energy Technology Islamabad. (PCRET)

4.1.2. Equipment used:

Following equipment's are used in this experiment;

- Digital multi meter (2420 source meter)
- Hot plat
- Magnetic stirrer
- Jar
- Dip coater

4.1.3. Material used.

Following materials are used in this experiment to establish concept of paper-based triboelectric nanogenerators.

- Toluene
- Copper tape
- Polyethylene
- Nanowires
- Paper

4.1.4. Proposed procedure.

First of all, temperature in hot plan is set at 85°C by using distilled water. The main purpose to set temperature at particular point is to purpose is to set polyethylene and to dissolve properly in toluene at 85°C. The boiling point for toluene which was set is 110.6 °C. To obtain proper and better disseverment of Polyethylene in toluene, 3 to 4 hours are required. Size of copper tape is 6x4.6cm (6cm long and 4.6cm in width) of each piece and same paper of size is cut for experiment. With full cautions, copper tape is placed and wrapped on paper. During wrapping and tapping, it was assured that the paper surface should be remain wrinkle free. After applying temperature, polyethylene is weighted in electronic digital scale and exact 0.10g of polyethylene is mixed with 50ml toluene for 120 min at 83°C. After 2 hours, 0.15g polyethylene is again added in the mixture for further 120min at 85°C.

After obtaining desired solution, paper slides of copper tape dipped in it for 4 to 5 second of each slide. After dipping in solution, paper slides are kept at room temperature for more than 30 min but less than 45 mints and kept it in oven at 40°C for 70min to get smoothness. Copper was tapped at paper having 6x4.6cm size which is used as positive charge electrode and the other side "dipped slides" are used as a negative charge electrodes. A number of copper tape slides which were dipped and without dipped in polymer was made. All Paper slides are adjusted in a way that the top and bottom side of paper should be arranged in a way that the top must be positive electrodes and bottom side should be negative electrode. The positive and negative sides are connected through nanowires. The length of nanowires were 17.6cm for measurement. Firstly, the measurements of 1x1 paper slides to contact each other by pressing for 30 seconds and this output is obtained at digital multi meter. Resistor of 1mΩ is used to get I-V graph with respect to time. Digital multi meter is used for I-V graph on which values for current and voltages are obtained. The value of current and voltages increased with respect to time as positive and negative slides are pressed each other to get the desired output. The same procedure repeated with all paper slides by connecting each other. Whole procedure repeated with and without resistor. Resistor is used to get output power. Output for all paper slides pattern i.e. 1*1, 2*2, 4*4, 6*6 with and without resistor are obtained.

The ingredients used in this experiment with its exact weight are listed in the following table.

Table 4.1 paper-based triboelectric nanogenerators material with weight

Sr. No	Items	Weight
1	Oven Temperature	85°C/40°C
2	Toluene	50ml
3	Copper tape size	6xcm4.6cm
4	Polyethylene	0.10g+0.15g
5	Nano-wires	17.6cm
6	Paper size	6xcm4.6cm
7	Resistor	1mΩ

4.1.5. Results:

4.1.6. Output performance characterization of the paper based-TENG versus different folds generation units

The maximum current is achieved when folds are pressed and current goes to negative when folds are released. In previous research the maximum current achieved was 0.6 µA but in this research we successfully achieved average current of 0.772µA.

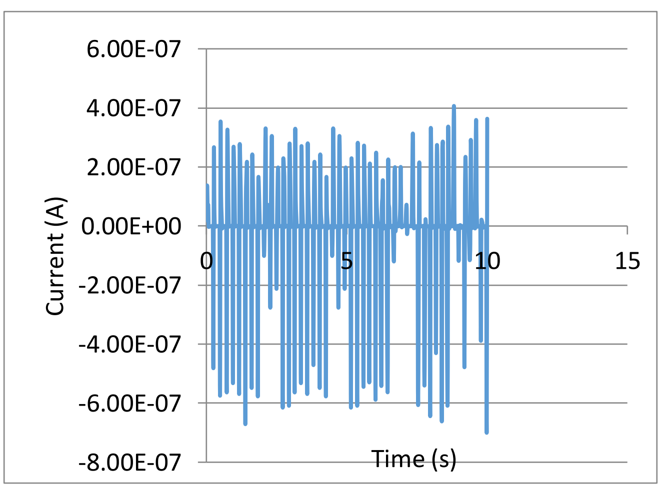


Figure 4.1.1 (1*1) fold I-T result.

