Design and simulation of Triboelectric Nanogenerator for empowering Pacemaker

Anju M Gupta[1] and Anand D Darji[2]

[1] Department of Electronics Design Technology, Shri Ramdeobaba College of Engineering and Management, Nagpur, Maharashtra, India, guptaam@rknec.edu

[2] Department of Electronics Engineering, Sardar Vallabhbhai National Institute of Technology,Ichchhanath, Surat,Gujrat, India.

Abstract

Nowadays, the demand for implantable electronic devices is increasing day by day. All these devices require batteries which have a fixed life once they are drained need to be exchanged. Surgical techniques require to replace drained battery creating bodily and psychological distress to patients and enhancing health care budgets. Living beings have a plentiful source of energy in the form of thermal, chemical, and mechanical. These energies can overcome battery limitation and enhance the lifelong performance of wearable electronics. Herein, a technique to improve the current driving capability of triboelectric Nanogenerator (TENG) by using multilayer structure which enclosed in capsule type structure composed of biocompatible materials is proposed. In this work, five-layered zigzag TENG and five-layered stacked structures proposed for increasing the current capacity. The proposed designs comprised of nanostructure Polytetrafluoroethylene as tribo layer and Aluminium as second tribo layer as well as the top electrode, gold (Au) as the bottom electrode, Polyimide as a substrate layer. In COMSOL Multiphysics simulation is done to compare different size TENGs. Furthermore, a single unit of stacked design TENG with or without microstructure and comb electrodes simulated. For implantable electronics, triboelectric energy harvesting technique is one of the developing technologies has incredible scope in the self-powered the system in treatment and diagnosis.

Keywords. Multiphysics, self-powered, biocompatible, triboelectric nanogenerator, energy harvesting

DOI Number: 10.14704/nq.2022.20.9.NQ44215 **Neuro Quantology 2022; 20(9):1857-1862**

1. Introduction

Nowadays, implantable medical devices are widely used in medical diagnosis, monitoring, and treatment of diseases. For instance, pacemakers and automated implantable cardioverter defibrillators (AICDs) playing a vital role in effective treatments of heart rate related problem. A Pacemaker is one of the implantable devices which is synchronizing the heart rate to a normal level. However, it requires a battery for functioning which has a limited life of 7-10 years. After battery exhausted patient has to undergo critical surgery for replacement of a battery. This exercise is costly, painful and time-consuming. To solve this problem many of the research going on replacing the battery with self powered pacemaker. Piezoelectric [1], triboelectric, electromagnetic [2], biocell [3] and thermionic energy harvesting [4] techniques are used to harvest biomechanical energy. Each of these has its limitation as electromagnetic works on the principle of faradays includes a magnet which is not compatible with body structure. It will make MRI inoperable in future. The thermionic system requires a large temperature change but inside a body, temperature difference is not so wide. The piezoelectric nano-generator is a good solution in comparison to both of mentioned techniques; however, limited material available makes it not feasible. The best choice is the triboelectric nanogenerator. Triboelectric nano-generator generates energy from mechanical vibration converted into electric energy. This report is giving an overview of techniques used to harvest energy for powering the pacemaker. This work emphasizes on different techniques and materials used [5] and challenges and solution for the same. The heart is a great and attractive source of energy has a capacity to power cardiac

pacemakers [The different approaches used for powering a pacemaker by harvesting energy from heart motion are discussed.

