

Flexible Dual-Mode Piezoelectric-Triboelectric Sensor Based on BaTiO₃- Embedded PVDF-TrFE Composite for Wearable Applications

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Abstract. This work presents a flexible dual-mode piezoelectric-triboelectric sensor (FDPTS) designed for wearable applications, integrating a pure PVDF-TrFE piezoelectric layer with a BaTiO₃-embedded PVDF-TrFE triboelectric layer. The bilayer structure harnesses the complementary strengths of piezoelectric and triboelectric mechanisms to enhance sensitivity and broaden the sensing range for both static and dynamic stimuli. Fabricated via a simple solution-casting method and using graphene-coated PDMS electrodes, the sensor achieves natural signal integration without the need for complex circuitry. Surface and mechanical analysis confirmed that BaTiO₃ enhances dielectric properties, β -phase crystallinity, and flexibility. The optimized sensor demonstrated a peak voltage output of ~1,000 mV at 10N force and a sensitivity of 89.14 mV/N, Surpassing single-mode designs. Durability tests showed stable performance over 10,000 cycles, and consistent output across independently fabricated devices. Application in real-time grip pressure detection further validated its potential for wearable healthcare systems. This scalable and low-cost FDPTS offers a robust solution for next-generation smart sensing technologies.

Keywords: Flexible Dual-Mode Sensor; Piezoelectric-Triboelectric Effect; PVDF-TrFE; Barium Titanate (BaTiO₃); Self-Powered Sensing.

1. Introduction

The rising demand for intelligent, wearable, and self-powered electronics has significantly propelled the development of flexible sensor technologies[1]. These sensors are pivotal in enabling advanced applications such as real-time healthcare monitoring, human-machine interaction[2], soft robotics, and prosthetic feedback systems[3]. At the core of such systems are flexible pressure sensors capable of transducing mechanical stimuli into electrical signals often without the need for external power supplies[4].

Among various self-powered transduction mechanisms, piezoelectric and triboelectric effects have emerged as the two most promising due to their lightweight nature, compatibility with soft substrates, and potential for low-cost, scalable fabrication [5], [6]. Piezoelectric nanogenerators (PENGs) utilize ferroelectric materials whose dipole orientations reconfigure under mechanical strain, producing fast and stable electrical responses under dynamic loads[7], [8]. In contrast, triboelectric nanogenerators (TENGs) harness contact electrification between dissimilar materials, followed by electrostatic induction, allowing for higher voltage outputs particularly under quasi-static or low-pressure conditions[4], [9].

However, both transduction methods have intrinsic limitations. PENGs exhibit reduced performance under low-frequency or static stimuli, while TENGs are vulnerable to environmental influences such as humidity and surface contamination, which compromise signal consistency over time[9]. To address these challenges, hybrid or dual-mode sensors that integrate both mechanisms have been explored[4], [6], [10], [11]. Such systems combine the surface charge transfer and interfacial friction of triboelectric with the bulk dipole polarization of piezoelectric, leading to enhanced sensing resolution, broader frequency response, and superior power output[4], [6]. Yet,

many existing hybrid designs suffer from drawbacks including multilayer complexity, fabrication cost, and the need for signal decoupling circuitry factors that impede their practical integration into compact wearable platforms[12], [13].

In this study, a scalable, low-cost, and structurally simplified dual-mode flexible sensor featuring a bilayer design was presented. The sensor comprises a pure PVDF-TrFE piezoelectric layer and a BaTiO₃ nanoparticle-embedded PVDF-TrFE triboelectric layer, strategically combined to exploit the complementary advantages of each transduction mechanism. PVDF-TrFE is selected for its high electroactive β -phase content and mechanical flexibility[14], [15], while BaTiO₃ nanoparticles enhance the dielectric constant, surface roughness, and charge trapping critical attributes for triboelectric enhancement[16], [17], [18]. For electrodes, graphene-coated PDMS films are utilized to provide excellent mechanical compliance, charge mobility, and environmental robustness [19], [20].

