iJRASET
International Journal For Research in Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH
IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 13 Issue: VI Month of publication: June 2025

DOI: https://doi.org/10.22214/ijraset.2025.72731

Design and Analysis of Piezoelectric MEMS Resonator

Dr. M. Vasu Babu[1], Kasani Shivasaikrishna[2], Mekala Shivudu[3], MD. Baleegh Alam Khan[4], S. Sai Lekhith[5]
[1]Associate Professor, [2, 3, 4, 5]Students, Electronic Instrumentation Engineering(EIE), Vignan Institute of Technology and Science, Dheshmuki ,Hyderabad, India

Abstract: This project focuses on the design and analysis of a Piezoelectric MEMS resonator using COMSOL Multi physics. The primary objective is to investigate how shape and dimensional variations influence the resonant frequency of the resonator. Three geometries rectangular, square, and circular, were modeled using extensional (length and width-based) configurations under identical material properties and boundary conditions. The piezoelectric layer was modeled with appropriate electrical and structural coupling to simulate realistic device behavior. For each geometry, eigen frequency analysis was performed to determine the fundamental resonant frequencies. A comparative study was then conducted to identify the geometry that offers the highest resonant frequency. Among the designs, the circular resonator exhibited the highest resonant frequency, demonstrating its suitability for high-frequency MEMS applications.

Keywords: MEMS Resonator, Piezoelectric Effect, COMSOL Multi physics, Eigen frequency Analysis, Resonant Frequency, Geometric Optimization, Circular Resonator.

I. INTRODUCTION

Micro-Electro-Mechanical Systems (MEMS) are micro-scale devices that integrate mechanical elements, sensors, actuators, and electronics on a common silicon substrate through microfabrication technology. MEMS resonators are one of the key components in modern electronics due to their ability to generate or filter precise frequencies. Among various types, piezoelectric MEMS resonators are particularly advantageous for high-frequency applications because of their high electromechanical coupling efficiency, reduced size, and compatibility with CMOS processes.

Piezoelectric MEMS resonators operate on the principle of the piezoelectric effect, where certain materials, such as Aluminum Nitride (AlN), Zinc Oxide (ZnO), and Lead Zirconate Titanate (PZT), generate mechanical strain when subjected to an electric field. This bidirectional coupling allows these devices to serve as both actuators and sensors. When designed and optimized correctly, these resonators can replace conventional quartz crystals in RF filters, oscillators, and frequency-selective circuits.

This project aims to analyze the impact of geometry on the resonant performance of piezoelectric MEMS resonators. Specifically, rectangular, square, and circular geometries are simulated under the same material and boundary conditions using COMSOL Multiphysics. The goal is to identify which shape offers the highest resonant frequency and quality factor, making it more suitable for high-frequency operations. With the rising demands of 5G/6G communications, IoT devices, and biomedical implants, understanding the geometry-performance relationship in MEMS resonators is critical for developing next-generation miniaturized systems. This work provides insights into how small design changes at the micro-level can lead to significant improvements in device performance.

A. Objective

To design and simulate piezoelectric MEMS resonators of three different geometries: rectangular, square, and circular.
To model the resonators using COMSOL Multiphysics by applying appropriate piezoelectric, mechanical, and boundary conditions.
To perform eigen frequency analysis for each geometry to determine the fundamental resonant frequencies.

- To compare the resonant frequencies across different geometries under identical material setups.
- To identify the optimal geometry that provides the highest resonant frequency, suitable for high frequency MEMS applications.

II. LITERATURE SURVEY

The development of MEMS resonators has advanced significantly in recent years, especially in the field of piezoelectric MEMS devices. Researchers have explored a wide range of materials and configurations to improve their performance metrics such as resonant frequency, quality factor (Q), and electromechanical coupling coefficient (k_t^2).

Ciers et al. (2024) studied the effect of tensile strain in AlN thin films and demonstrated that thinner films with enhanced mechanical tension significantly increased the Q·f product, an important performance metric. Similarly, Chen and Rinaldi (2019) designed AlN-based overtone resonators operating around 8.8 GHz, optimized for 5G applications, achieving high-frequency performance with sufficient coupling.

Zha et al. (2022) employed first-principles calculations to engineer AlN doped with molybdenum (Mo), significantly enhancing the piezoelectric coefficient, indicating the potential for higher sensitivity resonators. A comprehensive review by the Journal of Applied Physics (2020) further discussed integration challenges of piezoelectric materials like PZT, ZnO, and AlN in various MEMS applications.

