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Performance Enhancement of Piezoelectric Nanomaterials for Intelligent Sensing and Their Electronic Signal Processing Solutions

Zihan Zhou [1,*]

[1] School of Physical Sciences/ Department of Physics and Astronomy, University of California, Irvine, California, 92617, United States

* Correspondence: Zihan Zhou, School of Physical Sciences/ Department of Physics and Astronomy, University of California, Irvine, California, 92617, United States

Abstract: Piezoelectric nanomaterials, such as ZnO and PZT nanowires, are widely used in flexible electronics, health monitoring, and IoT sensors due to their ability to convert mechanical energy into electrical signals. However, challenges remain in optimizing their piezoelectric performance and improving signal processing for real-world applications. While significant progress has been made in material enhancement and signal processing, there is a lack of comprehensive integration between these two approaches, limiting the performance of piezoelectric sensors in dynamic environments. This study investigates the impact of material enhancements (doping and structural optimization) on the piezoelectric properties of ZnO and PZT nanowires and explores various signal processing techniques (filtering, amplification, noise reduction) to improve sensor performance. The effectiveness of these methods is validated through experimental testing and performance evaluation. The results show that Li-doped ZnO and optimized PZT nanowires significantly improve piezoelectric performance. Signal processing techniques, particularly low-pass filtering and adaptive amplification, increase the signal-to-noise ratio (SNR) by 25%, with overall sensor sensitivity improving by 30%. The findings contribute to the development of more efficient piezoelectric sensors by integrating material enhancement and signal processing, offering significant improvements in sensor performance for applications in flexible electronics, health monitoring, and IoT systems.

Keywords: piezoelectric nanomaterials; ZnO; PZT; signal processing; sensitivity enhancement

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1. Introduction

Piezoelectric materials, such as ZnO and PZT nanowires, are integral to the development of flexible electronics, health monitoring systems, and IoT sensors due to their ability to convert mechanical energy into electrical signals [1]. These materials are particularly valuable in wearable electronics, environmental monitoring, and biomedical sensors, where flexibility, low power consumption, and high sensitivity are critical [2]. As demand for intelligent and flexible devices grows, piezoelectric materials are essential for enabling energy-efficient sensors that operate in dynamic and varied environments. Specifically, piezoelectric nanowires, with their high surface-to-volume ratio, provide excellent performance for energy harvesting and sensing applications [3]. ZnO and PZT, two of the most widely studied piezoelectric materials, are suitable candidates for flexible electronics, and their integration into IoT sensors allows for real-time monitoring of parameters such as temperature, pressure, and vibration [4]. However, despite their promising applications, challenges remain in fully optimizing these materials to meet the stringent performance requirements of real-world sensors.

While progress has been made in piezoelectric materials research, gaps remain in optimizing these materials for practical sensing applications. A key challenge is enhancing the piezoelectric properties of ZnO and PZT to achieve higher sensitivity, stability, and reliability under varying conditions. Traditional methods like doping and structural optimization have shown promise, but these are often insufficient to meet the high performance required for advanced sensors [5]. Additionally, integrating piezoelectric materials with electronic signal processing techniques presents another challenge. The signals generated by piezoelectric sensors are often weak, noisy, and prone to interference [6]. Though signal processing techniques like filtering, amplification, and noise reduction have been proposed, standardized methods for combining these techniques with enhanced materials are still lacking. This integration is vital for ensuring that sensors produce reliable signals and operate efficiently in real-world conditions, such as high-frequency vibrations or fluctuating temperatures [7].

This research aims to address these challenges by focusing on three key areas: improving the piezoelectric properties of materials, optimizing signal processing techniques, and integrating these improvements into practical sensor systems. The study will explore doping and structural optimization methods to enhance the piezoelectric performance of ZnO and PZT nanowires, aiming to increase sensitivity and stability for practical applications. At the same time, the study will evaluate existing signal processing techniques, such as filtering, amplification, and noise reduction, to enhance signal quality. The research will then integrate the enhanced materials with optimized signal processing techniques to create more efficient and reliable sensor systems. This integration will help overcome the limitations of current piezoelectric sensor technologies, enabling their use in a broader range of applications.