This bilayer sensor design enables natural signal integration of piezoelectric and triboelectric outputs without the need for independent circuits or decoupling algorithms. Its complementary response to both dynamic and static pressures provide a versatile sensing platform for wearable and interactive electronics. To demonstrate its practical utility, a real-time grip pressure detection system was applied in this sensor, showcasing its relevance for smart wearable technologies and human-machine interaction.

2. Materials and Methods

2.1 Chemicals and Materials

P(VDF-TrFE), molar ratio 7:3, was purchased from Dongguan Jiaxin Plastic Raw Material Co., Ltd. 99.9% pure BaTiO₃ nanoparticles was purchased from Shanghai T-Micro Application Material Technology Co., Ltd. in China. Prefabricated 200 μ m PDMS films purchased from Shenzhen Songsen New Material Technology Co., Ltd. and liquid-phase graphene from Shenzhen Hongdachang Evolution Technology Co., Ltd. The solvent was analytical-grade dimethylacetamide. No compounds were purified before use.

2.2 Fabrication of the Piezoelectric and Triboelectric Layer

As illustrated in Fig. 1, 10 g of polymer was dissolved in 90 g of DMAc to make a 10 wt% P(VDF-TrFE) solution. The solution was magnetically agitated for 5h and ultrasonicated for 30 min to dissolve completely. To create the composite triboelectric layer, 0.4 g of BaTiO₃ nanoparticles were mixed with 19 g of the solution, resulting in a 48:1 polymer-to-filler mass ratio. Based on past investigations, a loading of $\sim$ 2 wt% was chosen for best β -phase improvement and dielectric performance in PVDF-based composites, avoiding agglomeration and mechanical degradation at larger filler contents ($>$ 4 wt%) The mixture was swirled for 4h and ultrasonicated for 30 min to disperse nanoparticles evenly.

The pure and composite solutions were cast onto clean glass substrates using a doctor-blade and dried at 70 °C for 5 h to eliminate solvent residues. To improve β -phase crystallization and piezoelectric characteristics, dry films were annealed at 90 °C for 1 hour. Optimization studies recommend annealing at 85-95 °C for optimal β -phase fraction of P(VDF-TrFE) (7:3), since greater durations may cause film shrinkage and offer no further benefit. The composite film is called Ba-Film.

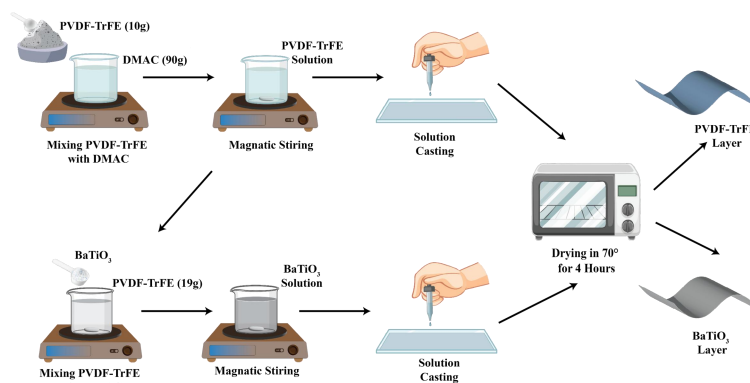


Fig. 1 PVDF-TrFE Composite and BaTiO₃ Preparation Process.

2.3 Preparation of Electrodes and Device Assembly

Fluid-phase graphene was uniformly coated on both sides of a 200 μm PDMS substrate to create electrode layers. The coatings were air-dried at room temperature for 4h to evaporate solvent and strengthen adhesion. As in Fig. 2(a) The bilayer sensor was built by laminating pure P(VDF-TrFE) and Ba-Film layers between graphene-coated PDMS electrodes, resulting in a 20 mm $\times$ 20 mm device area. Upper and lower electrodes had copper cables for signal collecting. The construction was encapsulated in PET tape for environmental stability and mechanical strength.