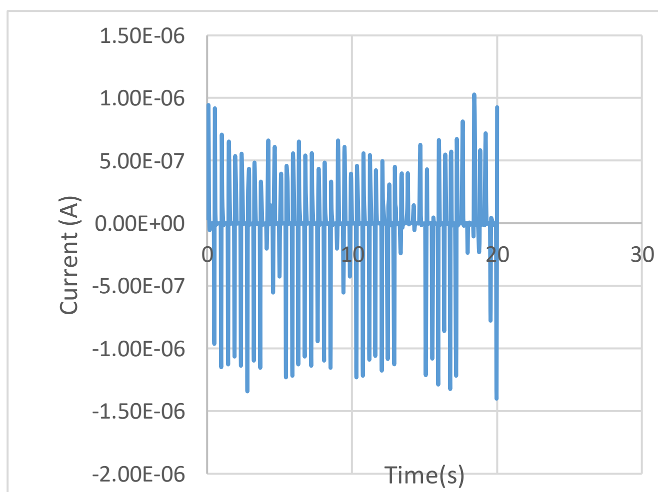


Figure 4.1.2 (2*2) fold I-T graph

In Figure **4.1.1** shows the output performance stability of the Paper based-TENG during continuous pressing of 1x1 fold for 10sec.The maximum peak current achieved at 8sec is 0.406µA and negative peak current achieved at 10th sec is -0.7µA.

In figure **4.1.2** shows the output performance stability of the Paper based-TENG during continuous pressing of 2x2 fold for 20sec. The positive peak current achieved at 17.6sec is 1.01µA and negative peak current achieved at 20th sec is -1.40µA.

4.1.7. Out-current excitation characterization of the paper based-TENG with Different-folds generation units

The maximum current is achieved when folds are pressed and current goes to negative when folds are released. In the given figures 4x4 fold and average value of current with respect to average time is taken by digital multimeter.