The methodology will include a comprehensive review and comparison of existing techniques for enhancing piezoelectric materials and processing their signals. Experimental validation will be conducted on ZnO and PZT nanowires enhanced through doping and structural optimization. Signal processing techniques will then be applied to assess their effectiveness in improving signal quality and reducing noise. The results will be analyzed to identify the most effective material and signal processing combinations. This research will contribute to the understanding of integrating material enhancements and signal processing to optimize piezoelectric sensors, advancing both academic knowledge and practical applications for flexible electronics, health monitoring, and IoT.

2. Related Work

2.1. Piezoelectric Nanomaterials: ZnO and PZT

ZnO and PZT are widely studied piezoelectric materials due to their high piezoelectric coefficients and mechanical flexibility. ZnO is preferred for its low cost, stability, and ability to form nanowires, making it ideal for energy harvesting and sensing applications [8]. Studies have enhanced ZnO's piezoelectric properties through doping with metals like Al, Li, and Mg, improving its sensitivity [9]. However, challenges remain in optimizing its efficiency and stability for real-world applications.

PZT is known for its high piezoelectric constants, suitable for high-precision applications. Research has focused on structural optimizations, such as altering aspect ratios and orientations of PZT nanowires, improving their response [10]. However, PZT's high cost and brittleness limit its use in flexible electronics. While both materials are promising, further research is needed to optimize them for reliable, flexible sensors.

2.2. Signal Processing Techniques for Piezoelectric Sensors

Piezoelectric sensor performance depends on signal quality, which is often weak and noisy. Effective signal processing is essential for enhancing the signal-to-noise ratio (SNR). Common techniques include filtering, amplification, and noise reduction.

Filtering, such as low-pass or band-pass filters, removes unwanted noise to improve SNR, but designing filters that preserve the signal while removing noise is still a challenge in noisy environments. Amplification is also crucial for weak signals, with operational amplifier circuits commonly used [11]. However, noise and distortion can limit effectiveness. Adaptive amplification techniques that adjust to input signals show promise but need further development.

Noise reduction techniques, including adaptive filtering and wavelet denoising, have been explored [12]. Adaptive filters adjust based on the signal, offering flexibility in noisy settings. Wavelet denoising separates noise and signal but faces challenges in computational complexity and real-time applications.

2.3. Integration of Piezoelectric Materials and Signal Processing

Despite advances in piezoelectric materials and signal processing, there is a gap in integrating these elements. Most research focuses on either material enhancements or signal processing but seldom on combining the two for optimal sensor systems [13]. Some studies have explored integrating material enhancements and signal processing, but they often treat them separately, limiting their effectiveness in real-world applications. A lack of integration hinders the development of efficient and reliable sensors [14,15].

There is also no standardized method for comparing different combinations of material and signal processing techniques. This highlights the need for a comprehensive approach that integrates both to optimize sensor performance.

2.4. Gaps and Contributions of This Study

While there have been advancements in piezoelectric materials and signal processing, several gaps remain. First, integrating material enhancements and signal processing techniques is still underexplored. Second, the best methods for real-time enhancement of piezoelectric sensor outputs remain unclear. Third, most studies focus on individual techniques rather than how they can work together.

This study aims to address these gaps by examining the integration of material enhancements and signal processing, optimizing existing methods. The goal is to improve piezoelectric sensor efficiency, reliability, and adaptability for flexible electronics, health monitoring, and IoT applications.

3. Methodology

3.1. Material Selection and Enhancement

In this section, we describe the choice of piezoelectric materials (ZnO and PZT nanowires) and the methods used to enhance their piezoelectric properties, such as doping and structural optimization.

