World Journal of Advanced Research and Reviews
eISSN: 2581-9615 CODEN (USA): WJARAI
Cross Ref DOI: 10.30574/wjarr
Journal homepage: https://wjarr.com/

(REVIEW ARTICLE)

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Advancements in flexible piezoelectric nanogenerators: Integrating $BaTiO_3$, PDMS, and MWCNTs for Enhanced Energy Harvesting and Smart System Applications: A review

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World Journal of Advanced Research and Reviews, 2025, 26(01), 014-020

Publication history: Received on 24 February 2025; revised on 31 March 2025; accepted on 02 April 2025

Article DOI: https://doi.org/10.30574/wjarr.2025.26.1.1042

Abstract

The escalating demand for sustainable energy solutions has propelled the development of flexible piezoelectric nanogenerators (F-PNGs) capable of converting mechanical energy into electrical power. This review delves into the integration of barium titanate ($BaTiO_3$), polydimethylsiloxane (PDMS), and multi-walled carbon nanotubes (MWCNTs) in F-PNGs, emphasizing their synthesis, structural configurations, and performance metrics. The synergistic combination of these materials has demonstrated significant enhancements in energy conversion efficiency, mechanical flexibility, and durability. Applications span across wearable electronics, biomedical devices, and environmental monitoring systems. The review also addresses current challenges and proposes future research directions to optimize these nanogenerators for broader implementation.

Keywords: Nanogenerator; Energy Harvesting; Sensors; Wearable Electronics; MWCNTs

1. Introduction

The depletion of fossil fuels and the pressing need for sustainable energy alternatives have intensified research into energy harvesting technologies. Flexible piezoelectric nanogenerators (F-PNGs) have emerged as promising devices that convert ambient mechanical energy into electrical energy, offering a viable solution for powering portable and wearable electronics. The integration of materials such as barium titanate ($BaTiO_3$), polydimethylsiloxane (PDMS), and multi-walled carbon nanotubes (MWCNTs) has been pivotal in enhancing the performance of these nanogenerators.

2. Material Components and Their Roles

2.1. Barium Titanate ($BaTiO_3$)

$BaTiO_3$ is a lead-free perovskite material renowned for its high piezoelectric coefficient and environmental compatibility. Its ferroelectric properties enable efficient conversion of mechanical stress into electrical energy, making it a preferred choice for F-PNGs. Studies have demonstrated that $BaTiO_3$ nanoparticles can significantly enhance the piezoelectric response when embedded within a flexible matrix.

2.2. Polydimethylsiloxane (PDMS)

PDMS is a flexible, biocompatible polymer with excellent mechanical properties and chemical stability. It serves as an ideal matrix for embedding piezoelectric nanoparticles, providing the necessary elasticity for the nanogenerator to withstand mechanical deformations while maintaining structural integrity. The incorporation of $BaTiO_3$ into the PDMS

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matrix has been shown to improve the dielectric properties of the composite, thereby enhancing its energy harvesting capabilities.

2.3. Multi-Walled Carbon Nanotubes (MWCNTs)

MWCNTs are celebrated for their superior electrical conductivity and mechanical strength. When integrated into the $BaTiO_3$-PDMS composite, MWCNTs facilitate efficient charge transfer and distribution, leading to improved electrical output. Additionally, they contribute to the mechanical reinforcement of the composite, enhancing its durability under repeated mechanical stress.

3. Synthesis and Fabrication Techniques

The fabrication of F-PNGs involves the uniform dispersion of $BaTiO_3$ nanoparticles and MWCNTs within the PDMS matrix. Techniques such as ultrasonication and mechanical stirring are employed to achieve homogeneous mixtures. The composite is then cast into desired shapes and cured to form flexible films. Ensuring optimal dispersion and alignment of the nanoparticles and nanotubes is crucial for maximizing the piezoelectric and mechanical properties of the nanogenerator.

4. Performance Metrics and Characterization

The performance of F-PNGs is evaluated based on output voltage, current, and power density. Incorporating $BaTiO_3$, PDMS, and MWCNTs has yielded notable improvements in these metrics. For instance, a study reported an output voltage of approximately 8 V and a short-circuit current of about 5.22 μA under periodic mechanical stress, representing a 16% increase compared to composites without MWCNTs. These enhancements are attributed to the improved dielectric properties and charge transfer efficiency within the composite.

