Japan Bilingual Publishing Co.

New Environmentally-Friendly Materials
https://ojs.bilpub.com/index.php/nefm

COMMUNICATION

A Novel Approach to Fabricate a Polyamide-Copper TENG in Vertical Contact-Separation Mode

Hitesh Kumar Sharma [1*] **,** ***Atul Kumar Sharma*** [1] **,** ***Vijay Janyani*** [2] **,** ***Dharmendra Boolchandani*** [2]

[1] *Materials Research Centre, Malaviya National Institute of Technology, Jaipur, Rajasthan 302017, India*

[2] *Department of Electronics Engineering, Malaviya National Institute of Technology, Jaipur, Rajasthan 302017, India*

ABSTRACT

In this study, a novel design concept for a contact-separation Triboelectric Nanogenerator (TENG) utilizing polyimide (PI) film and copper (Cu) tape is presented. The innovation lies in enhancing the surface area and roughness of the PI film using 1000-grit sandpaper, which is manually rubbed over the film. This surface treatment significantly improves charge transfer between the PI and Cu layers, thereby enhancing the electrical performance of the TENG. The modified (rubbed) PI-Cu TENG achieved an open-circuit voltage (V_{oc}) of 25 V and a short-circuit current (I_{sc}) of 0.7 μA. Compared to a pristine (untreated) PI film, the hand-rubbed PI-Cu TENG demonstrated an increase in performance. V_{oc} and I_{sc} were improved by 78.6% and 75%, respectively, due to the increased surface roughness and area, which facilitated more efficient charge transfer at the interface. Additionally, the instantaneous power density showed a notable increase of 68.18% relative to the pristine film. The prototype device was characterized using a two-probe I-V measurement system to obtain I_{sc} and V_{oc} responses. Morphological changes in the rubbed PI film were confirmed via Scanning Electron Microscopy (SEM), performed using an FEI Nova Nano FESEM 450, revealing the presence of scratch-induced torsional layers. Surface roughness and topographical features were further analyzed using Bruker Multimode-8 Atomic Force Microscopy (AFM).

Keywords: Triboelectric Energy Harvesters; FESEM; AFM; Four Probe IV-Testing

*CORRESPONDINGAUTHOR:
Hitesh Kumar Sharma, Materials Research Centre, MNITJ; Email: hitesh.mrc@mnit.ac.in

ARTICLEINFO
Received: 20 March 2025 | Revised: 23 April 2025 | Accepted: 5 May 2025 | Published Online: 13 May 2025
DOI: https://doi.org/10.55121/nefm.v4i1.411

CITATION
Sharma, H.K., Sharma, A.K., Janyani, V., et al.,2025. A Novel Approach to Fabricate a Polyamide-Copper TENG in Vertical Contact-Separation Mode. New Environmentally-Friendly Materials.4(1):57–66.DOI: https://doi.org/10.55121/nefm.v4i1.411

1. Introduction

The increasing global demand for sustainable and renewable energy sources has driven significant research into alternative energy harvesting technologies. With the rapid growth of portable electronics, wireless sensor networks, and the Internet of Things (IoT), there is a critical need for self-powered systems that can operate without frequent battery replacements [1]. Traditional energy sources, such as fossil fuels and conventional batteries, face limitations related to environmental impact, finite lifespan, and maintenance requirements. In this context, energy harvesting technologies that convert ambient energy from the environment into usable electrical power have gained substantial attention.

A number of mechanical energy sources are present around us, such as human walking, water flow, and wind energy [1–5]. These mechanical sources of energy are usually wasted and not used. It can be efficiently converted to usable electrical energy which can drive small mobile applications. Nonetheless, some energy harvesting technologies, including piezoelectric, electromagnetic, and electrostatic energy harvesters, have garnered a lot of interest, especially for small mobile applications [6–8]. In 2012, Dr. Wang and his team presented a new concept of energy harvester [2], called a triboelectric energy harvester (TENG), which is based on the principles of contact electrification and electrostatic induction [4]. Now, Triboelectric nano power generators (TENGs) are emerging as a vital energy source of generating electrical energy from such ambient mechanical vibration sources under different conditions. TENGs' low cost, high efficiency, ease of fabrication, adaptability, environmental friendliness, and variety are what make them appealing[1,3,6]. The discovery of TENGs created a new field for researchers to generate electrical energy and its integration with mobile applications. A number of researchers are also significantly working to enhance the TENG performance by various aspects such as appropriate material selection, device fabrication process, surface contact area, porous structure, and surface morphology [9–21].

TENG is a recently developed energy source that operates on the basis of electrostatic induction and the triboelectric effect [4]. The triboelectric effect is a contact electrification that works by charging two surfaces of different materials when they come into contact and are then separated or slid against each other. As a result, depending on the triboelectricseries (tribo-polarity of tribo-pair materials) and work function of materials, a charge transfer occurs and both surfaces oppositely charge either positively or negatively [2,7,22–27]. To drive this source of charges (electrons or ions) and to continually produce voltage and currents via it, an external load is connected. The performance of triboelectric energy harvesters depends heavily on material selection and device architecture. Triboelectric materials are ranked based on their tendency to gain or lose electrons, known as the triboelectric series [16–21]. As shown in **Figure 1**, TENG is divided into two categories based on the tribo-pair: metal-to-dielectric and dielectric-to-dielectric (**Figure 1(a)** and **(b)**). We used the metal-to-dielectric approach to realize novel PI-Cu TENG (**Figure 1(a)**). In metal-to-dielectric TENG, the dielectric layer will be negatively charged while the metal, which is the top layer, will be charged positively due to the concept of effective work function. This generates the charges as both layers move close to each other and then are separated. If the contact electrodes are connected to the external load resistance, then there would be a charge transfer between both electrodes, resulting in a current flow when they approach or are separated from each other [15–21,26–28].