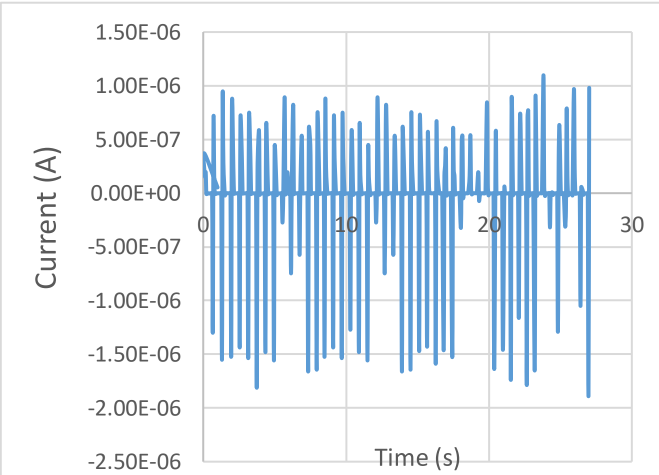


Figure 4.1.3 (4*4) fold I-T graph

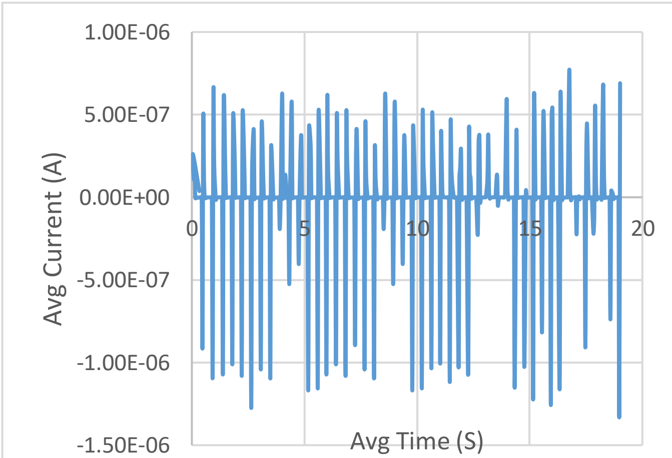
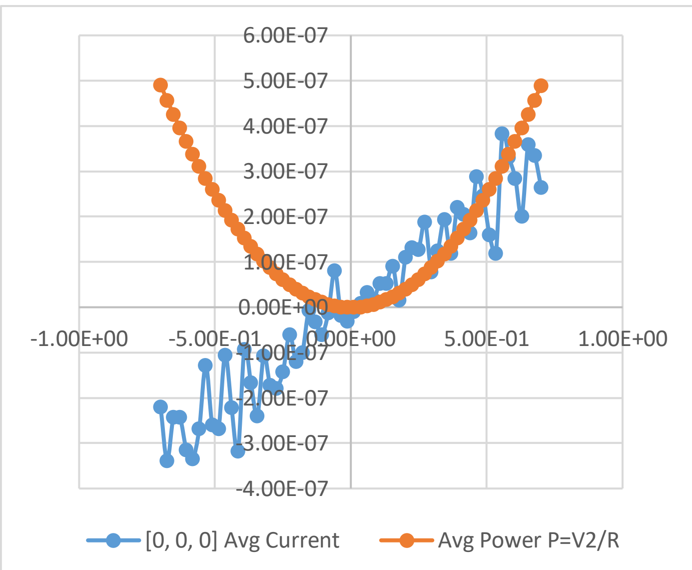


Figure 4.1.4 Average result for I-T graph

In figure **4.1.3** shows the output performance stability of the Paper based-TENG during continuous pressing of 4x4 fold for 300sec. The positive peak current achieved at 23.8sec is 1.10µA and negative peak current achieved at 26.9 sec is -1.89µA.

In figure **4.1.4** shows the average voltage obtained in Paper based-TENG. The average time for above folds is 20sec. The average peak current achieved at 16.7sec is 0.772µA and negative peak current achieved 19.9 sec is -1.330µA.

The optimum load resistance has a downward drift with increasing number of power generation units. Radically, the maximum output power can only be reached when the external load equals the internal impedance of the generator. R ∝ 1/jωC shows the output currents for different load resistances ranging from 100 kΩ to 110 MΩ. The maximum voltage of 305 V and current of 8.6 μA are obtained with load resistances of 1MΩ. However, a lower optimum load resistance is obtained with increasing number of power generation units according to the impedance mathematics.



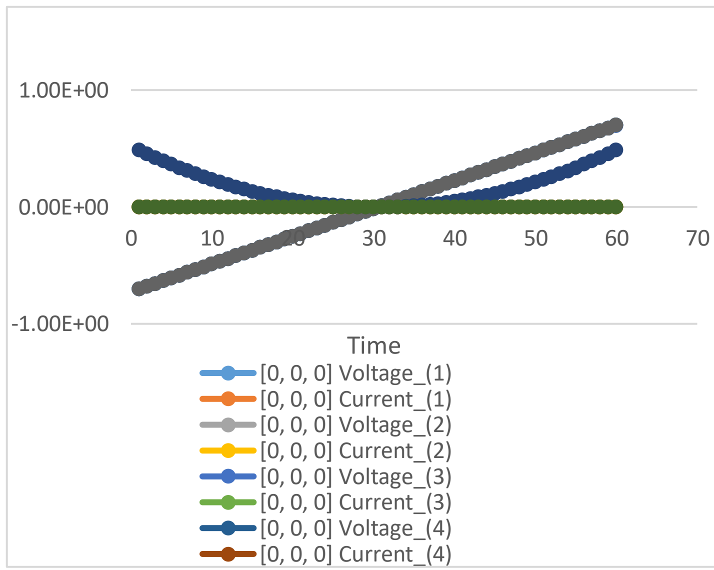
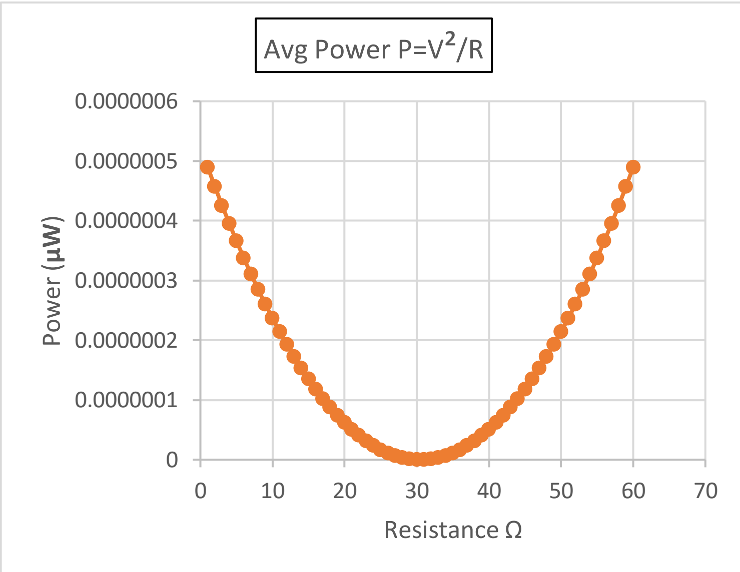