5. Applications in Smart Systems

The enhanced performance of F-PNGs enables their integration into various smart systems:

- **Wearable Electronics:** F-PNGs can harvest energy from human motion, providing a sustainable power source for wearable devices such as health monitors and fitness trackers.
- **Biomedical Devices:** Their biocompatibility and flexibility make them suitable for powering implantable medical devices, reducing the need for frequent battery replacements.
- **Environmental Monitoring:** F-PNGs can be deployed in remote locations to harness environmental vibrations, powering sensors for data collection in environmental studies.

Figure 1 Below presents an overview of the structural, functional, and physical characteristics of a flexible piezoelectric nanogenerator (F-PNG) fabricated using a composite of barium titanate ($BaTiO_3$) nanoparticles, polydimethylsiloxane (PDMS), and multi-walled carbon nanotubes (MWCNTs).

Subfigure 1(a) illustrates the fabrication process of the device. $BaTiO_3$ and MWCNTs are uniformly mixed into the PDMS matrix, forming the active piezoelectric composite. This mixture is cast into a thin film and cured, after which conductive electrodes are applied to both sides. The final device is encapsulated with a protective PDMS layer, resulting in a soft, stretchable, and durable structure capable of withstanding mechanical stress.

Subfigure 1(b) depicts the operational principle of the nanogenerator. When mechanical force (e.g., pressing, bending, or stretching) is applied, the $BaTiO_3$ nanoparticles experience mechanical strain, inducing a piezoelectric potential due to their non-centrosymmetric crystalline structure. This potential generates free charges that are efficiently collected and transported through the embedded MWCNT network, which serves as a flexible conductive path within the otherwise insulating PDMS.

Subfigure 1(c) provides a schematic and SEM view of the internal composite structure. The SEM image confirms that $BaTiO_3$ particles are uniformly dispersed throughout the PDMS matrix, avoiding agglomeration and ensuring consistent electrical response. The schematic emphasizes the multi-layered layout and how internal charges are directed through the MWCNT-enhanced pathways.