Because of the effective work function, the top layer of Cu metal in this structure will have a positive charge, while the PI polymer layer will have a negative charge. Because of its superior transparency and charge transport behavior, the PI has garnered attention and exhibits n-type behavior, acting as a supreme donor. The charge transfer capability in a triboelelectric pair is essentially determined by the work function. The output power of the TENG was increased by rubbing PI with sandpaper to improve the work function.

The primary objective of this research article is to develop and demonstrate an innovative fabrication methodology for a triboelectric nanogenerator (TENG) that leverages polyamide and copper as the constituent materials. The study aims to optimize the device architecture and surface properties to enhance its electrical performance and energy harvesting efficiency. Furthermore, the research seeks to explore the operational stability and scalability of the proposed TENG design, with an emphasis on advancing sustainable energy generation technologies. Through this work, the authors intend to contribute to the growing field of wearable and self-powered electronic devices by providing a viable and cost-effective approach for TENG manufacturing in vertical contact-separation configurations. This proved to be a unique method of fabricating the TENG without the need for costly equipment or a labour-intensive fabrication process. The TENG device is fabricated using the design specifications provided in **Table 1**.

Table 1. Design Parameters of TENG Device.

Parameters	Dimensions (mm)
Top electrode length	21
Top electrode width	21
Bottom electrode length	25
Bottom electrode width	25
Overlap area (mm^2)	441
Tribo-pair	PI-Cu

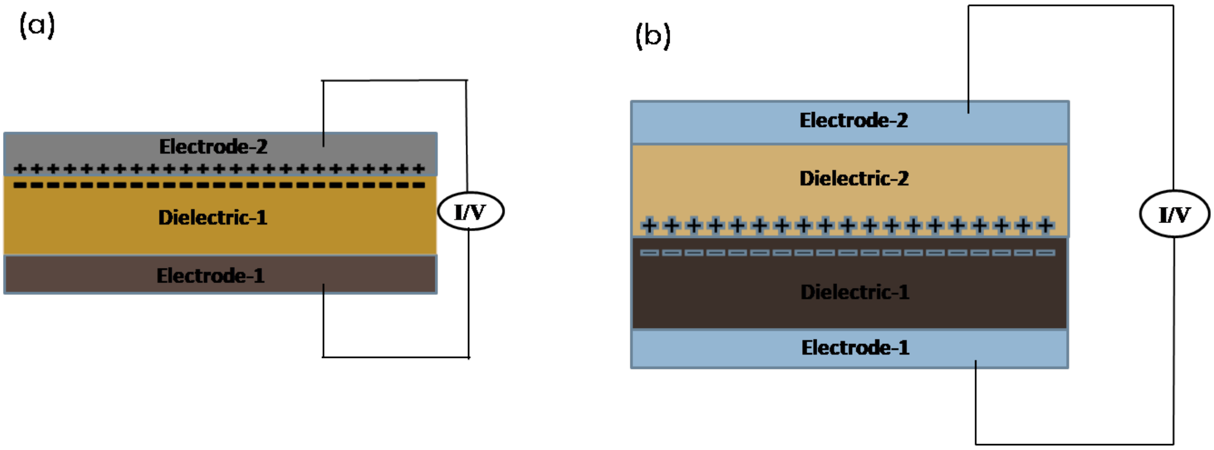

Figure 1. Two Categories Based on the Tribo-Pair: (**a**) Metal-to-Dielectric Approach. (**b**) Dielectric-to-Dielectric Approach.

2. Design and Fabrication

This TENG is designed as metal-to-insulator in which 2.1cm×2.1cm = 4.41 cm^2 polyamide (PI) is used as a bottom layer. This PI film is attached to the FR4 single-sided copper-polished substrate, which is commercially available. This copper is used as a bottom electrode for connection. The top tribo layer, which serves as a top contact electrode in and of itself, is realized using a single-sided copper tape that is 99.99% pure. This copper tape is connected beneath the cardboard, which makes it mechanically strong during manual tapping. The detailed parameters of design are shown in **Table 1**.

The pristine PI-Cu based TENG was fabricated and tested, and the morphology of pristine PI was altered to enhance the TENG properties by making significant changes in the roughness and surface area. The surface morphology of the pristine PI layer is changed by freely hand rubbing with 1000-grit sandpaper for 3 minutes and then cleaned with acetone and isopropanol. After this, thoroughly clean the entire device with de-ionised water and dry in a vacuum oven until the evaporation of DI water. The schematic of PI-Cu-based TENG is shown in **Figure 2**, in which the top layer is Cu tape and the bottom layer is polyamide (PI). The Cu tape itself acts as a contact electrode to transfer the charge for the top tribolayer, while the copper film patterned on the FR4 substrate is used for the bottom contact electrode. The schematic diagram and complete assembly of TENG are shown individually in **Figure 2(a)–(d)**.The complete process of generating short circuit current (I_{sc}) and open circuit voltage (V_{oc}) is depicted in **Figure 3**, illustrating the working mechanism of PI-Cu TENG through its separation, pressing, releasing, full separation, and re-pressing states (**Figure 3(a)–(e)**).