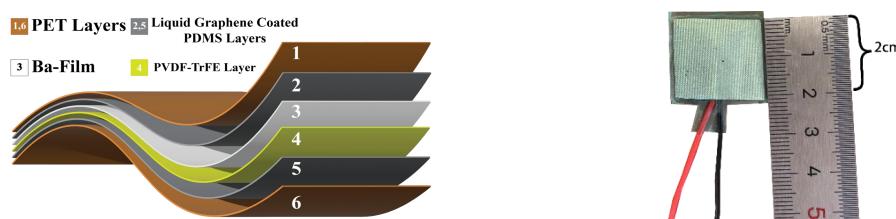


Fig. 2 (a) Layer Explanation Diagram of the Sensor. (b) Physical Diagram of the Sensor

2.4 Characterization

Scanning electron microscopy evaluated P(VDF-TrFE) and Ba-Film surface morphology. Canny edge detection in OpenCV quantified morphological edge contrast to qualitatively measure surface roughness variation. Tensile properties were tested using an ASTM D882-compliant Universal Testing Machine (UTM 4103, Shenzhen Sans Testing Machine Co., Ltd.) at a crosshead speed of 5 mm min⁻¹. Measurements were taken on five specimens (n=5) and given as mean $\pm$ standard deviation (< 5%). A unique vibration platform with a Model 25 MB Dynamics vibration exciter, a Hantek HDG2102B signal generator, and an MB500Y1 power amplifier evaluated electromechanical performance. A KISTLER 9712B50 force sensor monitored load, while a signal acquisition device (Jiangsu Donghua Test Technology Co., Ltd.) recorded voltage outputs in real time.

3. Results and Discussion

3.1 Microstructure and Surface Morphology

As illustrated in Fig. 3(a), the Ba-Film exhibits a rough, heterogeneous microstructure with visible ceramic particle inclusions. Such morphological complexity enhances interfacial polarization and charges trapping key contributors to improved triboelectric output[12], [17]. In contrast, the pure PVDF-TrFE piezoelectric layer shown in Fig. 3(b) presents a smoother, more uniform surface, indicating well-formed β -phase crystallinity ideal for stable piezoelectric behavior [7], [18].

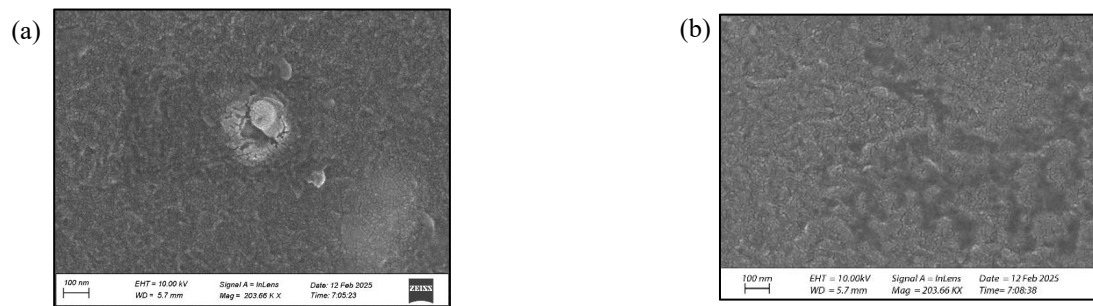


Fig. 3 (a) SEM Surface Morphology of Ba-Film (b) SEM Surface Morphology of pure PVDF-TrFE film

3.2 Working Mechanism of the FDPTS

To investigate the working principle of the proposed flexible dual-mode sensor, a customized structure was developed as shown in Fig. 4(a). The sensor consists of graphene-coated PDMS electrodes, a PVDF-TrFE piezoelectric layer, a PET insulation layer, and a Ba-Film, enabling simultaneous piezoelectric and triboelectric signal generation.