2. Energy Harvesting

2.1 Piezoelectric energy harvesting based Pacemaker

Zhong lin demonstrated piezoelectric effect based energy harvester which harvests energy from muscle and heart vibrations. Selection of material is very crucial for implantable devices. Zinc Oxide (ZnO), lead Zirconate (PZT), and Polyvinylidene fluoride or polyvinylidene difluoride (PVDF) are a widely used piezoelectric transducer material. ZnO material is very biocompatible provides good bio safety [8]. Li et al. in 2010, demonstrated that ZnO nano wire based nanogenerator when placed on the heart of a rat produced 3mV and 30pA average open circuit voltage and short circuit current respectively. Herein, heart movement converted into electricity which is used to drive implantable pacemaker. This nanogenerator was fabricated using ZnO nanowire of diameter 100 to 800nm and a length of 100 to 500 m [9]. To protect from body fluid the device was encapsulated with polyimide material. Ansari et al. proposed a fan-folded design of size 2 cm X 0.5 cm X 1 cm can able to generate 10 W power. In this, analytical model was presented and experimentally verified [10] using shaker controller circuit which was generating vibrations equivalent to heart. Lin Dong et al. proposed piezoelectric cantilever energy harvester by charging leads of a pacemaker. Lin Dong et al. proposed piezoelectric cantilever energy harvester by charging leads of the pacemaker. This new design with dual cantilever structure uses porous Polyvinylidene uoride triethylene material. This cantilever is wrapped around the pacemaker leads for picking up vibration due to heart motion and generated 0.5 V open circuit voltage and 43nA of short circuit current at 1Hz. By adding proof mass of 31.6 mg on it reduces the resonance frequency and improved performance by 1.82 times [11]. The study shows that keeping two cantilevers along with the proof mass is not sufficient to provide power to the pacemaker. Ning Li et al. demonstrated piezoelectric principle-based energy harvester which is directly powering pacemaker from the energy harvested from heart motion. The generator composed of two piezoelectric composites of PMNPT and Beryllium bronze, which has generated a high-output current of 15 A and open-circuit voltage of 15V when connected in series mode and 8 A and 20 in a series mode in vivo state-of-the-art performance. For encapsulation from body fluid, Parylene and Polydimethylsiloxane(PDMS) are used. Ning li demonstrated that implantation sites of energy harvester affects performance [12]. Dagdeviren et al. fabricated a flexible PZT mechanical energy harvester able to generate electric power from porcine heart motions[13]. A flexible PZT mechanical energy harvester (MEH) unit structure composed of 500nm thin layer of PZT sandwich between the thin bottom layer of Ti/Pt and thin top layer of Cr/Au electrodes. Twelve groups of 10 such structures were electrically connected in series for enhancing output voltage. Ten-unit structures were connected in parallel to increase output current. Encapsulation of these devices with biocompatible materials isolates them from bodily fluids and tissue, thereby minimizing the risks of failure or immune response. In vivo testing, the device implanted on the right ventricle of bovine heart generated the electrical power densities of 0.12 W/cm^2 and 0.18 W/cm^2 at orientation of 0 and 45 degrees.

2.2 Triboelectric energy harvesting based Pacemaker

The first implantable triboelectric nanogenerator was demonstrated by Zheng et al. implanted under the left chest skin of a rat. The device was able to generate power from the heart breathing of rate. The generated AC outputs was rectified using full wave rectifier and capacitor was charged to 3V in 275 min which is sufficient for a pacemaker to provide stimulation pulses to heart at several frequencies from 2 to 5 Hz [14]. Quang zhang et al. demonstrated implanted triboelectric based energy harvester for powering pacemaker. Zheng et al. fabricated Nano fibres on the PTFE using dry etching and for excellent elasticity, an arched titanium strip was used. For encapsulation, layers of PTFE, PDMS and Parylene C were used. When this iTENG was fixed on the heart of a Yorkshire porcine generated 14V and 5 A, open circuit and short circuit current respectively [15]. Han introduced symbiotic implantable triboelectric nanogenerator able to generate 65.2 V and 0.495 J from heartbeat and

able to power the pacemaker. In this paper, PTFE film surface density is enhanced by the corona discharge method. For encapsulation, the PDMS layer is used. In case of in vitro testing using the vibration of linear motor able to generate 210V.

Aluminium foil with nanostructure acts as contact layer as well as electrode of iTENG. For the spacer PET (400 m) is used between two tribolayer. Silver paste is used for fixing the electrodes. The whole assembly is enclosed in PDMS from body fluid [16]. Ye Ma et al. fabricated a self-powered and multifunctional implantable triboelectric active sensor (iTEAS) for an accurate and real time observing physiological and pathological state. The flexible iTEAS was tested on adult swine, which has generated open circuit voltage of 10V and short circuit current of 4 A on heart beating of swine [17].