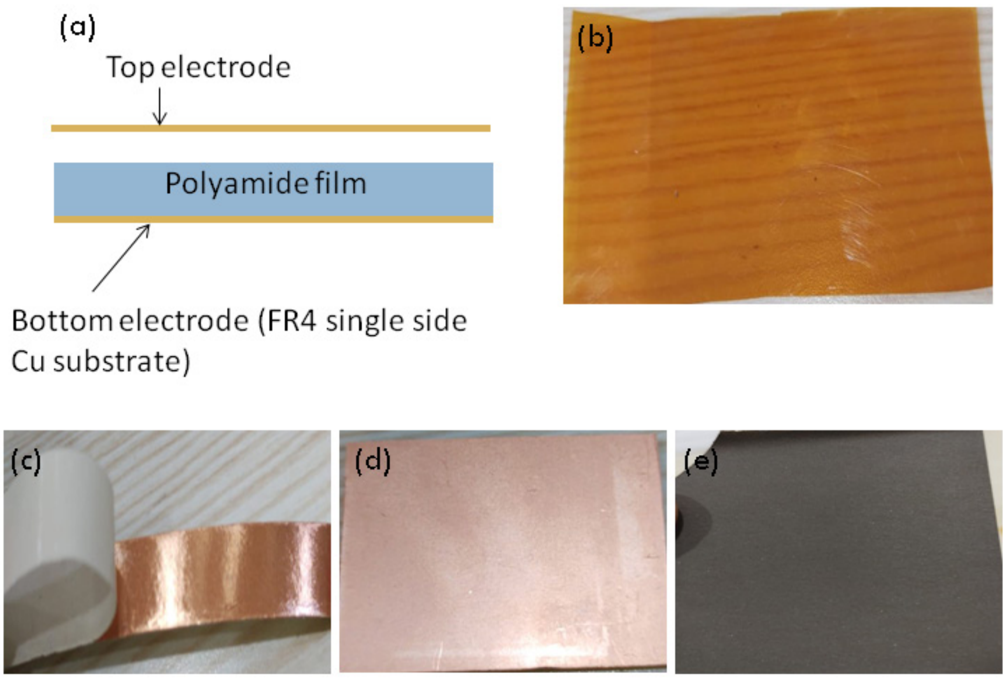

Figure 2. Schematic Diagram of (**a**) PI-Cu TENG, (**b**) Polyamide Film, (**c**) 99.99% Copper Tape, (**d**) FR4 Single Side Copper Substrate, and (**e**) 1000 Grit Sand Paper.

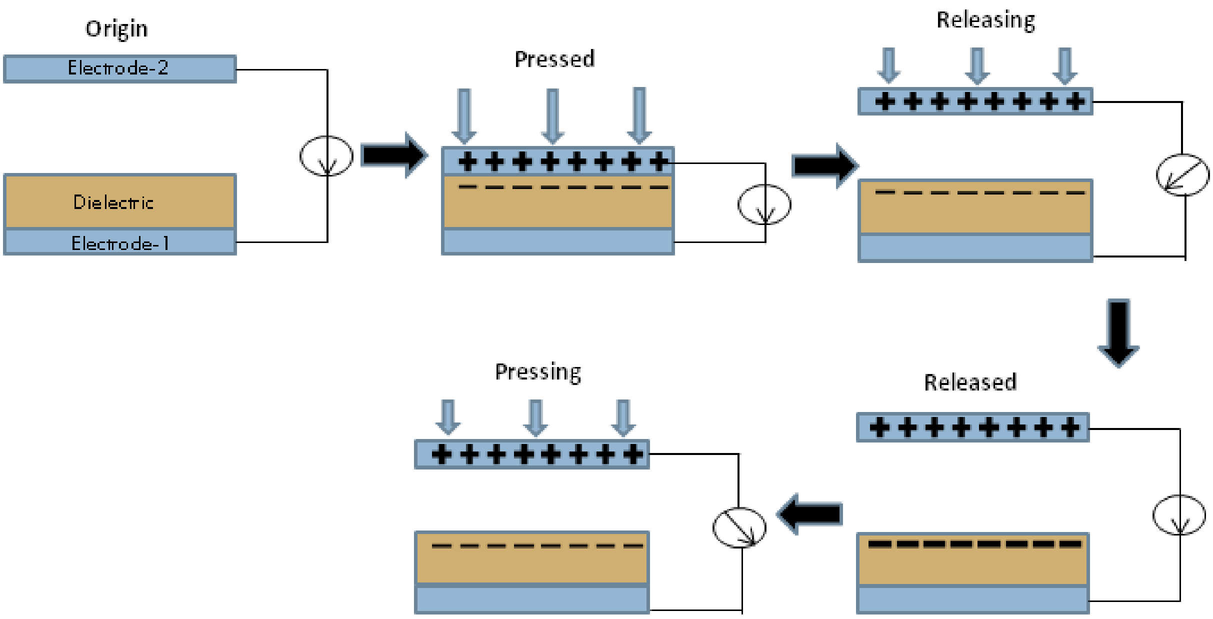

Figure 3. Working Mechanism of PI-Cu TENG as (**a**) Separation State, (**b**) Pressed State (Full Contact), (**c**) Releasing State, (**d**) Full Separation (Released State), and (**e**) Contact State(Again Pressing)

3. Experimental Results

The pristine PI-Cu and hand rubbed PI-Cu TENG were characterized by FESEM, AFM, and a probe IV characterization tool to observe the surface morphology, roughness and electrical properties of designed TENG.