Fig. 4(b) illustrates the working mechanism of the sensor. In the idle state in Fig. 4(c), no deformation occurs, dipoles remain randomly oriented, and no output is generated. Upon compression in Fig. 4(c-f), the PVDF-TrFE layer produces a transient piezoelectric signal due to dipole realignment. Concurrently, the Ba-Film contacts the PDMS electrode, triggering charge transfer via triboelectric effect due to their differing electron affinities.

During release as shown in Fig. 4(f), the piezoelectric layer depolarizes, reversing the signal, while separation at the triboelectric interface induces electrostatic potential, driving current through the load. Once fully relaxed, the system returns to equilibrium, with residual triboelectric charges possibly remaining until neutralized.

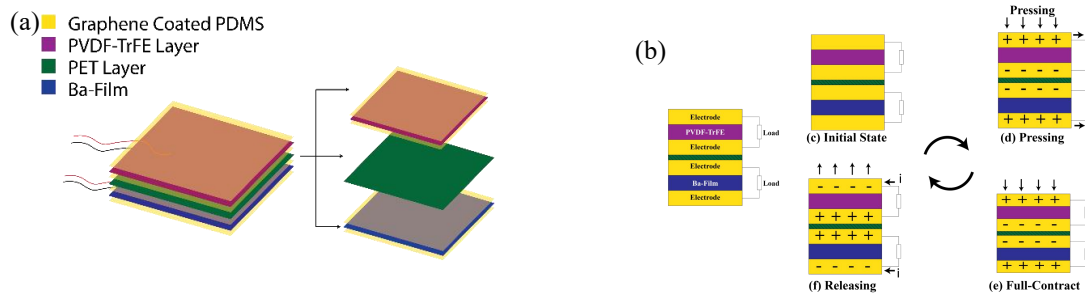


Fig. 4 (a) schematic structure of piezoelectric/triboelectric customized hybrid sensor (b)-(f) working mechanism of the sensor.

3.3 Output Performance of the FDPTS

Fig. 5(a) shows the experimental setup of the sensor, applied regulated cyclic stresses while recording the sensor's real-time voltage output. The 20×20 mm sensor was placed 2 cm from the vibration exciter's metal rod and monitored for voltage responses under different strains.

The dynamic piezoelectric performance was initially tested under a 5 N cyclic load at 1 Hz. As in Fig. 5(b), sensors with BaTiO₃ concentrations of 0.2 g (Sensor A), 0.4 g (Sensor B), and 0.6 g (Sensor C) showed peak output voltages of 185.7 mV, 395.4 mV, and 534.1 mV, Increased filler loading leads to better interfacial polarization and β -phase development, facilitated by well-dispersed BaTiO₃ nanoparticles [13], [18], [21]. Sensor C had the highest voltage response, but increases beyond 0.6 g caused particle agglomeration and flexibility loss in polymer-ceramic composites[22]. The optimal arrangement for flexible dual-mode sensing was Sensor C, which balances high electrical output with mechanical stability.

The study compared three device architectures: (i) PVDF-TrFE alone, (ii) BaTiO₃-embedded, and (iii) the suggested hybrid bilayer FDPTS. The vibration exciter applied forces from 0 to 10N, with each data point being the mean of ten samples. The corresponding results in Fig. 5(c) show a linear relationship between applied force and output voltage, described by

$$S = \frac{\Delta V}{\Delta F} \quad (1)$$

where ΔV is the change in output voltage and ΔF is the corresponding change in applied force. This relationship quantifies the sensor's ability to convert mechanical stimuli into electrical signals, emphasizing the reliability and consistency of the proposed hybrid sensor for practical force sensing applications. The sensitivity of the proposed structure (89.14 mV/N) significantly exceeds that of the other two structures, with sensitivities of 81.14 mV/N for Only PVDF-TrFE and 83.86 mV/N for Only BaTiO₃/PVDF-TrFE. This comparison clearly demonstrates that integrating the PVDF-TrFE layer with BaTiO₃ embedded PVDF-TrFE film substantially enhances the sensor's sensitivity.

