

High-Performance Flexible Piezoelectric Nanogenerator for Next-Generation Wireless Healthcare Monitoring

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Abstract

Recent developments point to the efficacy of P(VDF-TrFE)/BaTiO₃ composites as means to improve functionality of piezoelectric nanogenerators (PENG). In this work we develop a flexible and efficient PENG based on a poly(vinylidene fluoride-trifluoroethylene) (P(VDF-TrFE)) and barium titanate (BaTiO₃) composite, designated PVTB composite nanofibers. The barium titanate matrix improves overall piezoelectric response due to high dielectric constant and spontaneous polarization properties of BaTiO₃, and P(VDF-TrFE) provides excellent flexibility and processability. The resultant PENG demonstrates significant promise for use in self-powered electronic systems, producing electrical energy from mechanical energy. The composite nanofiber has an open circuit voltage (V_{OC}) of 40 V and short circuit current (I_{SC}) of 20 μ A, yielding a power density of 1.8 W/m², indicating effective energy conversion performance under mechanical excitation. Finally, results show that nano engineering that enhances device sensitivity and durability opens new pathways towards the next generation of flexible, multifunctional energy scavenging devices for use in wireless healthcare monitoring of patients.

Keywords: *poly(vinylidene fluoride-trifluoroethylene)(P(VDF-TrFE)), barium titanate (BaTiO₃), piezoelectric Nanogenerator (PENG), Wireless healthcare monitoring, self-powered electronics*

1. Introduction

In recent times, the market for smart electronic devices that contain the Internet of Things (IoT) is growing rapidly. Such devices intrinsically depend on reliable and perpetual power supply for continuous usability. Common batteries are used, but they typically have limitations of frequent recharging/replacement and the presence of hazardous chemicals, such as lead, having detrimental effects on human health and the environment. One sustainable alternative to batteries is the use of PENGs, because they can harvest electrical energy from ambient mechanical vibrations. PENG mechanisms, which convert mechanical energy to electric energy, are widely studied in energy scavenging devices, sensors and actuators as they are a simple structure [1]. PENGs have garnered wide interest for self-powered systems, specifically for biomedical and wearable systems. A significant number of studies relate to PENGs containing various piezoelectric materials, including ZnO, PZT, PVDF, and its co-polymers. Among such materials, PVDF and its co-polymers are particularly attractive candidates because they have advantages that include biocompatibility, flexibility, chemical stability and

low-cost [2]. Poly(vinylidene fluoride–trifluoroethylene) (P(VDF-TrFE)) is a ferroelectric copolymer with strong dielectrics and excellent breakdown strength and it exhibits, piezoelectric and ferroelectric behaviors [3]. Since they are biocompatible, the composites can be applied in advanced biomedical applications such as smart drug delivery systems and tissue engineering, opening up novel avenues. The ferroelectric copolymer, P(VDF-TrFE), shows remarkable piezoelectric properties in its β -phase. The piezoelectric properties of the P(VDF-TrFE) can be further enhanced by a simple strategy of electrospinning. This method is able to establish β -phase properties primarily through the means of mechanical stretch and electric poling. Further enhancement of performance is common with the addition of high dielectric material filler such as barium titanate (BaTiO_3).

Our continuing research investigates the P(VDF-TrFE) and BaTiO_3 nanoparticle incorporated composite as active and flexible materials that have improved dielectric and piezoelectric properties for potential applications in wearable sensors, energy scavenging devices, ultra-thin capacitors, and biomedical scaffolding along with their surface modifications, thin-film fabrication, and multi-functional integration into advanced electronic systems. The combination of the P(VDF-TrFE) and BaTiO_3 enhances the piezoelectric performance of the composite material and makes it a viable energy harvesting nanogenerator. Electrospinning mechanisms will help to improve the electrical performance of the piezoelectric materials through polymer chain alignment that is achieved through mechanical extension. At the same time, the electric field that is applied induces dipoles. The combined action largely increases the value of the piezoelectric coefficient. Hence, it improves the efficiency of energy conversion [4]. In this study, we fabricated barium titanate (BTO) incorporated poly(vinylidene fluoride-trifluoroethylene) [P(VDF-TrFE)] composite nanofibers using the electrospinning technique. The embedded composite nanofiber demonstrated V_{OC} of 40 volt and I_{SC} of $20\mu\text{A}$. This result indicates to a power density of approximately $1.8\text{W}/\text{m}^2$, clearly indicating an efficient energy conversion performance under mechanical excitation. Finally, the schematic of the proposed wireless healthcare system has been illustrated to demonstrate its overall architecture and functionality.