3.1. FE-SEM

Figure 4 presents a comparative analysis of the surface morphological characteristics of both pristine and mechanically modified polyamide (PI) films, as examined through field emission scanning electron microscopy (FE-SEM) using the FEI Nova Nano SEM 450 system (accelerating voltage: 5 kV, working distance: 5 mm) (**Figure 4(a)** and **(b)**). The high-resolution micrographs reveal significant topographical modifications induced by the mechanical abrasion process. The untreated PI film exhibits a relatively smooth and homogeneous surface morphology. In contrast, the hand-rubbed PI surface, treated with 1000-grit silicon carbide sandpaper demonstrates a distinct microstructured pattern characterized by aligned torsional scrapings and hierarchical surface features. This engineered topography increases the effective contact area compared to the pristine surface, as quantified through image processing analysis (ImageJ software) of the FE-SEM micrographs [18]. The torsional scraping creates multiple contact points that enhance triboelectric charge generation through two mechanisms: (1) increased true contact area during compressive loading, and (2) improved charge trapping capability at the nanoscale asperities [19,20].

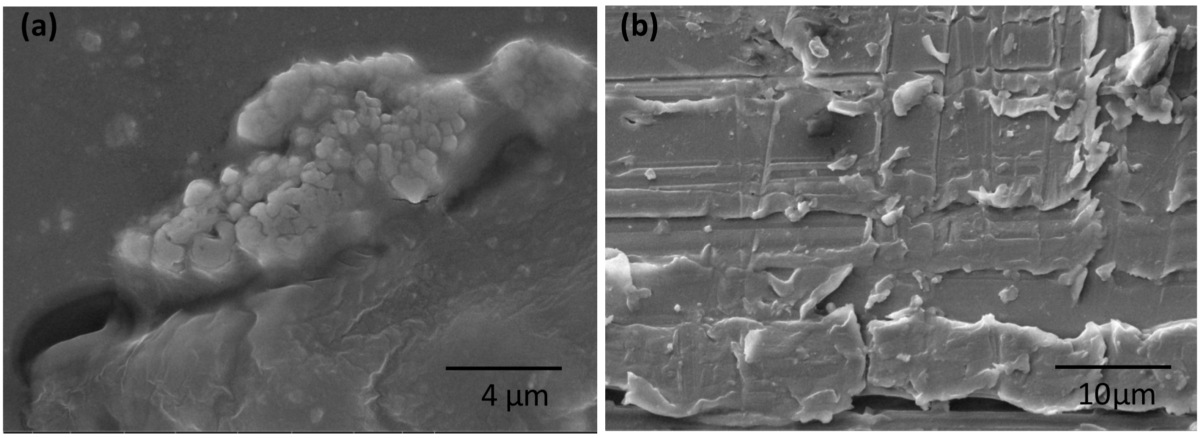

Figure 4. FESEM Images of (**a**) Pristine PI Film with Smooth Surfaces, and (**b**) Rubbed with 1000 Grit sand Paper Having Scratched Pattern.

This surface modification strategy directly contributes to the enhanced electrical output of the TENG device, yielding an improvement in open-circuit voltage (V_{oc} increasing from 14 V to 25 V) and an enhancement in short-circuit current (I_{sc} rising from 0.4 μA to 0.7 μA) compared to the unmodified counterpart.

3.2. AFM

Surface topography analysis was conducted using a Bruker MultiMode 8 Atomic Force Microscope (AFM) operating in tapping mode to quantitatively characterize the nanoscale morphological changes induced by mechanical rubbing of the polyimide (PI) films. The measurements employed an antimony (n-type) doped silicon RTESP-300 probe with a nominal resonant frequency of 300 kHz (±5%) and spring constant of 40 N/m (±2%), calibrated using the thermal tune method of the Nanoscope software. The AFM system was operated under ambient conditions (23±1°C, 45±5% RH) with a scan rate of 1.0 Hz over 5×5 μm² areas, acquiring 512×512 pixel resolution images.

High-resolution 2D and 3D topography maps (**Figure 5**) reveal distinct morphological differences between the pristine and modified PI surfaces (**Figure 5(a)–(d)**). The untreated film exhibits a homogeneous surface structure with a Gaussian height distribution (R_q = 30.2±2.5 nm) and maximum peak-to-valley roughness (R_{max}) of 48.8 (±2.5 nm) nm. Post-treatment analysis shows significant surface restructuring, with R_{max} increasing to 74.3 nm (±2.5 nm) and the development of anisotropic surface features.