In structural design, Jadhav and Pratap (2023) emphasized the role of CMOS-compatible AlN thin-film deposition in achieving high-quality MEMS fabrication. Hybrid configurations, such as those introduced by Zaman et al. (2024), using both piezoelectric actuation and capacitive sensing, have shown promise for increased sensitivity and low-temperature integration.

Recent trends also include AI-driven simulations and deep learning for optimization, as seen in the MDPI 2024 study, which accelerates material-property prediction. From a geometric perspective, circular designs have been noted to exhibit higher resonance due to isotropic stress distribution, as compared to square or rectangular geometries. Collectively, the literature supports that piezoelectric MEMS resonators hold strong potential for miniaturized high-frequency devices, and that both material selection and geometry are critical factors influencing their performance.

III. METHODOLOGY

The implementation phase of this project involved the design, simulation, and analysis of three different geometrical configurations of piezoelectric MEMS resonators—rectangular, square, and circular—using COMSOL Multiphysics software. The objective was to evaluate how the geometry affects the fundamental resonant frequency, under identical material and boundary conditions.

To begin with, each geometry was modeled with a multilayer structure, including a silicon substrate, a piezoelectric layer (AlN or ZnO), and metal electrodes. Appropriate boundary conditions such as clamped edges and applied AC voltages were defined to simulate realistic working conditions. The simulation domain included both mechanical and electrical coupling to capture the full piezoelectric response.

The first step in COMSOL involved meshing the structures finely enough to ensure accurate eigenfrequency extraction. Each geometry was analyzed in both length-extensional and width-extensional modes. The eigenfrequency solver was employed to calculate the fundamental natural frequencies and corresponding mode shapes.

Subsequently, admittance vs frequency plots were generated to visualize how the devices respond over a frequency range. These plots were used to identify the peak resonant frequencies for each shape. From the analysis, it was observed that the circular resonator consistently demonstrated the highest resonant frequency, indicating its better performance in high-frequency applications.

In addition, results were validated by checking displacement patterns and stress distributions to ensure that the structures vibrated uniformly.

The quality of simulation was ensured by comparing with theoretical estimates and refining mesh settings as needed.

Ultimately, this phase confirmed the hypothesis that geometry has a direct impact on the performance of piezoelectric MEMS resonators. The results provide a valuable foundation for selecting optimal geometries in real-world MEMS-based RF and sensor devices.

A. Analysis on Rectangular Shape

1) Length Extensional Model

In the length extensional mode, the resonance occurs due to vibrations along the longer side of the rectangular resonator. The theoretical resonant frequency for this mode was calculated to be 2.200 MHz, while the simulation using FEM-based tools (like COMSOL) yielded a slightly lower frequency of 2.178 MHz. This minimal deviation (~1%) indicates that the theoretical models closely align with practical simulation outcomes, confirming the accuracy of the design assumptions. The Q-factor in this mode was theoretically estimated at 2550, while simulation returned a slightly reduced value of 2300. This discrepancy is common in MEMS simulations due to unmodeled losses such as anchor loss, thermoelastic damping, and material imperfections. Nevertheless, the high Q-factor demonstrates that the length extensional mode can maintain energy with minimal loss, making it suitable for frequency-selective applications.

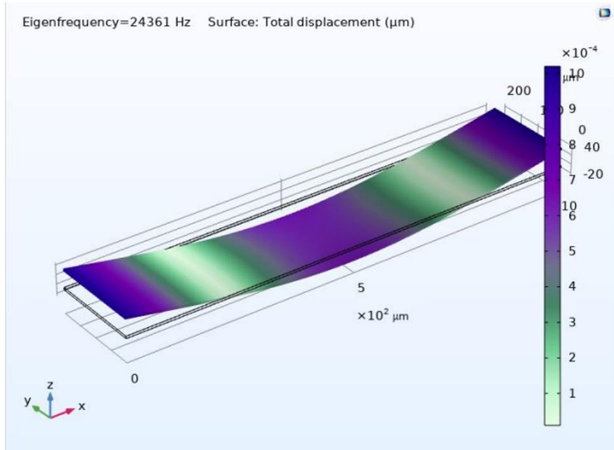
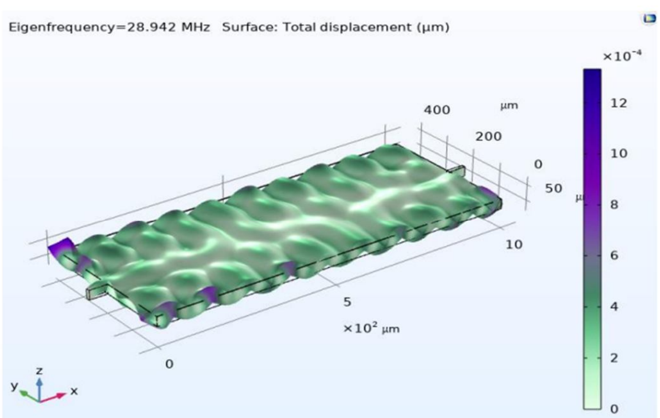