2. Experimental section

2.1. Materials

Materials used are poly(vinylidene fluoride-co-trifluoroethylene) (P(VDF-TrFE) (68/32) powder, Barium titanate (BaTiO_3)(BTO) powder and Ni-Cu coated polyester fabric electrodes.

2.2. Fabrication of P(VDF-TrFE)/BTO Composite nanofiber

The P(VDF-TrFE) solution was first prepared by mixing butan-2 one solvent and stirred for 4 hours at 60°C . Then 7% of BaTiO_3 powder was added and mixed using a sonicator for 90 minutes for homogeneous dispersion. After that solution was stirred again for 30 more minutes. This prepared solution was filled into syringe and is used in electrospinning machine. The flow rate was 1.2 ml/hour, and the nanofibers were collected on aluminium foil kept on rotating drum. The distance from the needle to the collector was 10cm. Finally, the nanofibers were dried at 60°C for 8hrs to remove leftover solvent. The pure P(VDF-TrFE) and P(VDF-TrFE)/BTO composite nanofibers are referred to as PVT nanofibers and PVTB composite nanofibers respectively.

3. Results and discussion

The SEM images of the as prepared pure PVT nanofibers and PVTB nano composite nanofiber showed a smooth surface and uniform thickness with no bead defects (Fig 1 a-b). The mean diameter for pure PVT and PVTB nano composite nanofiber was determined as 1051 nm and 451 nm respectively. The decrease in diameter of PVTB nanocomposite nanofibers in comparison to pure PVT nanofiber is due to the additional net charge coming from the BTO nanoparticles within the electrospinning the P(VDF-TrFE)/BTO solution enhancing the exerted force in the electrospinning jet and reducing the fiber diameter [5].

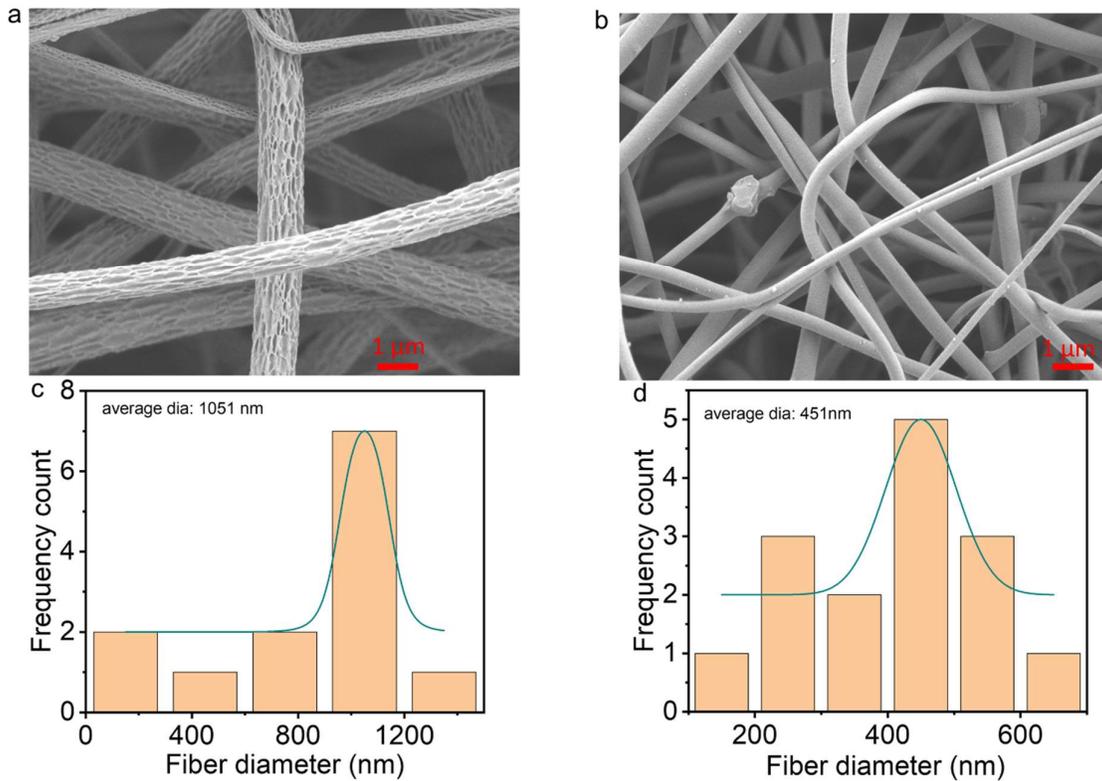


Figure 1: SEM image of (a) pure PVT nanofibers, (b) PVTB (7 wt%) composite nanofibers. Fiber diameter distribution of (c) pure PVT nanofibers, and (d) PVTB (7 wt%) composite nanofibers.