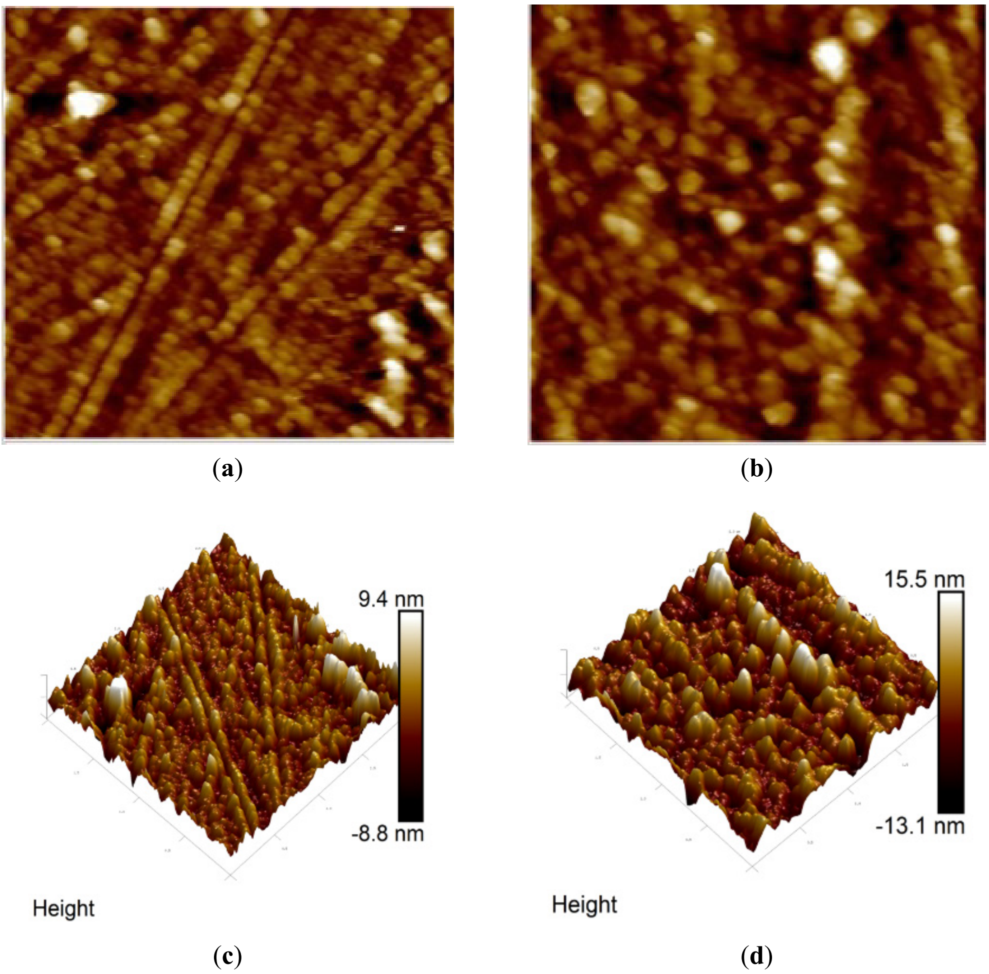

Figure 5. High-Resolution 2D and 3D Topography Maps. (**a**) 2D AFM Image of Pristine PI Film with Uniform Distribution of Particles, (**b**) 2D Image of Rubbed PI Filmas Scattered Particles, (**c**) 3D Image of Pristine PI Film, and (**d**) 3D Image of Rubbed PI Film.

The stacking pattern is converted into a distributed pattern with a good number of asymmetrical particles. These structural modifications enhance triboelectric performance by increasing true contact area, improving interlocking between contacting surfaces, and enhancing charge trapping at nanoscale defects.

3.3. TENG Electrical Characterization

The electrical characterization of the fabricated triboelectric nanogenerator (TENG) was systematically performed using precision measurement instrumentation, including the Agilent Technologies B1500A Semiconductor Device Analyzer (resolution: 10 fA current, 1 μV voltage) and MicroXact SPS-2200 two-probe IV-characterization system (input impedance > 10^{14} Ω). The evaluation protocol employed vertical contact-separation mode actuation through controlled manual tapping to simulate practical mechanical excitation conditions [27,28].

As demonstrated in **Figure 6**, comparative performance analysis between pristine and surface-modified TENG configurations reveals significant enhancement in output characteristics. The baseline Cu-PI TENG (untreated polyimide surface) exhibited peak-to-peak output parameters such as open-circuit voltage (V_{oc}): 14 V (±0.5 V) short-circuit current (I_{sc}): 0.4 μA (±0.02 μA) as shown in **Figure 6(a)** and **(b)**. The surface-engineered TENG (1000-grit sandpaper-treated PI) demonstrated 78.6% and 75% improvement in voltage and current outputs, respectively, such as enhanced Voc: 25 V (±0.5V) and improved I_{sc}: 0.7 μA (±0.02 μA) as shown in **Figure 6** (**c**) and (**d**). One complete cycle of generated peak to peak voltage and instrument set up during measurement is shown in **figure 6** (**e**) and (**f**).