In the comparative test, the size of films is 20 mm × 20 mm, and the frequency and amplitude of the input sinusoidal pressure were set to 2 Hz and 20 m/s², respectively. Two middle layers of electrodes and the upper and lower electrodes are used as negative and positive electrodes respectively. Fig 5 (d,e) indicates that when the films are pressed, the piezoelectric effect and the contact charging effect make electrons flow in the same direction. In this regard, Fig. 5(f,g) indicates that the peak output voltage of the sensor with a PVDF-TrFE film and Ba-Film approximately 150 mV and 620 mV, respectively. Then PVDF-TrFE and Ba-films are laminated together to provide a composite film. Fig. 5(h) illustrates the corresponding output voltage. It is observed that the peak value is 800 mV. The test results obtained reveal that the output voltage of the composite film is approximately the sum of the output voltages of the two films. It is concluded that piezoelectric and triboelectric effects can increase the output voltage of the sensor, thereby

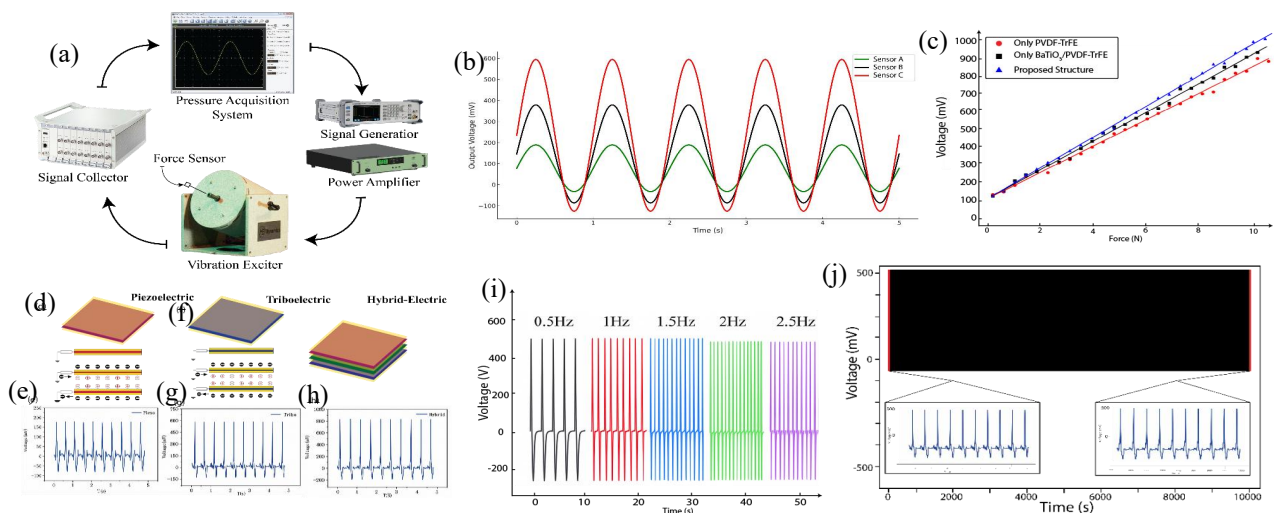


Fig. 5 (a) Diagram of the test platform. (b) Voltage output of sensors with different BaTiO₃ ratios in PVDF-TrFE. (c) Peak output voltage comparison of sensors with different structures. Schematic diagram of (d) electron transfer and (e) output voltage for the PVDF-TrFE film. Schematic diagram of (f) electron transfer and (g) output voltage for Ba-Film. Image (h) shows the output voltage for a hybrid structure. (i) Output voltage of the sensor under different frequencies of force. (j) The durability test of the sensor under a force cycle of 5 N.

improving the sensitivity.