Figure 4.3.1 Figure 4.3.2

In Figure **4.3.1** average current and average power obtain is shown. The maximum power which is obtained is 0.49μ**W** and maximum current is 0.380μA.

In figure **4.3.2** out flow chart for different voltages, current, avg current and avg power is shown. Output Power, voltage and current with varying load resistance at the original height of 4.3 degree. The resistance which is used is 1MΩ for the power. Colours shows the value for current time voltage and power which is calculated.

By that average current value with respect to time output power can be calculated for every for fold of paper by formula $P = V^2/R$. The whole values for current and voltage are taken with respect to time by the help of digital multi meter.



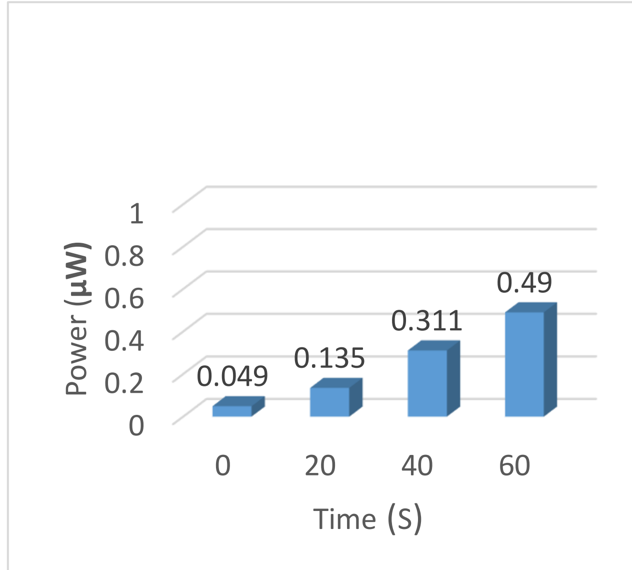


Figure 4.3.3 Figure 4.3.4In figure **4.3.3** Output power with varying load resistance at the original height of 4.3 degree. The resistance of 1M Ω is used for output power. At 60ohm the average power $4.901x10^{-7}$**.** The power is calculated by the formula P=V²/R.

In Figure **4.3.4** power generated for 0-20 sec is 0.049uW , for 20-40 sec is 0.135uW, for 40-60sec is 0.311uW and average maximum power is 0.49uW.That is the maximum power which is obtained in paper based triboelectric nanogenerator (TENG).