To investigate the role of materials in enhancing energy harvesting performance, piezoelectric nanogenerators were fabricated using PVTB composite nanofibers incorporated with 7 wt% BTO nanoparticles and compared with devices based on pure PVT nanofibers. The PVT-based PENG shows V_{OC} 14 V and I_{SC} 4.8 μ A, whereas the PVTB composite-based PENG exhibited significantly enhanced performance, delivering 40 V and 20 μ A, as illustrated in Fig. 2a. The pure nanofiber PVT based PENG generates V_{OC} of 14 V and I_{SC} of 4.8 μ A. In contrast, the composite nanofiber made of PVTB shows much better performance, with an output voltage of 40 V and a short-circuit current of 20 μ A. This reflects a 185% increase in voltage and a

316% increase in current, showing a significant improvement in PENG performance. The load voltage as a function of load resistance is presented in Figure 2c. The variation of power density with changing load resistance is also shown in the same figure.

Table 1. Comparison on power density of different nanofibers based PENGs.

Active material	Power density [$\mu\text{W}/\text{cm}^2$]	References
PVDF/GO NFs	0.62	[6]
GO/BaTiO ₃ /PVDF	0.65	[7]
Polydopamine modified BaTiO ₃ @P(VDF-TrFE) NFs	0.878	[8]
BT-P(VDF-TrFE) NFs	2.28	[9]
BT-PU/P(VDF-TrFE)	1.76	[10]
Pt-PVDF NFs	22	[11]
PEDOT PVDF NFs	8.5	[12]
P(VDF-TrFE)/BaTiO ₃	180	present work

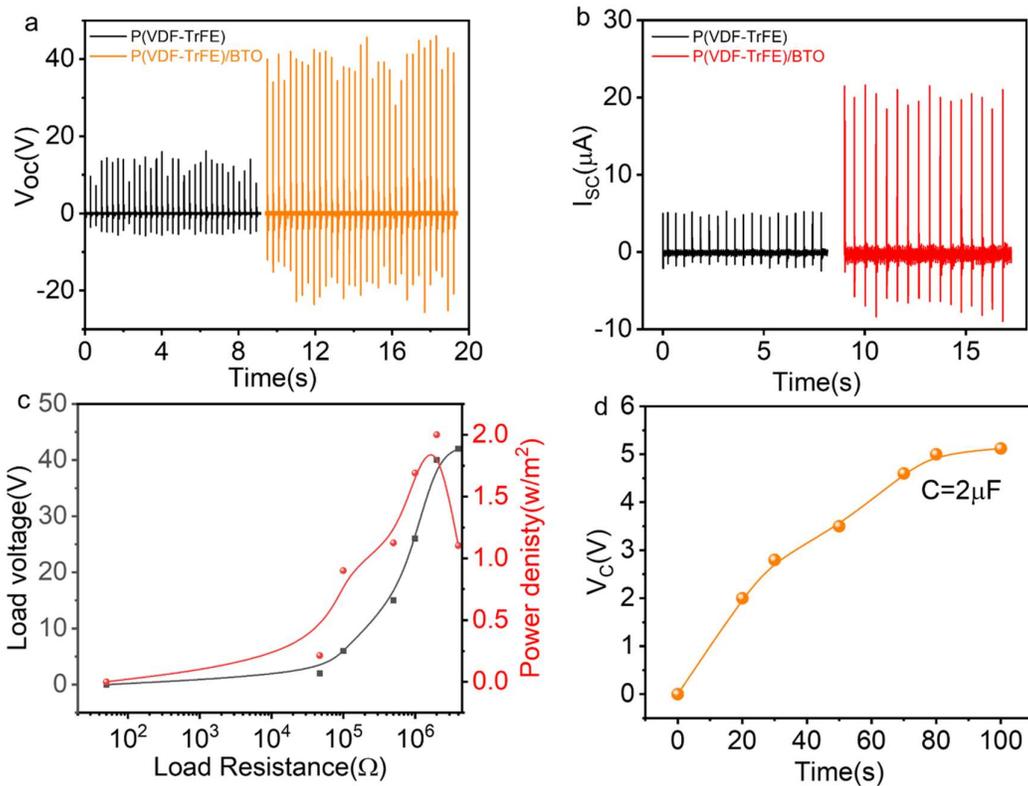


Figure 2: Energy harvesting performance study. (a) Open-circuit voltage comparison between pure PVT and PVTB composite nanofiber-based PENGs. (b) Short-circuit current comparison between pure PVT and PVTB composite nanofiber-based PENGs. (c) Load voltage and power

density of the PVTB composite nanofiber-based PENG as a function of load resistance. (d) Capacitor charging response of the PVTB composite nanofiber-based PENG.