3. Material And Methods

Although, different techniques available for harvesting energy for powering pacemaker to avoid the problem of battery replacement. The challenge is to design small size, biocompatible, very sensitive energy harvester which can drive pacemaker without creating any discomfort to patients. Electromagnetic, thermoelectric, and piezo-electric are techniques used for making pacemaker self-powered. Herein, triboelectric energy harvesting method is discussed which has great scope to be used to power pacemaker, however, it suffers from low output current. A solution for increasing current of TENG by using five layered zigzag structure is provided. By connecting five-layered in parallel the current density can be increased. The whole structure can be encapsulated in a capsule structure composed of PDMS and parylene materials to protect from body fluid. The proposed design composed of nanostructure PTFE as tribo layer and Aluminium as second tribo layer as well as the top electrode, Gold (Au) as the bottom electrode, Polyimide as a substrate layer. The whole structure will be enclosed by PDMS and parylene cover to protect from body fluid. Herein, a single unit of the stacked structure TENG with or without micro structure is simulated in COMSOL multiphysics. The "electrostatics" module of COMSOL used to calculate the electric potential distribution usi ng "stationary" study. The result shows that the optimum size micro structure can increase the open circuit voltage of TENG. Furthermore, comb structure electrodes TENG is compared with a flat electrode structure and found that the comb structure gives better performance.

4. Results and Discussion

4.1. Simulation of Proposed design

The proposed design for energy harvesting from heart motion five-layered zigzag structure (figure 1) compared with five-layered stacked structure (figure 2). In zigzag structure tribo layers arranged symmetrical way to avoid parasitic effects. In this design same tribo layers are deposited both sides of substrate. The proposed design composed of nanostructure PTFE as tribo layer and Aluminium as the second tribo layer as well as the top electrode, Gold (Au) as a bottom electrode, Polyimide as a substrate layer. The whole structure will be enclosed by PDMS and parylene cover to protect from body fluid.

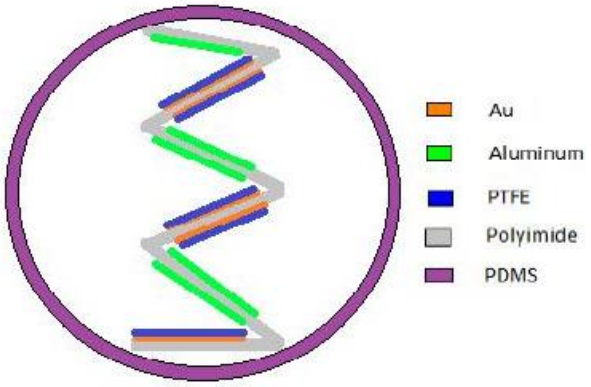

Figure 1. Five-layered zigzag structure TENG

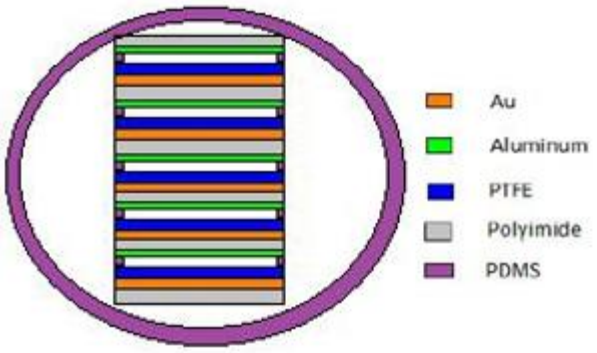

Figure 2. Five-layered stacked structure TENG

Single unit of both the structure is simulated in COMSOL Multiphysics. Herein, the zigzag structure is simulated for three different

dimensions 39mm X 61mm x 0.5mm, 39mm X 61mm x 0.5mm,10mm X 20mm x 0.5mm and compared as shown in figure3.

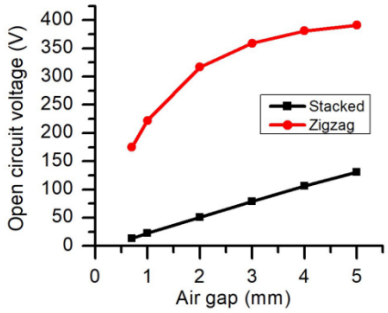

Figure 3. Simulation result shows a comparison of two different structures.

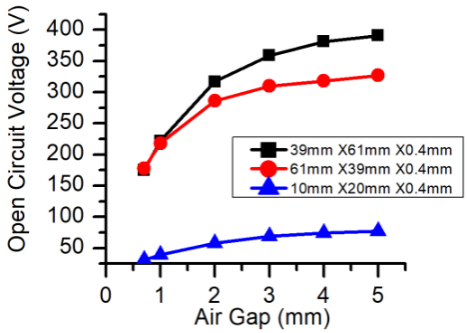

Figure 4. Simulation result shows the effect of variation of dimensions of TEG.