3.4 Application Test

a real-time grip pressure detection system was developed by embedding two FDPTS units onto a wearable glove. The sensors were affixed to the index finger and thumb using PET tape, as

illustrated in Fig. 6(a), enabling simultaneous detection of pressure applied during grasping tasks. In the experimental procedure, three fruits peach, apple, and grape as shown Fig. 6(b) in were selected based on their varying sizes, surface textures, and required grip intensities. A volunteer wore the glove and held each fruit naturally, applying pressure with the index finger for approximately five seconds before releasing. The collected voltage signals revealed distinct patterns corresponding to each fruit. As shown in Fig. 6(c) the apple, being the largest and firmest, produced the highest index finger voltage peaks (~ 0.09 mV), indicative of a strong grip and dynamic pressure fluctuations. The peach generated moderately high peaks (~ 0.065 mV) with a smoother waveform as shown in Fig. 6(d), reflecting a medium grip and enhanced sensor contact due to its soft, textured skin. In contrast, the grape being small and delicate resulted in the lowest peaks (~ 0.035 mV index, ~ 0.01 mV thumb) as depicted in Fig. 6(e), consistent with a gentle grip and low force application. These findings

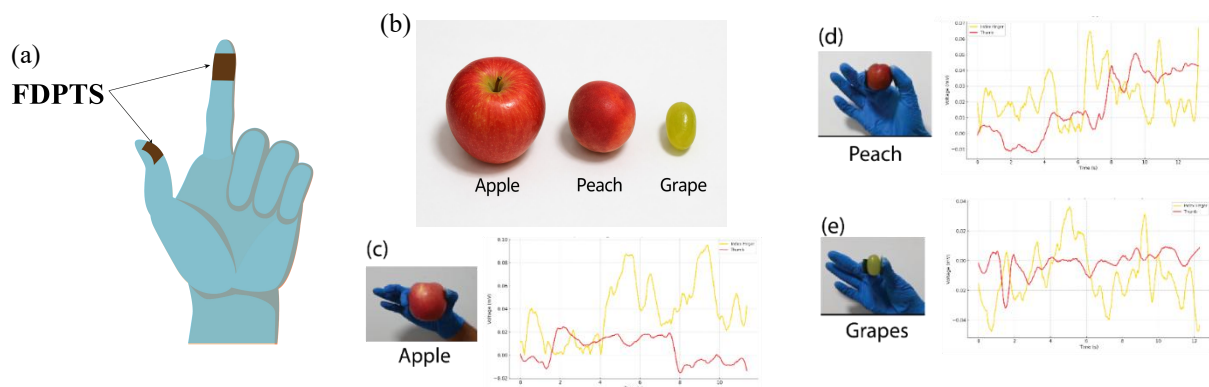


Fig. 6 a) FDPTS placement on Thumb and Index fingers. (b) Different kinds of fruits for testing. Output Waveforms of the Thumb and Index Finger While Pressing the (c) Apple, (d) Peach, (e) Grape.

confirm that the FDPTS can accurately distinguish varying grip intensities and dynamic force interactions. This application highlights the sensor's practical relevance for wearable electronics, particularly in fields such as rehabilitation monitoring, prosthetic feedback, robotic manipulation, and human-machine interfaces. By enabling precise and real-time pressure detection, the FDPTS-based glove system provides a foundation for next-generation tactile feedback and interactive control in smart wearable devices.

4. Summary

In this work, a flexible dual-mode piezoelectric-triboelectric sensor (FDPTS) based on a BaTiO_3 -embedded PVDF-TrFE composite was successfully designed and fabricated to achieve high sensitivity and stability for wearable sensing applications. The optimized composite structure, comprising a pure PVDF-TrFE piezoelectric layer and a BaTiO_3 -doped PVDF-TrFE triboelectric layer, effectively couples the advantages of both transduction mechanisms within a simple bilayer configuration. The addition of BaTiO_3 nanoparticles enhanced dielectric polarization, β -phase crystallinity, and interfacial charge trapping, yielding a maximum output voltage of $\sim 1,000$ mV under a 10N load, a sensitivity of 89.14 mV N^{-1} , and excellent durability over 10,000 loading cycles. Application testing using a glove-based system verified the FDPTS's ability to distinguish subtle variations in grip pressure and dynamic tactile interactions, underscoring its promise for wearable electronics, prosthetic feedback, and human-machine interfaces. Overall, the proposed FDPTS demonstrates a scalable, low-cost, and reliable approach to self-powered sensing, providing a versatile platform for next-generation intelligent tactile and health-monitoring systems.