The instantaneous power density was calculated using the equation: $P = \frac{V_L^2}{A.R_L}$, where A is the effective area and R_L is the load resistance. The calculated power density is 1.8 W/m². Table 1 presents the power density comparison of electrospun nanofiber-based piezoelectric nanogenerators. Among the materials compared, PVTB demonstrates the highest power density performance. The generated voltage from the PENG made from composite was stored in a commercial capacitor (C=2 μF) as shown in Figure 2d. The capacitor charged up to 5 V in 100 s. The energy stored in the capacitor was calculated using the equation $W = \frac{CV_s^2}{2}$, where C is the capacitance and V_s is the saturation voltage. The energy stored in the capacitor from composite PENG is calculated to be 25 μJ, emphasizing its potential for high-efficiency energy harvesting applications.

In addition to the energy harvesting performance study, the potential use of the composite PENG as a sensor for healthcare monitoring—particularly for infarct-related conditions—is proposed for future applications, as illustrated in Figure 3. The proposed wireless healthcare monitoring system combines a NodeMCU ESP8266A, a PENG sensor made of a PVTB composite, and a wearable display watch for real-time activity and health tracking. The PENG sensor uses the piezoelectric properties of P(VDF-TrFE) and the high dielectric constant of BaTiO₃ to efficiently convert biomechanical energy, like body movements or vibrations, into electrical signals. These signals transmit wirelessly to the NodeMCU ESP8266A, which serves as the central processing and communication unit. The microcontroller collects, processes, and sends health data via Wi-Fi to a connected wearable watch, where vital information such as motion intensity, step count, and alert notifications is displayed in real time. This setup allows for energy-autonomous, intelligent, and continuous monitoring, making it perfect for modern wearable healthcare solutions.

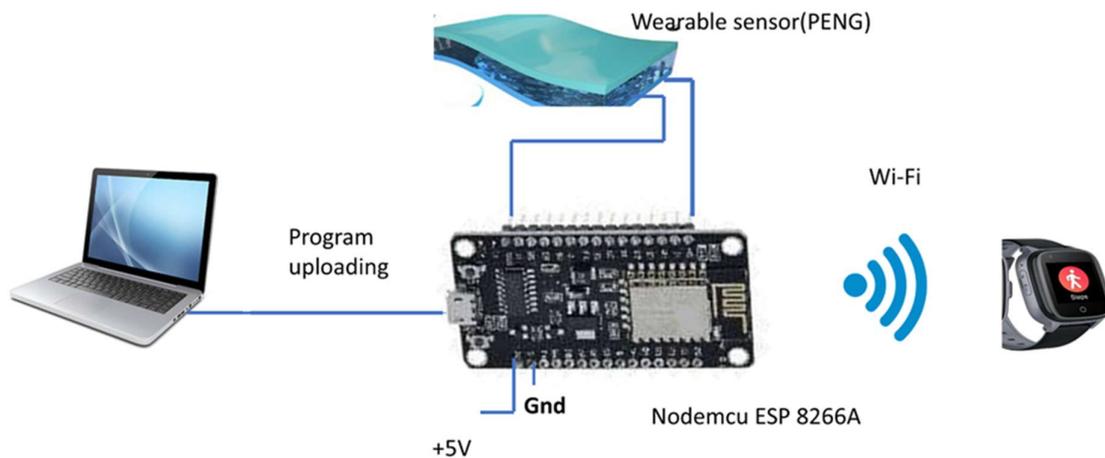


Figure 3: Schematic of proposed wireless healthcare system.

4. Conclusions

This study presents the enhanced performance of a PENG using composite nanofibers made from and BaTiO₃ nanoparticles. The PVT nanofiber generated an output voltage of 14 V and a short-circuit current of 4.8 μ A. By incorporating BaTiO₃ nanoparticles into the nanofiber structure, the output voltage increased to 40 V and the current to 20 μ A—corresponding to improvements of 185% and 316%, respectively. Additionally, the energy output significantly rose to 25 μ J in 2 μ F. These enhancements are attributed to the BaTiO₃ particles, which promote dipole alignment and improve the dielectric properties, thereby facilitating more efficient conversion between mechanical and electrical energy. Looking ahead, integrating this PENG with wireless modules could enable real-time data streaming, making it highly suitable for IoT and healthcare applications such as remote monitoring systems. In summary, the PVTB composite PENGs show great potential as compact, self-powered, and efficient energy harvesters, supporting the advancement of intelligent, mobile healthcare devices and untethered sensing solutions for the growing ecosystem of the Internet of Things.

Conflict of Interest

The authors declare no conflict of interest.

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