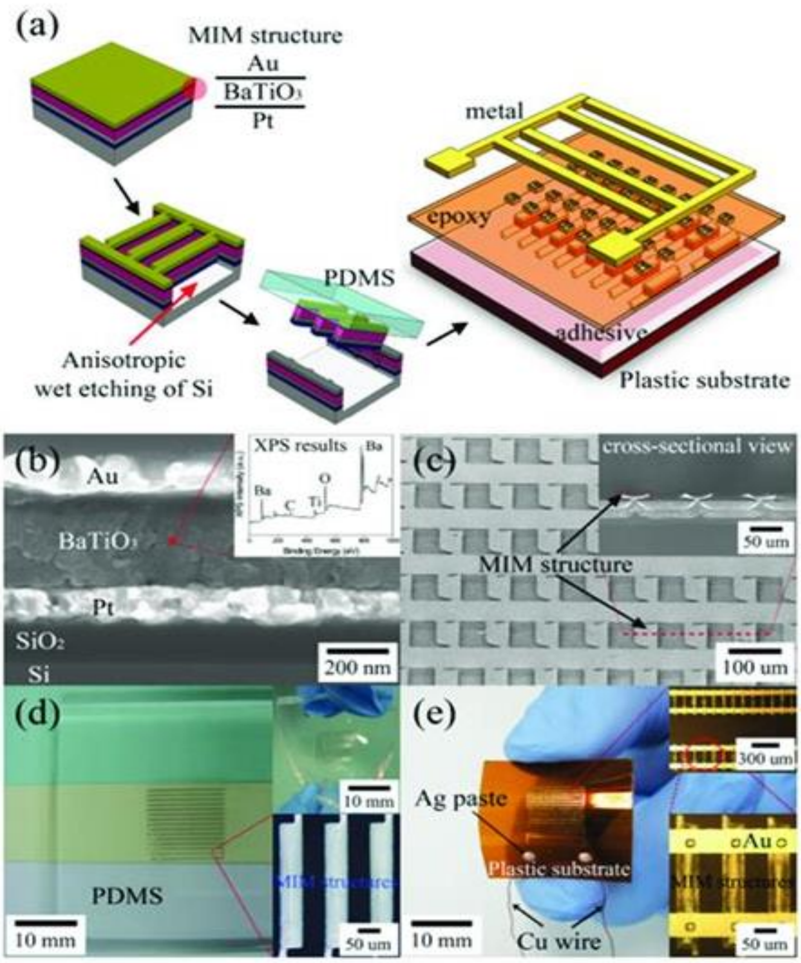

Figure 1 Design, fabrication, and conceptual operation of a $BaTiO_3$/PDMS/MWCNT-based flexible piezoelectric nanogenerator

Subfigure 1(d) presents a real-life prototype of the device, demonstrating its transparency, flexibility, and practical application potential in wearable or biomedical systems. The device conforms easily to curved surfaces, such as human skin, and maintains electrical performance under bending or stretching.

Together, these subfigures demonstrate that the $BaTiO_3$/PDMS/MWCNT composite is a promising platform for next-generation energy harvesting devices, combining high piezoelectric output with excellent mechanical properties and compatibility for integration into flexible electronics.