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6. References

- [1] Z. Wang, V. Waga Arachchi, C. Alahakoon, and S. Hasnat Sayem, "A Flexible Dual-Mode Piezoelectric-Piezoresistive Sensor Based on MXene/PVDF-TrFE Hybrid Film," *IEEE Sensors J.*, vol. 25, no. 12, pp. 21141-21150, Jun. 2025, doi: 10.1109/JSEN.2025.3567589.
- [2] ZHONG J, MA Y, and SONG Y, "A Flexible Piezoelectret Actuator/Sensor Patch for Mechanical HumanMachine Interfaces," *ACS Nano*, vol. 13, no. 6, pp. 7107-7116, 2019, doi: 10.1021/acsnano.9b02437.
- [3] ZHU M, SUN Z, and ZHANG Z, "A P P L I E D S C I E N C E S A N D E N G I N E E R I N G Haptic-feedback smart glove as a creative human-machine interface (HMI) for virtual/augmented reality applications," 2020. [Online]. Available: <http://advances.sciencemag.org/>
- [4] Z. Han, P. Jiao, and Z. Zhu, "Combination of Piezoelectric and Triboelectric Devices for Robotic Self-Powered Sensors," *Micromachines*, vol. 12, no. 7, p. 813, Jul. 2021, doi: 10.3390/mi12070813.
- [5] G. Suo et al., "Piezoelectric and Triboelectric Dual Effects in Mechanical-Energy Harvesting Using BaTiO₃ /Polydimethylsiloxane Composite Film," *ACS Appl. Mater. Interfaces*, vol. 8, no. 50, pp. 34335-34341, Dec. 2016, doi: 10.1021/acsami.6b11108.
- [6] S. Sriphan and N. Vittayakorn, "Hybrid piezoelectric-triboelectric nanogenerators for flexible electronics: Recent advances and perspectives," *Journal of Science: Advanced Materials and Devices*, vol. 7, no. 3, p. 100461, Sep. 2022, doi: 10.1016/j.jsamd.2022.100461.
- [7] G. G. Genchi et al., "P(VDF-TrFE)/BaTiO₃ Nanoparticle Composite Films Mediate Piezoelectric Stimulation and Promote Differentiation of SH-SY5Y Neuroblastoma Cells," *Adv Healthcare Materials*, vol. 5, no. 14, pp. 1808-1820, Jul. 2016, doi: 10.1002/adhm.201600245.
- [8] X. Chen et al., "High-Performance Piezoelectric Nanogenerators with Imprinted P(VDF-TrFE)/BaTiO₃ Nanocomposite Micropillars for Self-Powered Flexible Sensors," *Small*, vol. 13, no. 23, p. 1604245, Jun. 2017, doi: 10.1002/smll.201604245.
- [9] Z. Wang, Y. Yang, N. Li, T. Yao, and J. An, "Octopus-shaped self-powered motion sensor based on the triboelectric and piezoelectric effect," *Materials Technology*, vol. 37, no. 12, pp. 2001-2010, Oct. 2022, doi: 10.1080/10667857.2021.1885227.
- [10] M. Pan, C. Yuan, X. Liang, J. Zou, Y. Zhang, and C. Bowen, "Triboelectric and Piezoelectric Nanogenerators for Future Soft Robots and Machines," *iScience*, vol. 23, no. 11, p. 101682, Nov. 2020, doi: 10.1016/j.isci.2020.101682.
- [11] A. Khan et al., "Piezoelectric and triboelectric nanogenerators: Promising technologies for self-powered implantable biomedical devices," *Nano Energy*, vol. 119, p. 109051, Jan. 2024, doi: 10.1016/j.nanoen.2023.109051.
- [12] [Y. Yang et al., "Flexible piezoelectric pressure sensor based on polydopamine-modified BaTiO₃/PVDF composite film for human motion monitoring," *Sensors and Actuators A: Physical*, vol. 301, p. 111789, Jan. 2020, doi: 10.1016/j.sna.2019.111789.
- [13] D. Khare, B. Basu, and A. K. Dubey, "Electrical stimulation and piezoelectric biomaterials for bone tissue engineering applications," *Biomaterials*, vol. 258, p. 120280, Nov. 2020, doi: 10.1016/j.biomaterials.2020.120280.
- [14] AHMED A, KHOSO N A, and ARAIN M F, "Development of Highly Flexible Piezoelectric PVDF-TRFE/Reduced Graphene Oxide Doped Electrospun Nano-Fibers for Self-Powered Pressure Sensor," *Polymers*, vol. 16, no. 13, 2024, doi: 10.3390/polym16131781.
- [15] V. Bhavanasi, V. Kumar, K. Parida, J. Wang, and P. S. Lee, "Enhanced Piezoelectric Energy Harvesting Performance of Flexible PVDF-TrFE Bilayer Films with Graphene Oxide," *ACS Appl. Mater. Interfaces*, vol. 8, no. 1, pp. 521-529, Jan. 2016, doi: 10.1021/acsami.5b09502.
- [16] K. Shi, X. Huang, B. Sun, Z. Wu, J. He, and P. Jiang, "Cellulose/BaTiO₃ aerogel paper based flexible piezoelectric nanogenerators and the electric coupling with triboelectricity," *Nano Energy*, vol. 57, pp. 450-458, Mar. 2019, doi: 10.1016/j.nanoen.2018.12.076.
- [17] H. Si et al., "Size effects of polydopamine-coated BaTiO₃ nanoparticles on the piezoelectric performance of P(VDF-TrFE)/BaTiO₃ composite," *Journal of Materiomics*, vol. 10, no. 4, pp. 857-869, Jul. 2024, doi: 10.1016/j.jmat.2023.10.006.