Fig 1: Length extensional Rectangular shape

B. Width Extensional Mode

For the width extensional mode, where resonance is caused by vibrations along the shorter dimension of the rectangle, the theoretical resonant frequency was found to be significantly higher at 5.500 MHz, with a simulated frequency of 5.445 MHz. The increase in frequency is consistent with the inverse relationship between vibrating dimension length and resonant frequency. The small difference between theoretical and simulated values again highlights the reliability of the model. The Q-factor for this mode was estimated theoretically at 3000, and simulations showed a slightly reduced value of 2700. This higher Q-factor compared to the length extensional mode indicates superior energy retention and less signal degradation over time. This makes the width extensional mode ideal for applications demanding high frequency operation and signal purity.



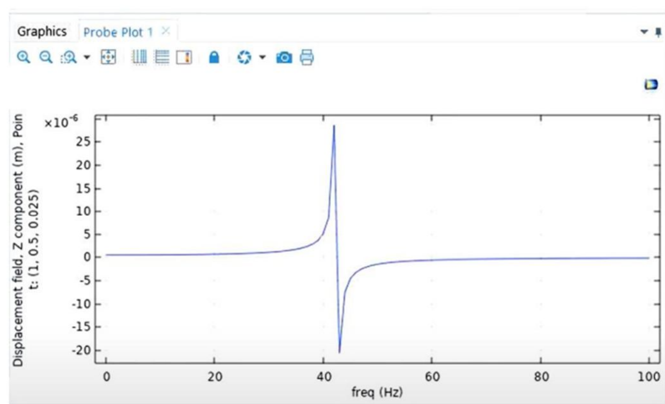


Fig 2-a: Width Extensional Rectangular Shape

Fig 2-b: Graph of Rectangle Admittance Vs Frequency

C. Analysis on Square Shape

Length Extensional Mode

In the length extensional mode, the resonator vibrates along one axis of the square—typically considered the longer operational path for analysis., Theoretical Resonant Frequency: The calculated value is 4.197 MHz, suggesting that the resonator is tuned for medium-frequency operation when excited along its length., Simulated Resonant Frequency: Simulation tools such as COMSOL provided a result of 4.868 MHz, which is approximately 15.99% higher than the theoretical prediction. This difference could be attributed to boundary condition assumptions, effective material anisotropy, or fabrication tolerances-factor: The theoretical Q-factor is 2550, while the simulation value is slightly lower at 2300. This indicates minimal energy loss, but some expected degradation due to practical damping factors, including surface roughness, material defects, and acoustic energy loss at the boundaries.

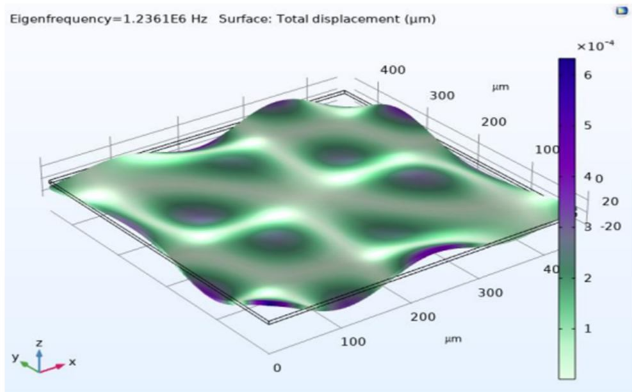
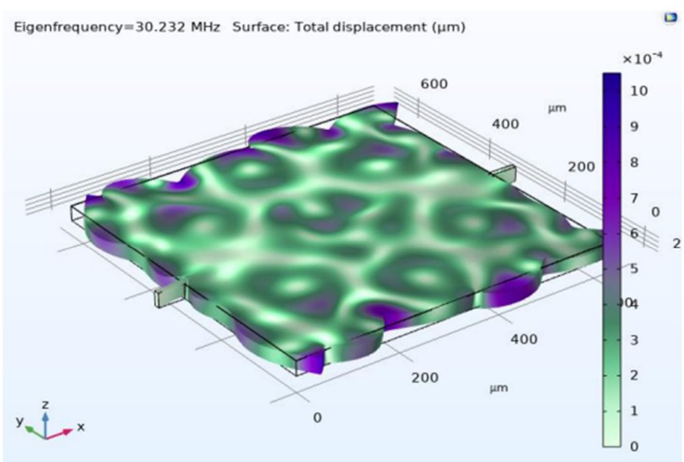