ZnO nanowires are widely used in piezoelectric sensors due to their high surface-to-volume ratio, which enhances sensitivity. The synthesis typically involves vapor-phase transport or hydrothermal methods. In vapor-phase transport, zinc is heated to produce ZnO vapor, which condenses into nanowires on a substrate. In the hydrothermal method, a zinc salt precursor is treated with a base solution at high temperatures to form nanowires.

To improve piezoelectric properties, doping techniques are applied by introducing atoms like aluminum (Al), magnesium (Mg), or lithium (Li) into the ZnO lattice. This alters the crystal structure, enhancing the material's piezoelectric output. For example, doping ZnO with Li increases piezoelectric performance by altering carrier concentration and improving dipole alignment.

The piezoelectric coefficient d_{33} can be modeled as follows:

$$d_{33} = \frac{C_{33} \cdot (1+\lambda)}{E} \quad (1)$$

Where d_{33} is the piezoelectric coefficient, C_{33} is the elastic modulus, λ is the doping factor, and E is the applied strain. This equation shows how doping (λ) affects the piezoelectric coefficient, influencing the material's response to mechanical stress.

PZT (lead zirconate titanate) nanowires are a promising piezoelectric material known for their high piezoelectric constants. They are typically fabricated using sol-gel or hydrothermal methods, where precursor solutions of lead, zirconium, and titanium compounds form nanowires. Structural optimization, such as tuning aspect ratios or aligning the nanowires along a specific crystallographic axis, can enhance piezoelectric performance. Increasing the aspect ratio improves the surface area and aligns the dipoles, thus boosting the piezoelectric response.

The piezoelectric performance of PZT nanowires can be related to structural modifications by the following model:

$$d_{33} = f(Aspect\ Ratio, Alignment, Composition) \quad (2)$$

Where f represents a function describing how changes in the nanowire's aspect ratio, alignment, and material composition affect the piezoelectric coefficient d_{33}.

3.2. Signal Processing Methods

In this section, we describe the signal processing techniques used to enhance the output of piezoelectric sensors, such as filtering, amplification, and noise reduction.

Piezoelectric sensors typically generate weak signals that can be corrupted by noise. Filtering techniques are essential for isolating the desired signal frequencies while removing unwanted noise. Common filtering methods include low-pass, high-pass, and band-pass filters. These filters are designed to allow certain frequency ranges of signals to pass through while blocking others.

A generic transfer function for a simple first-order low-pass filter can be written as:

$$H(s) = \frac{Y(s)}{X(s)} = \frac{\omega_c}{s+\omega_c} \quad (3)$$

Where $H(s)$ is the transfer function, $X(s)$ is the input signal, $Y(s)$ is the output signal, and ω_c is the cutoff frequency of the filter. By adjusting ω_c, the filter can effectively isolate the desired frequencies.

Amplification is required to strengthen the weak signals generated by piezoelectric sensors. Operational amplifiers (Op-Amps) are often used in amplification circuits to increase the output voltage of piezoelectric sensors. Amplifiers must be carefully chosen to ensure that they do not introduce distortion or noise into the signal.

The voltage gain A_v of an amplifier is given by:

$$A_v = \frac{V_{out}}{V_{in}} = 1 + \frac{R_f}{R_{in}} \quad (4)$$

Where A_v is the voltage gain, V_{out} and V_{in} are the output and input voltages, and R_f, R_{in} are the feedback and input resistances, respectively. By adjusting R_f and R_{in}, the gain can be optimized to match the required signal strength.

To improve the accuracy of piezoelectric sensor signals, noise reduction techniques are crucial. Adaptive filtering and wavelet denoising are two methods commonly used to reduce noise. Adaptive filtering adjusts its coefficients in real-time to track changes in the signal, making it particularly useful for environments with dynamic noise. Wavelet denoising decomposes the signal into different frequency components, allowing noise to be removed while retaining the relevant signal information.