- [18] K. Sobolev et al., "Effect of Piezoelectric BaTiO₃ Filler on Mechanical and Magnetoelectric Properties of Zn_{0.25}Co_{0.75}Fe₂O₄/PVDF-TrFE Composites," *Polymers*, vol. 14, no. 22, p. 4807, Nov. 2022, doi: 10.3390/polym14224807.
- [19] M. Parmeggiani et al., "PDMS/Polyimide Composite as an Elastomeric Substrate for Multifunctional Laser-Induced Graphene Electrodes," *ACS Appl. Mater. Interfaces*, vol. 11, no. 36, pp. 33221-33230, Sep. 2019, doi: 10.1021/acsami.9b10408.
- [20] J. Yang et al., "Facile Fabrication of Robust and Reusable PDMS Supported Graphene Dry Electrodes for Wearable Electrocardiogram Monitoring," *Adv Materials Technologies*, vol. 6, no. 9, p. 2100262, Sep. 2021, doi: 10.1002/admt.202100262.
- [21] K. Lau, Y. Liu, H. Chen, and R. L. Withers, "Effect of Annealing Temperature on the Morphology and Piezoresponse Characterisation of Poly(vinylidene fluoride-trifluoroethylene) Films via Scanning Probe Microscopy," *Advances in Condensed Matter Physics*, vol. 2013, pp. 1-5, 2013, doi: 10.1155/2013/435938.
- [22] P. Panpho, T. Charoonsuk, N. Vittayakorn, T. Bongkarn, and R. Sumang, "Flexible hybrid piezo/triboelectric energy harvester based on a lead-free BNT-BT-KNN ceramic-polymer composite film," *Ceramics International*, vol. 50, no. 23, Part C, pp. 52041-52050, Dec. 2024, doi: 10.1016/j.ceramint.2024.03.208.