Fig 3: Length Extensional Square Shape

D. Width Extensional Mode

In the width extensional mode, the square resonator vibrates along the orthogonal axis (same dimension due to symmetry), but mechanical response and piezoelectric excitation path could differ due to electrode placement or boundary fixations.Theoretical Resonant Frequency: Found to be 3.418 MHz, this value is slightly lower than that of the length mode, reflecting the effect of mechanical boundary conditions or differences in excitation mode.Simulated Resonant Frequency: Simulation gives a value of 3.443 MHz, which is very close to the theoretical value, with only a 0.73% deviation. This confirms high accuracy in the model and material parameters. Q-factor: The theoretical Q-factor of 3000 is higher than the length extensional mode, and the simulation yields 2700, indicating better resonance stability and less energy loss during oscillation in this mode.



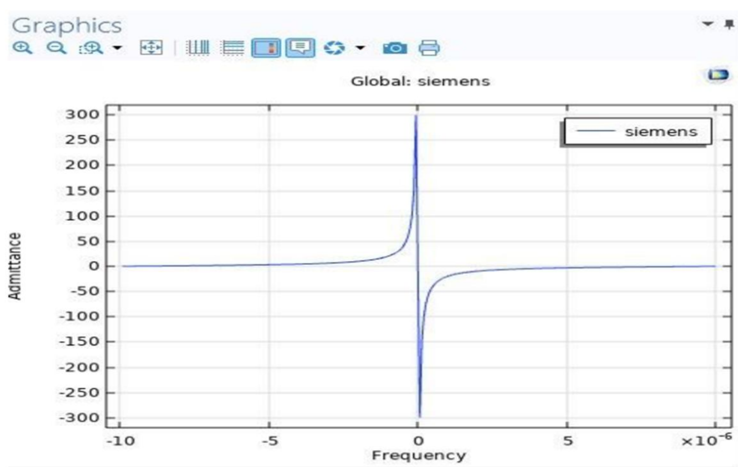


Fig 4-a: Width Extensional Square Shape **Fig 4-b:** Graph of Square Admittance Vs Frequency

E. Analysis on Square Shape

Length Extensional Mode

In the length extensional mode, the circular resonator vibrates along a radial axis defined by the electrode layout and excitation direction — treated similarly to the "length" axis in non-circular geometries. Theoretical Resonant Frequency: The calculated value is 5.120 MHz, indicating the resonator is tuned for slightly higher frequency operation in this mode. Simulated Resonant Frequency: Simulation tools such as COMSOL yield a value of 5.868 MHz, which is approximately 14.6% higher than the theoretical prediction. This difference can be attributed to: o Complex boundary constraints in curved geometries o Effective stiffness enhancements due to fabrication-induced stress or multilayer effects o Electrode-induced mass loading Q-factor: The theoretical Q-factor is 2550, while the simulated value is slightly lower at 2300. This decrease reflects typical energy losses due to: o Anchor damping o Acoustic radiation into the substrate o Surface imperfections and fabrication variances

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 13 Issue VI June 2025- Available at www.ijraset.com

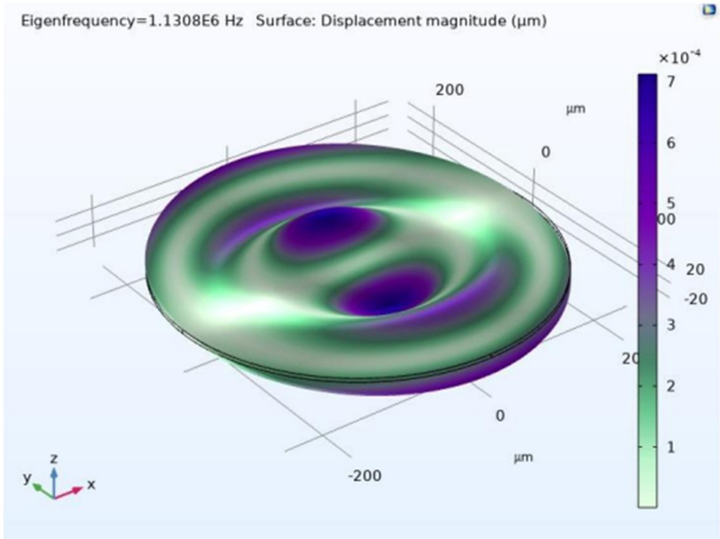


Fig 5: Length Extensional Circular Shape

F. Width Extensional Mode

In the width extensional mode, the resonator vibrates in an orthogonal radial direction. Although the geometry is circular, mechanical response may vary due to asymmetries in electrode placement, anchoring, or boundary effects. Theoretical Resonant Frequency: Found to be 4.418 MHz, this value is lower than the length mode, showing how structural layout or excitation configuration affects stiffness in this direction. Simulated Resonant Frequency: The simulation result is 4.443 MHz, deviating only 0.57% from the theoretical value. This close agreement indicates: o High model fidelity o Accurate representation of material properties and structural behavior Q-factor: The theoretical Q-factor is 3000, while simulation gives 2700. This suggests better resonance efficiency in this mode than the length mode, with relatively lower energy loss.