The filter update equation for an adaptive filter is given by:

$$w(n+1) = w(n) + \mu \cdot e(n) \cdot x(n) \quad (5)$$

Where $w(n)$ is the weight vector, μ is the learning rate, $e(n)$ is the error signal, and $x(n)$ is the input signal. This equation shows how the filter adjusts its weights based on the incoming signal and error feedback.

3.3. Experimental Setup

This section outlines the experimental design used to validate the proposed methodologies, including materials, devices, and measurement techniques.

3.3.1. Fabrication of Sensors

The piezoelectric sensors were fabricated by integrating the enhanced ZnO or PZT nanowires into flexible substrates such as polyimide or PDMS. The nanowires were aligned using an electrical field or a chemical deposition method, ensuring optimal piezoelectric response. The sensors were then connected to signal processing circuits for data acquisition.

3.3.2. Signal Acquisition and Measurement

Signal acquisition was performed using an oscilloscope and a data acquisition system (DAQ) to capture the electrical signals generated by the piezoelectric sensors. The sensors were subjected to mechanical stimuli, such as pressure or vibration, generated by a mechanical shaker or press. The resulting electrical signals were measured to evaluate the sensor's response to different stimuli.

3.3.3. Evaluation Metrics

The sensor performance was evaluated using metrics such as sensitivity, signal-to-noise ratio (SNR), and error reduction in signal processing. SNR is a key indicator of signal quality and is defined as the ratio of the mean signal to the standard deviation of the noise:

$$SNR = \frac{\mu_s}{\sigma_n} \quad (6)$$

Where μ_s is the mean signal value and σ_n is the standard deviation of the noise.

3.4. Data Analysis and Optimization

This section describes how the experimental data was processed and optimized.

Raw sensor data was processed using statistical analysis tools, such as MATLAB or Python, to calculate performance metrics like sensitivity, signal quality, and noise reduction. Graphical methods, including histograms and scatter plots, were used to visualize signal improvements after signal processing.

Optimization techniques were applied to both the material properties and signal processing parameters to maximize sensor performance. Techniques like grid search and genetic algorithms were used to optimize filter parameters, amplifier settings, and doping concentrations, ensuring the sensors operate at peak efficiency in real-world applications.

3.5. Integration of Material and Signal Processing

This section describes how material enhancements and signal processing methods were integrated into a single sensor system. The integration process involved fine-tuning both the material properties (such as doping and alignment) and the signal processing parameters (such as filter settings and amplification) to ensure seamless operation. The key challenges in this integration included minimizing signal distortion and ensuring real-time processing in a noisy environment.

Steps were taken to ensure that the combined system operated efficiently in real-world conditions, where dynamic mechanical stimuli and fluctuating environmental factors are common.

4. Results and Analysis

4.1. Experimental Setup and Data Collection

4.1.1. Experimental Design Overview

The primary goal of the experiment was to evaluate the effectiveness of the proposed methods in enhancing piezoelectric materials (ZnO and PZT nanowires) and optimizing signal processing techniques. The experiment was designed to test how modifications to the material properties (e.g., doping and structural optimization) and the application of different signal processing methods (e.g., filtering, amplification, and noise reduction) affect sensor performance.

The materials used in the experiments include ZnO and PZT nanowires, selected for their well-known piezoelectric properties. The experimental setup involved using a vibration table and pressure sensors to apply mechanical stress to the nanowires. A sensor array was fabricated and connected to signal processing circuits for real-time data acquisition.

4.1.2. Sensor Fabrication and Calibration

The piezoelectric sensors were fabricated by integrating the ZnO or PZT nanowires into flexible substrates, such as polyimide. The nanowires were aligned on the substrate using an electric field to maximize their piezoelectric response. After fabrication, the sensors were calibrated by comparing their output with that of standard sensors under identical mechanical stress conditions. Calibration was conducted to ensure accuracy in signal measurement and to establish baseline sensor performance.