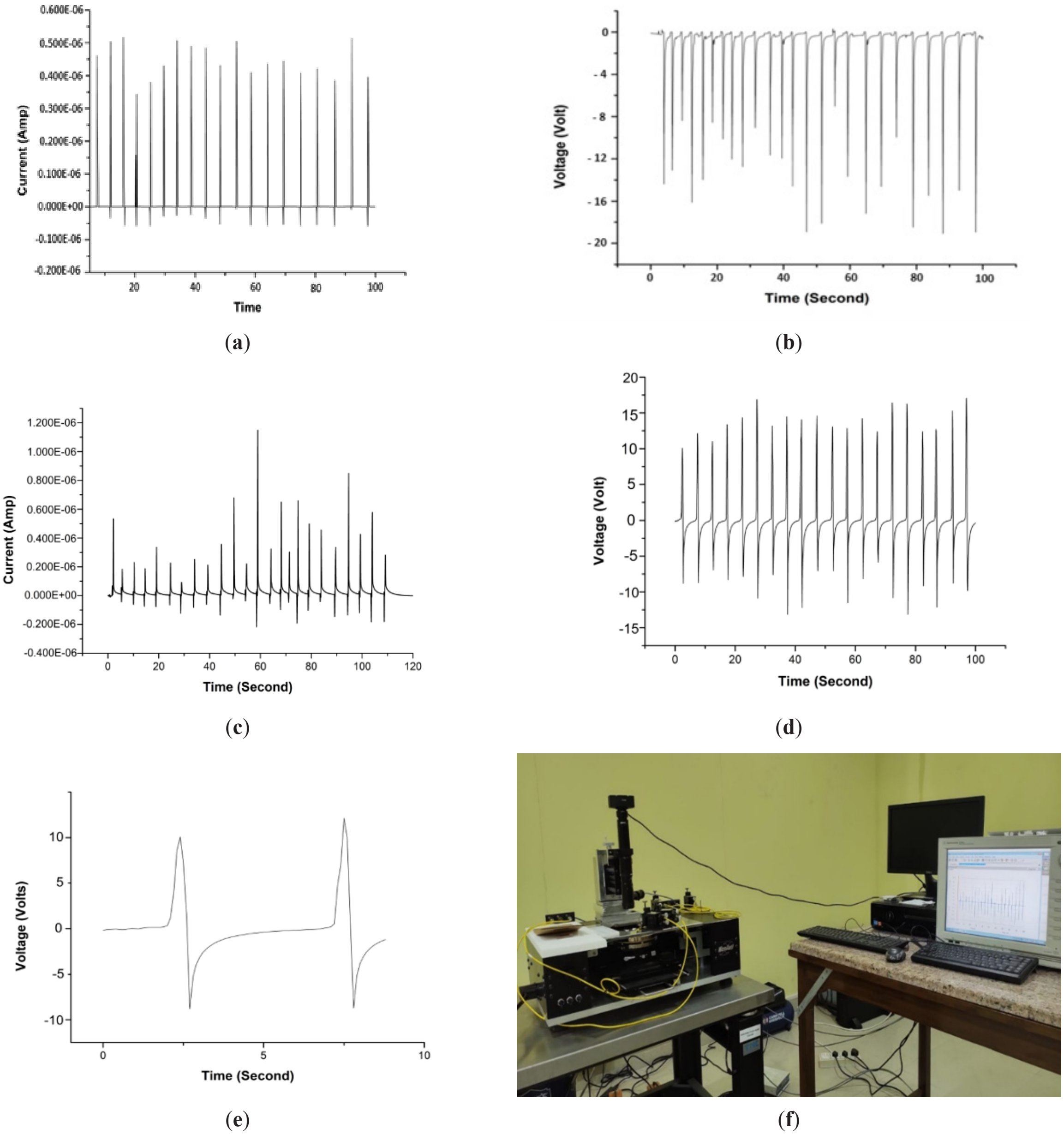

Figure 6. Comparative Performance Analysis Between Pristine and Surface-Modified TENG Configurations. (**a**) Short Circuit Current (Isc), (**b**) Open Circuit Voltage (Voc) of Pristine PI Film, (**c**) Short Circuit Current (Isc), (**d**) Open Circuit Voltage (Voc) of Rubbed PI Film,(**e**) One Complete Cycle of Generated Voltage, and (**f**) Device Testing in IV Measuring Tool Using Two Probe Method.

The instantaneous power output was calculated as

$$P_{max} = (V_{oc} \times I_{sc}) = 17.5\mu W \quad (1)$$

with corresponding power density of 3.96 μW/cm² (active area: 4.41 cm²). This represents a 2.70 fold improvement over the pristine device (1.26 μW/cm²), validating the efficacy of surface modification (**Table 2**) [15-22].

Table 2. Electrical Results of Designed PI-Cu TENG.

Parameters	Experimental results	
	pristine PI film	**rubbed PI film**
Peak Voltage (V)	14	25
Peak current (μA)	0.4	0.7
Instantaneous power (μW)	5.6	17.5
Instantaneous power density (μW/cm^2)	1.26	3.96

To examine the impact of aging or self-life on the TENG's output performance, this fabricated device was also evaluated over time. This is what **Figure 7** shows.