4.2. Water droplets movement.

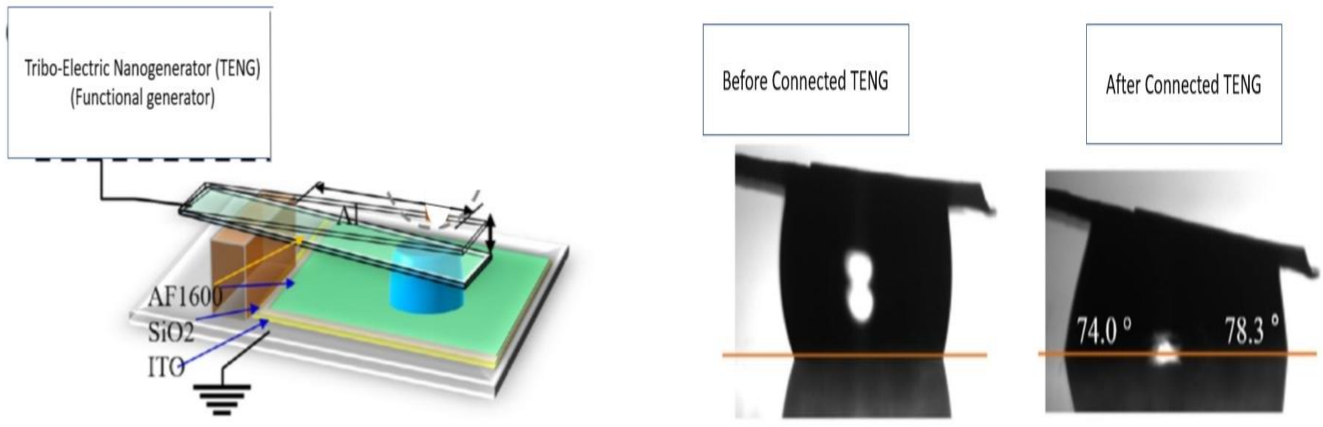


Figure 4.3 Water droplet movement about 4 Degree.

Movement of water droplet on Aluminum foil is done through paper-based TENG generated Voltages. Output performance of the Paper based-TENG with original height ranging from 74.0 to 78.3 degree under the connection of electrically connected functional generator with TENG. Negative side of paper based triboelectric nanogenerator is connected with ITO and positive side with Al foil with the help of nanowires. When system is operated for 120 second AF1600 and Sio2 increased the power of TENG and the water droplet laying on the surface of Al foil start getting height from his original position to maximum position and got height about 4.3 degree which is captured by camera.

Chapter 5

Conclusions and Future Work

CHAPTER 5. CONCLUSIONS AND FUTURE WORK

5.1. Conclusion

In summary, triboelectric power generator (TENG) was conceptualized, fabricated and characterized for wearable energy harvesting. Art of paper folding, has been successfully combined with the triboelectric energy conversion process to create a new type of paper based-TENG device with excellent deformability, flexibility and stretch ability. The conducting and non conducting process has been employed to maximize the charge storage in the coper tape and enhance the power generation by increasing number of folding papers. In previous research different parameters has been determinedly analyzed. It has been found that with increasing number of energy generation units and careful control of the original height of the device, the performance can be essentially enhanced.

Endless, less expensive and free of carbon energy is gained from RES's and triboelectric nanogenerators (TENGs) which assures the reduction of fuel and to broaden the concept of independent power generation. The mechanical and chemical energy is converted in to electrical energy which is sufficient to operate many small electronic apparatus. Paper-based triboelectric nanogenerators produces sufficient amount of power which can be used in many day to day applications i.e. automatic dust removal face mask, removal of sulphur dioxide and so on.

The previous research which was based on paper-based triboelectric nanogenerators (paper-based TENGs) has many limitations because concept was not matured as TENG based power generation applications started in 2012. This technology is developing by leaps and bounds but still it needs more attention to eradicate the certain limitations such as efficiency and output. There are numerous methods of power generation from paper-based triboelectric nanogenerators but the approach which is opted/proposed in this thesis successfully improved the efficiency of TENG 10% as compared the other proposed methods.

But now using the effect of triboelectric, main goal of this thesis was to make self-powered system. This research showed the combination of higher ranked triboelectric material and size optimization which ensured the high power generation. This research demonstrated a new type of triboelectric nanogenerator which is fabricated using copper tape coated with polyethylene $(C_2H_4)_n$ as the non-conduct layer. Paper is used to separate conducting and non-conducting material. To further enhance the output of the paper-based TENG, a number of polyethylene coated surfaces which is non-conducting and conducting surfaces which is copper tape are combined together for output power. As surface area of conducting and non-conducting material is increased the output power increased. Moreover when the number of papers increased with respect to folding pattern, output power is increased.