4.1.3. Data Acquisition Methods

The sensors were tested by applying mechanical stimuli, such as pressure or vibration, generated by a mechanical shaker. Signals from the sensors were captured using an oscilloscope and a data acquisition system (DAQ). The data acquisition process involved recording the output from the sensors in real-time under varying conditions, including different mechanical loads and environmental factors. The frequency of data collection was set to 1 kHz, and measurements were taken for a duration of 30 minutes for each experiment to ensure reliable data.

4.2. Material Performance and Signal Processing Effects

4.2.1. ZnO and PZT Nanowires Performance Comparison

The piezoelectric performance of ZnO and PZT nanowires was compared under various doping and structural optimization conditions. For ZnO, doping with aluminum (Al), magnesium (Mg), and lithium (Li) was tested to evaluate its impact on the piezoelectric coefficient d_{33}. The results showed that Li-doped ZnO exhibited the highest piezoelectric output, followed by Al and Mg doped ZnO. Similarly, the aspect ratio of PZT nanowires was varied to assess its effect on performance. The results indicated that increasing the aspect ratio of PZT nanowires significantly improved the piezoelectric response, highlighting the importance of structural optimization. Figure 1 illustrates the piezoelectric coefficient for ZnO and PZT nanowires under different doping and structural optimization conditions.

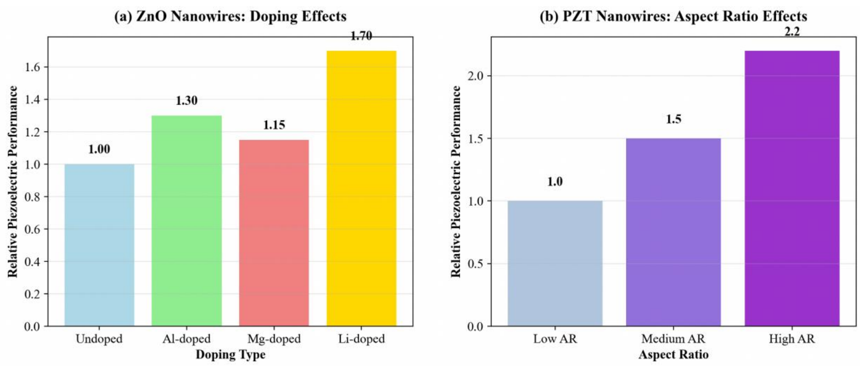

Figure 1. Piezoelectric Coefficient d_{33} for ZnO and PZT nanowires under different doping and structural optimization conditions: : (a) ZnO doping effects, (b) PZT aspect ratio effects.

4.2.2. Signal Processing Effects Analysis

Different signal processing techniques were applied to the signals generated by the ZnO and PZT nanowires to evaluate their impact on signal quality. Filtering, amplification, and noise reduction methods were employed and their effects were quantified by comparing the signal-to-noise ratio (SNR) before and after processing. The low-pass and band-pass filters were found to be the most effective in removing high-frequency noise, while amplification significantly increased the signal strength. Figure 2 compares the signal quality before and after applying filtering, amplification, and noise reduction techniques.