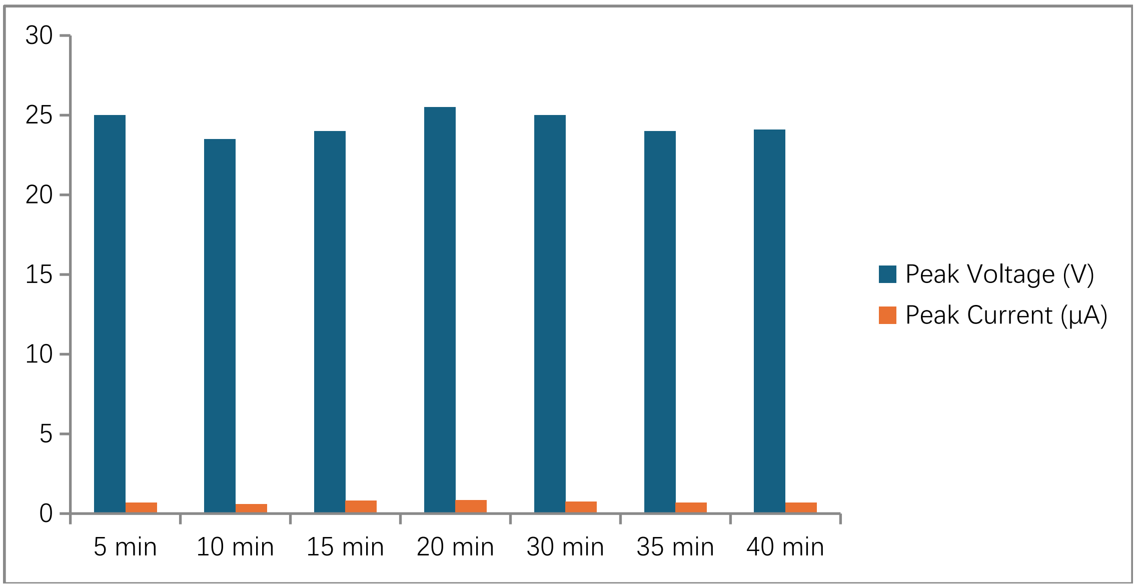

Figure 7. The Self Life/Aging Effect Over the Period of Time.

4. Conclusions

This study demonstrates the successful fabrication and performance enhancement of a contact-separation mode triboelectric nanogenerator (TENG) utilizing commercially available polyamide (PI) film and high-purity (99.99%) copper tape as triboelectric layers. Through systematic surface engineering, we achieved significant improvement in power generation capability by implementing a mechanical texturing process using 1000-grit silicon carbide sandpaper. Comparative analysis between pristine and surface-modified devices revealed substantial performance enhancement, with the textured PI-Cu TENG exhibiting open-circuit voltage (V_{oc}) increased from 14 V to 25 V (78.6% improvement), short-circuit current (I_{sc}) increased from 0.4 μA to 0.7 μA (75% improvement). The Power output characteristics revealed such as maximum instantaneous power: 17.5 μW (68% increase vs. pristine) and power density: 3.96 μW/cm² (68.18% increase vs. pristine).

The surface modification approach presents a cost-effective and scalable solution for TENG performance enhancement, requiring no specialized equipment or complex processes. The durability tests demonstrated and indicated excellent mechanical stability of the textured surface.

Author Contributions

Conceptualization, H.K.S.; methodology, H.K.S.; investigation, H.K.S.; resources, V.J. and D.B.; data curation, H.K.S. and A.K.S.; writing—original draft preparation, H.K.S. and A.K.S.; writing—review and editing, V.J. and D.B.; visualization, H.K.S.; supervision, V.J. and D.B.; project administration, V.J. All authors have read and agreed to the published version of the manuscript.

Funding

This work received no external funding.

Institutional Review Board Statement

Not Applicable.

Informed Consent Statement

Not Applicable.

Data Availability Statement

On this Journal page and upon authors request.

Acknowledgments

This study was conducted at the Malaviya National Institute of Technology's Materials Research Centre in Jaipur. The authors express their gratitude to the MRC team, especially Mr. Bhupesh Sharma and Mr. Shubham Gautam, who helped us with the FESEM and IV-characterization facility, respectively.

Conflicts of Interest

No Conflict of interest

References

[1] Wang, S., Lin, L., Xie, Y., et al., 2013. Sliding triboelectric nanogenerators based on in-plane charge separation mechanism. Nano Letters. 13(5), 2226–2233. DOI: https://doi.org/10.1021/nl400738p

[2] Rathore, S., Sharma, S., Swain, B.P., et al., 2018. A critical review on triboelectric nanogenerator. IOP Conference Series: Materials Science and Engineering. 377, 012186.

[3] Dhakar, L., Tay, F.E.H., Lee, C., 2015. Development of a broadband triboelectric energy harvester with SU-8 micropillars. Journal of Microelectromechanical Systems. 24(1), 91–99. DOI: https://doi.org/10.1109/JMEMS.2014.2317718

[4] Wiles, J.A., Grzybowski, B.A., Winkleman, A., et al., 2003. A tool for studying contact electrification in systems comprising metals and insulating polymers. Analytical Chemistry. 75(18), 4859–4867. DOI: https://doi.org/10.1021/ac034275j

[5] Diaz, A.F., Guay, J., 1993. Contact charging of organic materials: ion vs. electron transfer. IBM Journal of Research and Development. 37(2), 249–260.

[6] Yun, B.K., Kim, H.S., Ko, Y.J., et al., 2017. Interdigital electrode based triboelectric nanogenerator for effective energy harvesting from water. Nano Energy. 36, 233–240. DOI: https://doi.org/10.1016/j.nanoen.2017.04.048

[7] Horn, R.G., Smith, D.T., 1992. Contact electrification and adhesion between dissimilar materials. Science. 256(5055), 362–364.