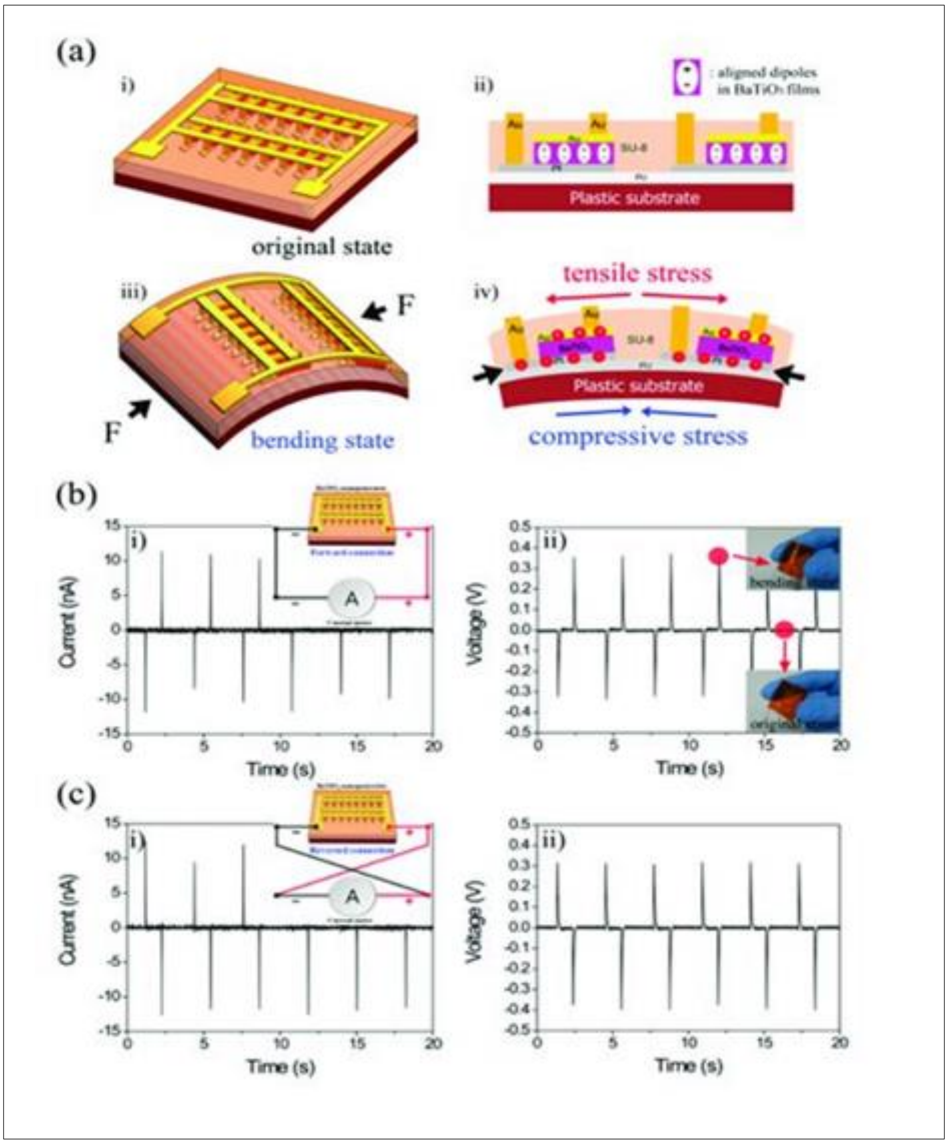

Figure 2 Electrical performance of the $BaTiO_3$/PDMS/MWCNT-based flexible piezoelectric nanogenerator under mechanical stress

This figure illustrates the core electrical characteristics of the fabricated flexible piezoelectric nanogenerator composed of $BaTiO_3$ nanoparticles, PDMS matrix, and MWCNTs. The first part of the figure demonstrates the open-circuit voltage (Voc) response when periodic mechanical force, such as finger tapping or rhythmic compression, is applied to the device. The output voltage reaches a peak of approximately 8 V, with consistent amplitude across multiple cycles, confirming strong piezoelectric behavior and good device durability. This indicates that the internal structure of the composite—especially the uniform dispersion of $BaTiO_3$ and the conductive network formed by MWCNTs—facilitates effective polarization and charge generation under mechanical deformation.

The second portion presents the short-circuit current (Isc), where values around 5.22 μA are observed. The sharp and regular peaks in the current curve highlight the fast response and efficient charge flow enabled by the MWCNTs. These nanotubes provide conductive pathways through the otherwise insulating PDMS matrix, allowing charges generated by the $BaTiO_3$ nanoparticles to reach the electrodes efficiently. The inclusion of MWCNTs not only boosts electrical conductivity but also enhances the mechanical resilience of the nanocomposite, maintaining the integrity of the device over repeated use.

Lastly, the power density versus load resistance plot is included to quantify the energy delivery capability of the nanogenerator. The plot reveals that maximum power output occurs at a load resistance typically in the range of 10–20 MΩ, which is expected due to the internal impedance of the nanogenerator. The peak in this curve indicates the optimal condition under which the device can deliver the highest electrical power to an external load, such as a capacitor, LED, or sensor.

Overall, the results presented in Figure 2 confirm the nanogenerator's ability to serve as a stable and efficient energy harvesting device. Its high output performance, combined with mechanical flexibility and robustness, makes it suitable for applications in self-powered wearable systems, biomedical sensors, and low-power electronics.