The maximum open-circuit voltage is shown by 39mmx61mmx0.5mm dimension structure, as shown in figure4 is better as compared to other designs. This is done to understand and enhance the triboelectric effect and consequently to optimize future prototype.

4.2. Simulation of microstructure design

As per literature from that is concluded that the surface modification can increased surface charge density using different technologies such as micro/nanostructure fabrication, ion injection, porous structure. However, the improvement in performance is about 4 to 6 times the original surface. Furthermore, single unit of stacked structure TENG with or without microstructure is simulated (figure 5). It was found that optimum size micro structure can enhance the output voltage of TENG.

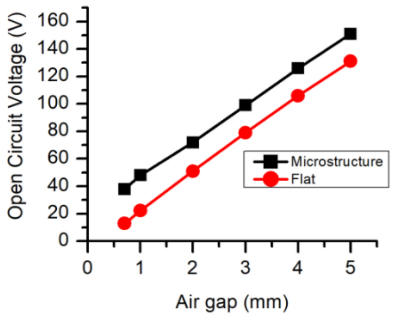

Figure 5. Simulation result shows a comparison of microstructure and flat structure TEG.

4.3 Simulation of proposed design with Comb structure electrode

Because of increasing, surface charge density the comb structure electrodes (figure6) TENG was com-pared with a flat electrode structure. It is concluded that the comb structure shows better performance as compared to flat electrode structure figure7.

To increase current density five-layered zigzag structure and a five-layered stacked structure are simulated in COMSOL physics. The electrostatic physics is used. Surface charge density calculated

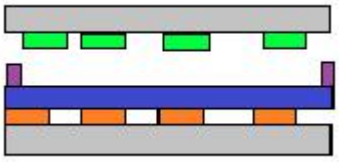

Figure 6. Triboelectric generator with comb structure electrode.

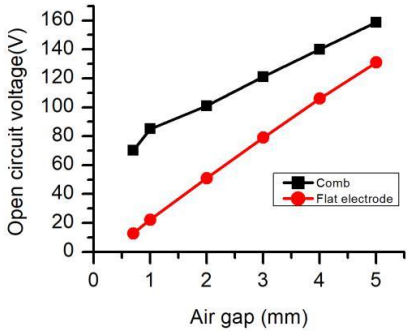

Figure 7. Simulation result shows comparison of comb electrode and flat electrode output.

using the formula given in the theoretical modelling part was 287nC/m^2. Due to myocardium synchronous expansion and contraction of the entire cardiac muscular mass attached multilayered structure layers contact and separate thus the charge transfer takes place results in the generation of power. The result shown in table 1 shows that zigzag structure is good option for energy harvesting. When all layers of TENG are connected in parallel current is enhanced by five times. The details of the structure are listed in the table 2.

Table 1. Result

Design	Open Circuit voltage	DC current
[16]H.Ouyang	65.2V	0.5µA
Proposed Zigzag structure	391V	16µA
Proposed stacked structure	131V	5.5µA

Table 2. Details of Proposed design

Layer No	Material Details	Dimensions in mm
Substrate	Polyimide	39 X 61 X 0.1 mm^3
Tribolayer	PTFE	39 X 61 X 0.1 mm^3
Bottom Electrode	Au	39 X 61 X 0.001 mm^3
Top Electrode	Aluminium	39 X 61 X 0.001 mm^3
Encapsulation	PDMS	39 X 61 X 0.1 mm^3

4.4. Fabrication process for proposed structure

Fabrication of nanostructure on five pieces of Al foil (39mm X 61mm X 0.1mm) uses etching method. Nanostructure on five pieces of PTFE layer (39mm X 61mm X 0.1mm) will be formed after the nanoscale masking with the Au nanoparticles on the PTFE surface. After that Deposition of 100nm gold (Au) will be done on the other sides of all five pieces of PTFE for the bottom electrodes. After that sticking of tribo layers on polyimide substrate and alternate spaces will be done (figure 8). Deposition of PDMS and Parylene layer on PTFE is done for encapsulation of Zigzag triboelectric nanogenerator.