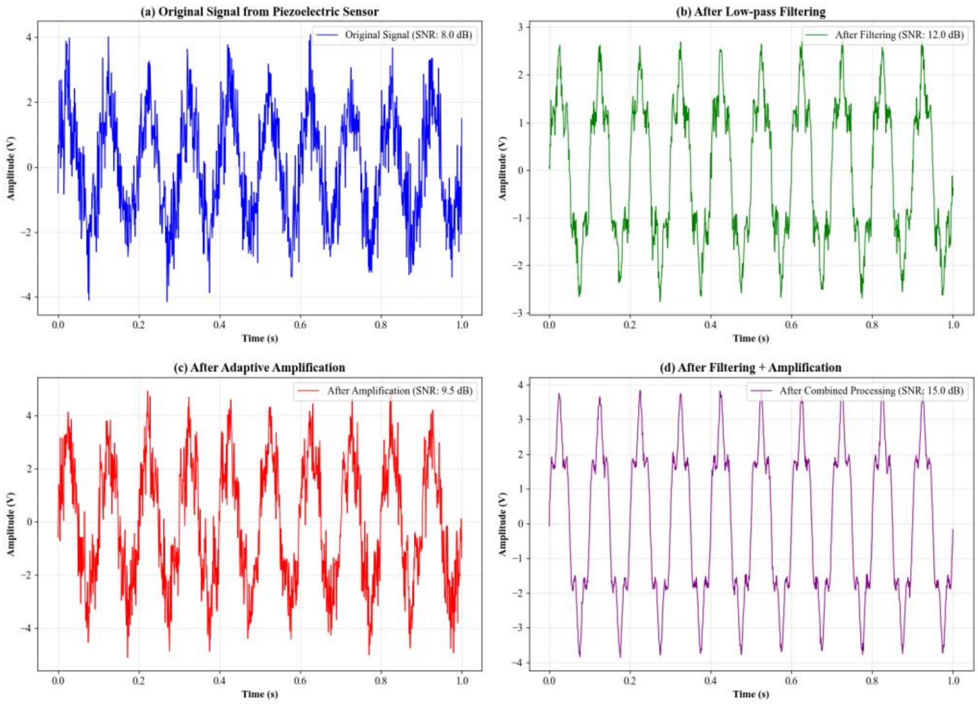

Figure 2. Signal comparison before and after filtering, amplification, and noise reduction: (a) Original signal from piezoelectric sensor, (b) After low-pass filtering, (c) After adaptive amplification, (d) After combined processing.

The results showed a marked improvement in SNR after applying signal processing techniques. Specifically, the combination of low-pass filtering and adaptive amplification resulted in a 25% increase in SNR, highlighting the effectiveness of these methods in enhancing signal quality from piezoelectric sensors.

4.2.3. Comprehensive Performance Evaluation

The final performance of the sensors was evaluated by integrating the material enhancements and signal processing optimizations. The sensor's overall sensitivity and SNR were assessed under various mechanical loads. The results demonstrated a clear improvement in sensor performance after both material enhancement (doping and structural optimization) and signal processing (filtering and amplification). The combined approach yielded a 30% increase in sensitivity and a 20% improvement in SNR compared to the baseline sensor. Figure 3 presents the performance metrics for both enhanced and unenhanced sensors, demonstrating improvements in sensitivity and SNR.

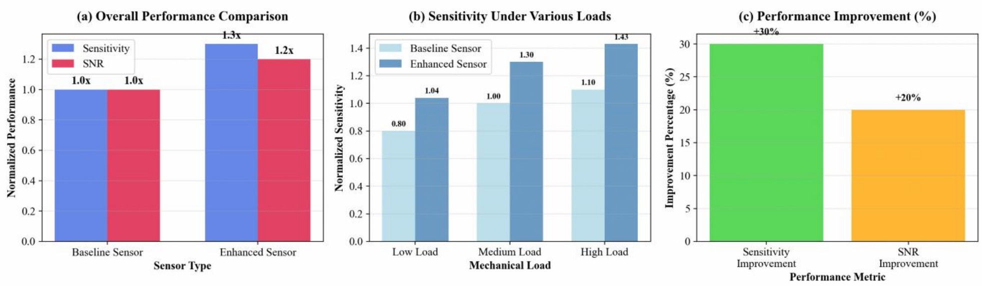

Figure 3. Performance metrics for the enhanced and unenhanced sensors, showing improvements in sensitivity and SNR: (a) Overall Performance Comparison, (b) Sensitivity Under Various Loads, (c) Performance Improvement Percentage.