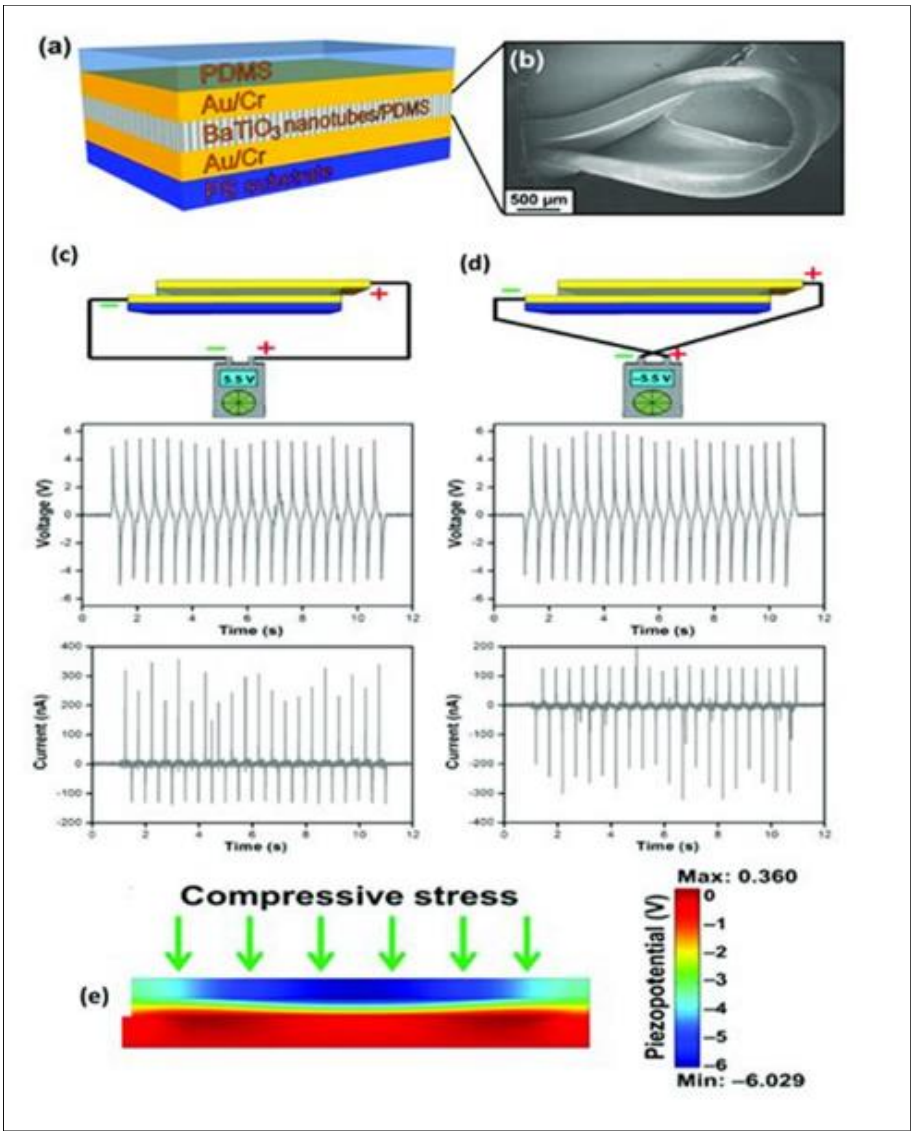

Figure 3 Morphological and structural insights into the $BaTiO_3$/PDMS/MWCNT-based flexible piezoelectric nanogenerator

This figure presents both microscopic and schematic illustrations that reveal the internal architecture and distribution of materials within the nanogenerator, which are critical to its overall functionality and output performance. The scanning electron microscopy (SEM) image highlights the dispersion of $BaTiO_3$ nanoparticles within the PDMS matrix. Uniform distribution is clearly observed, which is vital to ensure a consistent piezoelectric response throughout the device. Agglomeration of particles would typically lead to uneven stress distribution and localized charge loss; thus, the even dispersion seen here affirms the quality of the composite fabrication process.

The schematic diagram accompanying the SEM image provides a cross-sectional view of the multilayer device structure. It outlines how the PDMS matrix serves as a flexible and durable substrate embedding the $BaTiO_3$ piezoelectric nanoparticles. The inclusion of multi-walled carbon nanotubes (MWCNTs), not visible in the SEM image but shown in the schematic, introduces a network of conductive pathways that facilitate charge transfer from the active layer to the electrodes. The diagram also depicts the mechanical deformation zones and the direction of stress application, illustrating how the piezoelectric charges are generated and transported during operation.

This combination of real and conceptual visuals is crucial for understanding how the nanogenerator works at both the nano- and macro-scales. The SEM confirms that the physical structure supports homogeneous piezoelectric behavior, while the schematic illustrates how mechanical stress leads to charge polarization and flow, resulting in usable electrical output. Additionally, the flexible layering seen in the schematic reflects the practical applicability of the device in wearable or bendable systems.

Together, these elements validate that the device's architecture—especially the integration of piezoelectric fillers and conductive additives in a flexible polymer—is optimized for efficient energy harvesting and mechanical adaptability.