5.2. Future Works

For the future work following suggestions can be taken into account for further research

- The proposed approach is only for experiment on laboratory scale but this concept can be flourished/broaden on large scale by testing other materials as positive and negative electrodes.
- Output and efficiency can be increased by the combination of copper with other materials as positive electrode.
- Paper quality and spin coating can also play an important role to maximize output.
- More compact form can be practiced if industrialized on large scale.

REFERENCES

1. Fan, X., et al., Ultrathin, rollable, paper-based triboelectric nanogenerator for acoustic energy harvesting and self-powered sound recording. ACS nano, 2015. **9**(4): p. 4236-4243.

2. Lee, K.Y., et al., Hydrophobic sponge structure-based triboelectric nanogenerator. Advanced materials, 2014. **26**(29): p. 5037-5042.

3. Fan, F.-R., Z.-Q. Tian, and Z.L. Wang, Flexible triboelectric generator. Nano energy, 2012. **1**(2): p. 328-334.

4. Wang, Z.L., Triboelectric nanogenerators as new energy technology and self-powered sensors–Principles, problems and perspectives. Faraday discussions, 2015. **176**: p. 447-458.

5. Wang, S., et al., Freestanding triboelectric-layer-based nanogenerators for harvesting energy from a moving object or human motion in contact and non-contact modes. Advanced materials, 2014. **26**(18): p. 2818-2824.

6. Wang, Z.L., Triboelectric nanogenerators as new energy technology for self-powered systems and as active mechanical and chemical sensors. ACS nano, 2013. **7**(11): p. 9533-9557.

7. Wang, Z., J. Chen, and L. Lin, Energy Environ. Sci. 2015, 8, 2250; b) ZL Wang. Faraday Discuss, 2014. **176**: p. 447.

8. Zhang, Q., et al., Green hybrid power system based on triboelectric nanogenerator for wearable/portable electronics. Nano Energy, 2019. **55**: p. 151-163.

9. Sultana, A., et al., A pyroelectric generator as a self-powered temperature sensor for sustainable thermal energy harvesting from waste heat and human body heat. Applied Energy, 2018. **221**: p. 299-307.

10. Xu, C., et al., On the electron-transfer mechanism in the contact-electrification effect. Advanced Materials, 2018. **30**(15): p. 1706790.

11. Xu, C., et al., Raising the working temperature of a triboelectric nanogenerator by quenching down electron thermionic emission in contact-electrification. Advanced Materials, 2018. **30**(38): p. 1803968.

12. Zhu, G., et al., A shape-adaptive thin-film-based approach for 50% high-efficiency energy generation through micro-grating sliding electrification. Advanced materials, 2014. **26**(23): p. 3788-3796.

13. Wang, Z.L., T. Jiang, and L. Xu, Toward the blue energy dream by triboelectric nanogenerator networks. Nano Energy, 2017. **39**: p. 9-23.

14. Li, M., A.L. Porter, and Z.L. Wang, Evolutionary trend analysis of nanogenerator research based on a novel perspective of phased bibliographic coupling. Nano Energy, 2017. **34**: p. 93-102.

15. Peng, H., et al., Forecasting potential sensor applications of triboelectric nanogenerators through tech mining. Nano Energy, 2017. **35**: p. 358-369.

16. Ahmed, A., et al., Environmental life cycle assessment and techno-economic analysis of triboelectric nanogenerators. Energy & Environmental Science, 2017. **10**(3): p. 653-671.

17. Bai, Y., et al., Washable multilayer triboelectric air filter for efficient particulate matter PM2. 5 removal. Advanced Functional Materials, 2018. **28**(15): p. 1706680.

18. Chen, S., et al., Self-powered cleaning of air pollution by wind driven triboelectric nanogenerator. Nano Energy, 2015. **14**: p. 217-225.

19. Wang, B., et al., Emerging nanogenerator technology in China: A review and forecast using integrating bibliometrics, patent analysis and technology roadmapping methods. Nano energy, 2018. **46**: p. 322-330.

20. Lee, J.H., et al., Control of skin potential by triboelectrification with ferroelectric polymers. Advanced materials, 2015. **27**(37): p. 5553-5558.