[8] Fan, F.R., Tian, Z.Q., Wang, Z.L., 2012. Flexible triboelectric generator. Nano Energy. 1(2), 328–334. DOI: https://doi.org/10.1016/j.nanoen.2012.01.004

[9] Fan, F.R., Lin, L., Zhu, G., et al., 2012. Transparent triboelectric nanogenerators and self-powered pressure sensors based on micropatterned plastic films. Nano Letters. 12(6), 3109–3114. DOI: https://doi.org/10.1021/nl300988z

[10] Feng, Y., Zhang, L., Zheng, Y., et al., 2019. Leaves based triboelectric nanogenerator (TENG) and TENG tree for wind energy harvesting. Nano Energy. 55, 260–268. DOI: https://doi.org/10.1016/j.nanoen.2018.10.075

[11] Jeon, J.J., Cheedarala, R.K., Kee, C.D., et al., 2013. Dry-type artificial muscles based on pendent sulfonated chitosan and functionalized graphene oxide for greatly enhanced ionic interactions and mechanical stiffness. Advanced Functional Materials. 23(48), 6007–6018. DOI: https://doi.org/10.1002/adfm.201203550

[12] Wang, S., Lin, L., Wang, Z.L., 2012. Nanoscale triboelectric-effect enabled energy conversion for sustainably powering portable electronics. Nano Letters. 12(12), 6339–6346. DOI: https://doi.org/10.1021/nl303573d

[13] Luo, J., Fan, F.R., Zhou, T., et al., 2015. Ultrasensitive self-powered pressure sensing system. Extreme Mechanics Letters. 2, 28–36. DOI: https://doi.org/10.1016/j.eml.2015.01.008

[14] Zhong, J., Zhong, Q., Fan, F., et al., 2013. Finger typing driven triboelectric nanogenerator and its use for instantaneously lighting up LEDs. Nano Energy. 2(4), 491–497. DOI: https://doi.org/10.1016/j.nanoen.2012.11.015

[15] Zhu, G., Pan, C., Guo, W., et al., 2012. Triboelectric-generator-driven pulse electrodeposition for micropatterning. Nano Letters. 12(9), 4960–4965. DOI: https://doi.org/10.1021/nl302560k

[16] Chen, J., Huang, Y., Zhang, N., et al., 2016. Micro-cable structured textile for simultaneously harvesting solar and mechanical energy. Nature Energy. 1(10), 16138. DOI: https://doi.org/10.1038/nenergy.2016.138

[17] Khan, U., Kim, S.W. 2016. Triboelectric nanogenerators for blue energy harvesting. ACS Nano. 15(7), 10(7), 6429–6432. DOI: https://doi.org/10.1021/acsnano.6b04213

[18] Wang, Z.L., 2020. Triboelectric nanogenerators as new energy technology and self-powered sensors—principles, problems, and perspectives. Faraday Discussions. 176, 447–458. DOI: https://doi.org/10.1039/C4FD00159A

[19] Yang, Y., Zhang, H., Lin, Z.H., et al., 2013. Human skin based triboelectric nanogenerators for harvesting biomechanical energy and as self-powered active tactile sensor systems. ACS Nano. 7(10), 9213–9222. DOI: https://doi.org/10.1021/nn403838y

[20] Seung, W., Gupta, M.K., Lee, K.Y., et al., 2017. Nanopatterned textile-based wearable triboelectric nanogenerator. ACS Nano. 11(9), 8830–8837. DOI: https://doi.org/10.1021/acsnano.7b02975

[21] Wu, C., Wang, A.C., Ding, W., et al., 2019. Triboelectric nanogenerator: a foundation of the energy for the new era. Advanced Energy Materials. 9(1), 1802906. DOI: https://doi.org/10.1002/aenm.201802906

[22] Zhu, G., Lin, Z.H., Jing, Q., et al., 2013. Toward large-scale energy harvesting by a nanoparticle-enhanced triboelectric nanogenerator. Nano Letters. 13(2), 847–853. DOI: https://doi.org/10.1021/nl4001053

[23] Nafari, A., Sodano, H.A., 2017. Surface morphology effects in a vibration based triboelectric energy harvester. Smart Materials and Structures. 27(1), 015029.

[24] Cheedarala, R.K., Song, J.I., 2020. Sand-polished Kapton film and aluminum as source of electron transfer triboelectric nanogenerator through vertical contact separation mode. International Journal of Smart and Nano Materials. 11(1), 38–46. DOI: https://doi.org/10.1080/19475411.2020.1727991

[25] Gomes, A., Rodrigues, C., Pereira, A.M., et al., 2018. Influence of thickness and contact area on the performance of PDMS-based triboelectric nanogenerators. arXiv:1803.10070v1. DOI: https://doi.org/10.48550/arXiv.1803.10070

[26] Chen, H., Xu, Y., Zhang, J., et al., 2018. Theoretical system of contact-mode triboelectric nanogenerators for high-energy conversion efficiency. Nanoscale Research Letters. 13(1), 346. DOI: https://doi.org/10.1186/s11671-018-2764-2

[27] Sharma, A., Agarwal, P., 2018. Impact of rough surface morphology of diluted polydimethylsiloxane (PDMS) polymer film on triboelectric energy harvester performance. In Proceedings of the 2018 International Conference on Sustainable Energy, Electronics, and Computing Systems (SEEMS), Greater Noida, India, 26–27 October 2018; pp. 1–4.

[28] Sharma, A., Agarwal, P., 2020. Performance enhancement of the triboelectric energy harvester by forming rough surface polymer film using poly-dimethyl-siloxane (PDMS) +25 wt% water solution. International Journal of Digital Signals and Smart Systems. 4(1–3), 40–49.