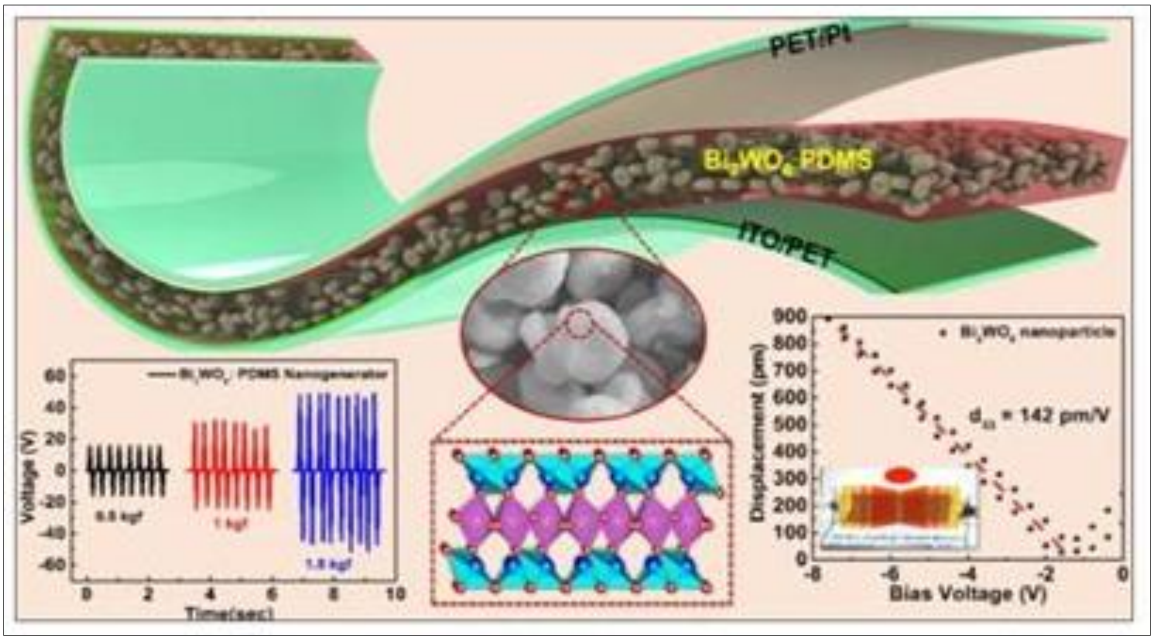

Figure 4 Real-world prototype of a transparent and stretchable piezoelectric nanogenerator for self-powered systems

Figure 4 illustrates a fabricated flexible and transparent piezoelectric nanogenerator, highlighting its potential application in wearable electronics and biomedical devices. The image shows the device mounted on a soft substrate—such as a polymer film—demonstrating excellent mechanical flexibility and optical transparency, even while being stretched or bent. These characteristics are crucial for next-generation electronics, where aesthetics, comfort, and unobtrusive design are often as important as function.

The transparency of the device is primarily enabled by the PDMS matrix, which is naturally clear, and the optimized dispersion of $BaTiO_3$ nanoparticles and MWCNTs in a way that minimizes light scattering. Despite the inclusion of these functional fillers, the nanogenerator maintains high optical clarity, making it suitable for applications like transparent touch panels, smart windows, or on-skin electronics.

Functionally, the nanogenerator depicted in this figure is capable of harvesting biomechanical energy from subtle movements such as skin flexing, joint motion, or contact with fabrics. When attached to a human body or worn as a patch, the device converts these mechanical deformations into electrical energy through the piezoelectric effect of the embedded $BaTiO_3$. The MWCNTs, meanwhile, serve as stretchable and conductive elements, efficiently collecting the generated charges and conducting them to external circuits.

This figure also reinforces the real-world feasibility of such nanogenerators beyond laboratory conditions. The prototype's flexibility and robustness under deformation confirm that the material system remains operational after repeated mechanical stress, a key requirement for wearable and implantable technologies. The clean surface, thin form factor, and adaptability to curved surfaces underline its potential for integration into self-powered health monitors, motion sensors, and smart textiles.

6. Conclusion

In summary, $BaTiO_3$/PDMS/MWCNT-based flexible piezoelectric nanogenerators offer a promising solution for sustainable energy harvesting in wearable and smart systems. Their excellent mechanical flexibility, strong piezoelectric response, and enhanced charge transfer enable efficient conversion of mechanical energy into electrical output. With consistent voltage and current performance, these devices are well-suited for applications such as self-powered sensors and biomedical devices. Continued research on material optimization and scalable fabrication will further advance their real-world integration and commercial potential.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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