21. McCarty, L.S. and G.M. Whitesides, Electrostatic charging due to separation of ions at interfaces: contact electrification of ionic electrets. Angewandte Chemie International Edition, 2008. **47**(12): p. 2188-2207.

22. Musa, U.G., et al., The charging events in contact-separation electrification. Scientific reports, 2018. **8**(1): p. 1-8.

23. Moore, A.D., Electrostatics: exploring, controlling, and using static electricity: including the Dirod manual. 1997: Laplacian Press.

24. Diaz, A. and R. Felix-Navarro, A semi-quantitative tribo-electric series for polymeric materials: the influence of chemical structure and properties. Journal of Electrostatics, 2004. **62**(4): p. 277-290.

25. Zhang, Y., et al., Electric field and humidity trigger contact electrification. Physical Review X, 2015. **5**(1): p. 011002.

26. Zhang, X.-S., et al., Penciling a triboelectric nanogenerator on paper for autonomous power MEMS applications. Nano Energy, 2017. **33**: p. 393-401.

27. Xia, K., et al., Folding triboelectric nanogenerator on paper based on conductive ink and teflon tape. Sensors and Actuators A: Physical, 2018. **272**: p. 28-32.

28. Xia, K., et al., A triboelectric nanogenerator as self-powered temperature sensor based on PVDF and PTFE. Applied Physics A, 2018. **124**(8): p. 520.

29. Russo, A., et al., Pen-on-paper flexible electronics. Advanced materials, 2011. **23**(30): p. 3426-3430.

30. Jiang, D.-K., et al., Genetic variants in STAT4 and HLA-DQ genes confer risk of hepatitis B virus–related hepatocellular carcinoma. Nature genetics, 2013. **45**(1): p. 72-75.

31. Tao, L., et al., K. Fan, DL Kaplan, X. Zhang, RD Averitt, and FG Omenetto,"Metamaterials on paper as a sensing platform,". Adv. Mater, 2011. **23**: p. 3197-3201.

32. Jao, Y.-T., et al., A textile-based triboelectric nanogenerator with humidity-resistant output characteristic and its applications in self-powered healthcare sensors. Nano Energy, 2018. **50**: p. 513-520.

33. Han, Y., et al., Si@ void@ C nanofibers fabricated using a self-powered electrospinning system for lithium-ion batteries. ACS nano, 2018. **12**(5): p. 4835-4843.

34. Feng, Y., et al., based triboelectric nanogenerators and their application in self-powered anticorrosion and antifouling. Journal of Materials Chemistry A, 2016. **4**(46): p. 18022-18030.

35. He, X., et al., A highly stretchable fiber-based triboelectric nanogenerator for self-powered wearable electronics. Advanced Functional Materials, 2017. **27**(4): p. 1604378.

36. Simons, A. and H. Otoo, Minimization of Heat Transfer losses at the Shell Bitumen Plant, Takoradi, Ghana. International Journal of Scientific Research and Innovative Technology, 2014. **1**(5).

37. Lu, L., et al., Ultrahigh strength and high electrical conductivity in copper. Science, 2004. **304**(5669): p. 422-426.

38. Yabuki, A. and N. Arriffin, Electrical conductivity of copper nanoparticle thin films annealed at low temperature. Thin Solid Films, 2010. **518**(23): p. 7033-7037.

39. Chen, J., et al., Polyethylene glycol and solutions of polyethylene glycol as green reaction media. Green Chemistry, 2005. **7**(2): p. 64-82.

40. Orr, I.G., Y. Hadar, and A. Sivan, Colonization, biofilm formation and biodegradation of polyethylene by a strain of Rhodococcus ruber. Applied microbiology and biotechnology, 2004. **65**(1): p. 97-104.

41. Ng, N., et al., Secondary organic aerosol formation from m-xylene, toluene, and benzene. 2007.

42. Thelander, C., et al., Effects of crystal phase mixing on the electrical properties of InAs nanowires. Nano letters, 2011. **11**(6): p. 2424-2429.

43. Lo, H.-w. and Y.-C. Tai, Parylene-based electret power generators. Journal of Micromechanics and Microengineering, 2008. **18**(10): p. 104006.