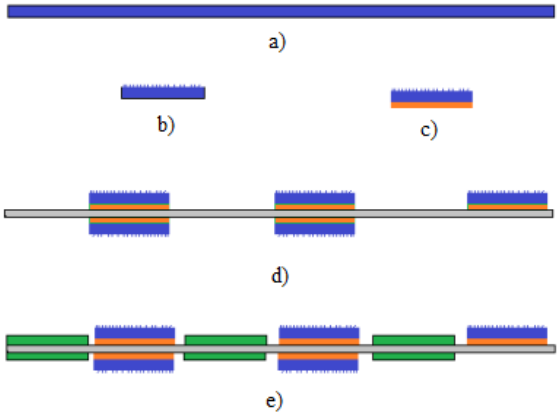

Figure 8. Fabrication process: a)PTFE layer b) formation of nanostructure on PTFE cutting into five pieces c) deposition of gold bottom electrode on other side of PTFE layer d)Sticking of PTFE tribolayer on alternate spaces e) pasting of aluminium layer as top electrode on alternate spaces.

5. Conclusion

In this study, different techniques for harvesting energy from heart motion is reviewed. From the study, it is concluded that triboelectric energy harvesting has promising scope to use as a self-powered system in vivo electronics as compared to other existing technology. In this work, five-layered zigzag TENG and five-layered stacked structure proposed for increasing the current capacity. The proposed design composed of nanostructure PTFE as tribo layers and Aluminium as second tribo layer as well as the top electrode, Au as the bottom electrode, Polyimide as a substrate layer. The whole structure is enclosed by PDMS and parylene cover to protect from body fluid. A single unit of both the designs is simulated and from the result, it is concluded that zigzag de-sign gives better open-circuit voltage. In COMSOL Multiphysics simulation is done to compare different size TEGs are simulated. Furthermore, single-unit stacked design TENG with or without micro is simulated and from the result, it is concluded that creating of micro and nanostructure improves the result. For enhancing the current capability of TENG the comb simulated and compared with the flat electrode structure.

Acknowledgments

Authors wish to acknowledge encouragement, support and suggestions from colleagues and financial support from organizations.

References

[1] Ansari M and Karami M A 2015 *J. Phys.: Conf. Ser.* **660** 012121

[2] Abiri P, Abiri A, Packard R S, Ding Y, Yousefi A, Ma J, Bersohn M, Nguyen K L,Markovic D and Moloudi S 2017 *Sci.Rep.* 7 6180

[3] Southcott M, MacVittie K, Halamek J, Halamkov L, Jemison W D, Lobel R and Katz E 2013 *Phys.Chem.Chem.Phys.***15** 278–6283

[4] Leonov V, Torfs T, Fiorini P and Van Hoof C 2007 *IEEE Sens. J.* **7** 650-7

[5] Li J and Wang X 2017 *APL Mater.* **5** 073801

[6] Starner T 1996 *IBM Syst. J.* **35** 618–29

[7] Zhang Y, Lu B, Lu C and Feng X 2017 *Proc. R. Soc.* **473** 2207 0615

[8] Irimia-Vladu M 2014 *Chem. Soc. Rev.* **43** 588–610

[9] Li Z, Zhu G, Yang R, Wang A C and Wang Z L 2010 *Adv. Mater.* **22** 2534–37

[10] Karami M A and Inman D J 2011 *ASME J. Vib. Acoust.* **133** 011002

[11] Dong L, Han X, Xu Z, Closson A B, Liu Y, Wen C, Liu X, Escobar G P, Oglesby M and Feldman M 2019 *Adv. Mater. Technol.* **4** 1800148

[12] Li N, Yi Z, Ma Y, Xie F, Huang Y, Tian Y, Dong X, Liu Y, Shao X and Li Y 2019 *ACS nano* **13** 2822–30

[13] Dagdeviren C, Yang B D, Su Y, Tran P L, Joe P, Anderson E, Xia J, Do-raiswamy V, Dehdashti B, and Feng X 2014 *Proc. Natl. Acad. Sci.* **111** 1927–32

[14] Zhang Q, Shi B, Fan F, Wang X, Yan L,Yuan W, Wang S, Liu H, Li Z and Wang Z L 2014 *Adv. Mater.* **26** 5851–6

[15] Zheng Q, Zhang H, Shi B, Xue X, Liu Z, Jin Y, Ma Y, Zou Y, Wang X and An 2016 *ACS nano* **10** 6510–8

[16] Ouyang H, Liu Z, Li N, Shi B, Zou Y, Xie F, Ma Y, Li Z, Li H and Zheng Q 2019 *Nat. Commun.* **10** 1821

[17] Ma Y, Zheng, Liu Y, Shi B, Xue X, Ji W, Liu Z, Jin Y Q, Zou Y and An Z 2016 *Nano lett.* **16** 6042–51