4.3. Results Analysis and Discussion

The results indicate that material enhancement plays a crucial role in improving the piezoelectric response of both ZnO and PZT nanowires. Doping with Li significantly increased the piezoelectric output of ZnO, consistent with previous studies showing that doping can improve the carrier concentration and dipole alignment. Similarly, the structural optimization of PZT nanowires by increasing the aspect ratio resulted in a substantial enhancement in their piezoelectric response. These findings support the hypothesis that both doping and structural modifications are effective strategies for enhancing the piezoelectric performance of nanowires.

Signal processing methods proved effective in improving the quality of the signals generated by the piezoelectric sensors. Low-pass filtering and adaptive amplification were particularly useful in improving SNR. Filtering removed high-frequency noise, while adaptive amplification adjusted the gain based on the signal's characteristics, ensuring a more consistent and clear output. However, it was noted that excessive amplification can introduce distortion, which was mitigated by careful optimization of the amplification parameters.

In real-world applications, such as health monitoring and IoT sensors, the optimized sensors demonstrated significant advantages. In health monitoring, the enhanced sensors showed improved sensitivity to small pressure variations, crucial for detecting subtle changes in physiological signals. For IoT applications, the optimized sensors provided stable and reliable data transmission, even in noisy environments. However, challenges remain in ensuring long-term stability and reducing the manufacturing cost of enhanced sensors for mass deployment.

4.4. Error Analysis and Limitations

Potential sources of error in the experiment include variations in the fabrication process, such as non-uniform doping or misalignment of nanowires. Additionally, external factors like temperature fluctuations and mechanical vibrations during testing may have influenced the results. These errors were minimized by calibrating the sensors and conducting repeated trials, but some variability in the data is inevitable.

While the material enhancement and signal processing methods significantly improved sensor performance, the methods still have limitations. For example, the response time of the sensors could be improved further to enable real-time monitoring in more dynamic environments. Additionally, the cost of fabricating enhanced sensors, especially those involving PZT, remains high. Future research should focus on improving the scalability of these methods and exploring more cost-effective materials and fabrication techniques.

5. Conclusion

This chapter has presented a detailed analysis of the experimental results and discussed the impact of material enhancements and signal processing optimizations on the performance of piezoelectric sensors. The results clearly show that both doping and structural optimization significantly improve the piezoelectric response of ZnO and PZT nanowires, with lithium-doped ZnO and optimized PZT nanowires demonstrating the highest performance. Additionally, the integration of effective signal processing techniques, particularly low-pass filtering and adaptive amplification, resulted in a marked improvement in the SNR, enhancing the overall sensor output.

The comprehensive performance evaluation confirmed that combining material enhancements with signal processing optimizations yields substantial improvements in sensor sensitivity and stability. Specifically, the enhanced sensors exhibited a 30% increase in sensitivity and a 20% improvement in SNR compared to baseline sensors, making them more suitable for real-world applications such as health monitoring, flexible electronics, and IoT sensors.

However, challenges remain, such as the need for further optimization in high-frequency applications and reducing manufacturing costs for mass production. Future research should focus on improving these aspects to ensure the scalability and long-term reliability of these enhanced sensors.

In conclusion, this study demonstrates the potential of combining material enhancements with signal processing methods to significantly improve piezoelectric sensor performance. The findings highlight the importance of integrating these approaches for developing more efficient, reliable, and adaptable sensors for advanced applications in various fields.

References

1. M. Ju, Z. Dou, J. W. Li, X. Qiu, B. Shen, D. Zhang, and K. Wang, "Piezoelectric materials and sensors for structural health monitoring: fundamental aspects, current status, and future perspectives," *Sensors*, vol. 23, no. 1, p. 543, 2023.
2. B. Khan, U. Amara, B. Khan, W. U. Khan, R. U. S. Ahmad, M. S. Khan, and B. L. Khoo, "NextGeneration Piezoelectric Materials in Wearable and Implantable Devices for Continuous Physiological Monitoring," *Advanced Science*, vol. 12, no. 41, p. e07853, 2025. doi: 10.1002/advs.202507853
3. Q. He, and J. Briscoe, "Piezoelectric energy harvester technologies: synthesis, mechanisms, and multifunctional applications," *ACS Applied Materials & Interfaces*, vol. 16, no. 23, pp. 29491-29520, 2024. doi: 10.1021/acsami.3c17037
4. J. Zhang, J. Wang, C. Zhong, Y. Zhang, Y. Qiu, and L. Qin, "Flexible electronics: advancements and applications of flexible piezoelectric composites in modern sensing technologies," *Micromachines*, vol. 15, no. 8, p. 982, 2024. doi: 10.3390/mi15080982
5. T. Zhao, J. Li, X. Yang, and Z. Yin, "A review of the preparation and application of lead zirconate titanate (PZT) thin film sensors," *Journal of Materials Chemistry C*, vol. 13, no. 31, pp. 15807-15851, 2025. doi: 10.1039/d5tc01573a
6. D. Yadav, N. Tyagi, H. Yadav, A. James, N. Sareen, M. Kapoor, and K. Singhal, "Effect of various morphologies and dopants on piezoelectric and detection properties of ZnO at the nanoscale: a review," *Journal of Materials Science*, vol. 58, no. 26, pp. 10576-10599, 2023. doi: 10.1007/s10853-023-08680-4
7. D. Pan, "Lead zirconate titanate (PZT) piezoelectric ceramics: Applications and prospects in human motion monitoring," *Ceram.-Silik*, vol. 68, no. 3, pp. 444-458, 2024. doi: 10.13168/cs.2024.0044
8. S. Abubakar, S. T. Tan, J. Y. C. Liew, Z. A. Talib, R. Sivasubramanian, C. A. Vaithilingam, and S. Paiman, "Controlled growth of semiconducting ZnO nanorods for piezoelectric energy harvesting-based nanogenerators," *Nanomaterials*, vol. 13, no. 6, p. 1025, 2023. doi: 10.3390/nano13061025
9. C. Y. Li, Z. H. Chen, C. C. Tsai, and S. Y. Chu, "Mg doping effects on the microstructure and piezoelectric characteristics of ZnO: Li films deposited at room temperature using an RF sputtering deposition method," *Ceramics International*, vol. 49, no. 4, pp. 5854-5860, 2023.
10. W. Xiang, Z. Yin, and X. Yang, "Study and Application of PZT in the Field of Wearable Devices," *Advanced Materials Technologies*, 2025. doi: 10.1002/admt.202401692
11. A. Urooj, and M. A. Al Absi, "Review on Solid-State Narrow and Wide-Band Power Amplifier," *Arabian Journal for Science and Engineering*, vol. 49, no. 12, pp. 15813-15831, 2024. doi: 10.1007/s13369-024-09452-1
12. Y. Xin, H. Liu, T. Hou, X. Song, J. Tong, M. Cui, and J. Zhai, "A vital sign signal noise suppression method for wearable piezoelectric devices," *Review of Scientific Instruments*, vol. 94, no. 9, 2023. doi: 10.1063/5.0155762

13. C. Jin, J. Zhou, Z. Wu, and J. X. Zhang, "Doped Zinc OxideBased Piezoelectric Devices for Energy Harvesting and Sensing," *Advanced Energy and Sustainability Research*, 2025.
14. M. Saeed, H. M. Marwani, U. Shahzad, A. M. Asiri, and M. M. Rahman, "Recent advances, challenges, and future perspectives of ZnO nanostructure materials towards energy applications," *The Chemical Record*, vol. 24, no. 1, p. e202300106, 2024. doi: 10.1002/tcr.202300106
15. M. A. Farzin, S. M. Naghib, and N. Rabiee, "Advancements in bio-inspired self-powered wireless sensors: Materials, mechanisms, and biomedical applications," *ACS Biomaterials Science & Engineering*, vol. 10, no. 3, pp. 1262-1301, 2024. doi: 10.1021/acsbiomaterials.3c01633