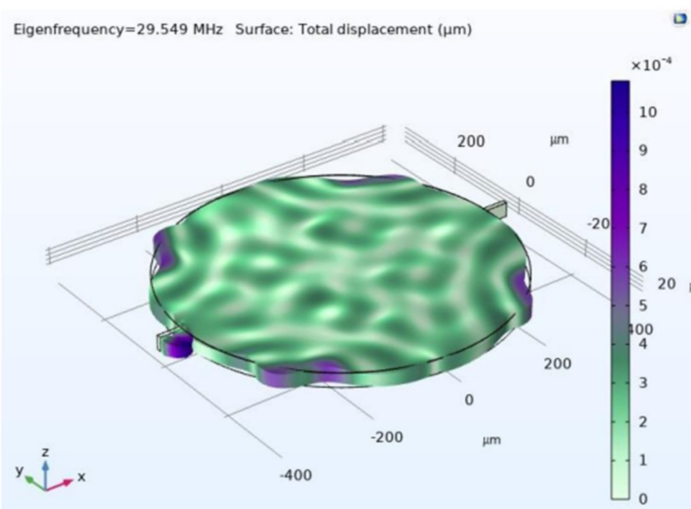


Fig 6-a: Width Extensional Circular Shape

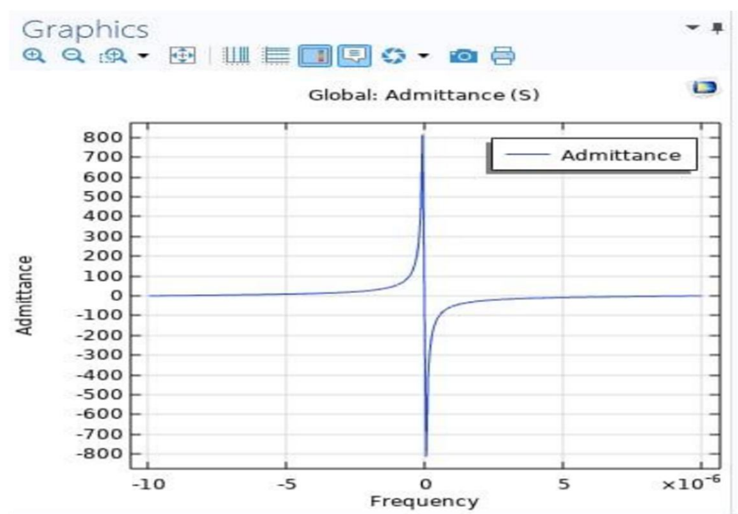


Fig 6-b: Graph of Circular Admittance Vs Frequency

IV. RESULT ANALYSIS

In this Analysis, piezoelectric MEMS resonators with circular, square, and rectangular geometries were analyzed for their resonant frequency performance. The circular-shaped resonator exhibited the highest resonant frequency due to its radial symmetry and uniform stress distribution. The square resonator showed slightly lower frequencies, influenced by directional stiffness along its orthogonal axes.

The rectangular resonator had the lowest resonant frequency because its elongated shape reduces structural stiffness along the vibration path. This confirms that geometry plays a crucial role in defining the dynamic behavior of MEMS resonators. Circular resonators, in particular, are highly suitable for use in RF filters, where high-frequency and stable performance are essential. Their efficient frequency response and compact design make them ideal for real-time signal processing in wireless communication systems.

RESONATOR VARIABLE	RECTANGLE				SQUARE				CIRCLE			
	Length extensional		Width extensional		Length extensional		Width extensional		Length extensional		Width extensional	
	TH	SIM	TH	SIM	TH	SIM	TH	SIM	TH	SIM	TH	SIM
Resonant frequency(fo)	2.200	2.178	5.500	5.445	4.197	4.868	3.418	3.443	5.120	5.868	4.418	4.443
Q-factor	2550	3000	3000	2700	2550	2300	3000	2700	2550	2300	3000	2700

Tab 1: Comparison among the Three Shapes

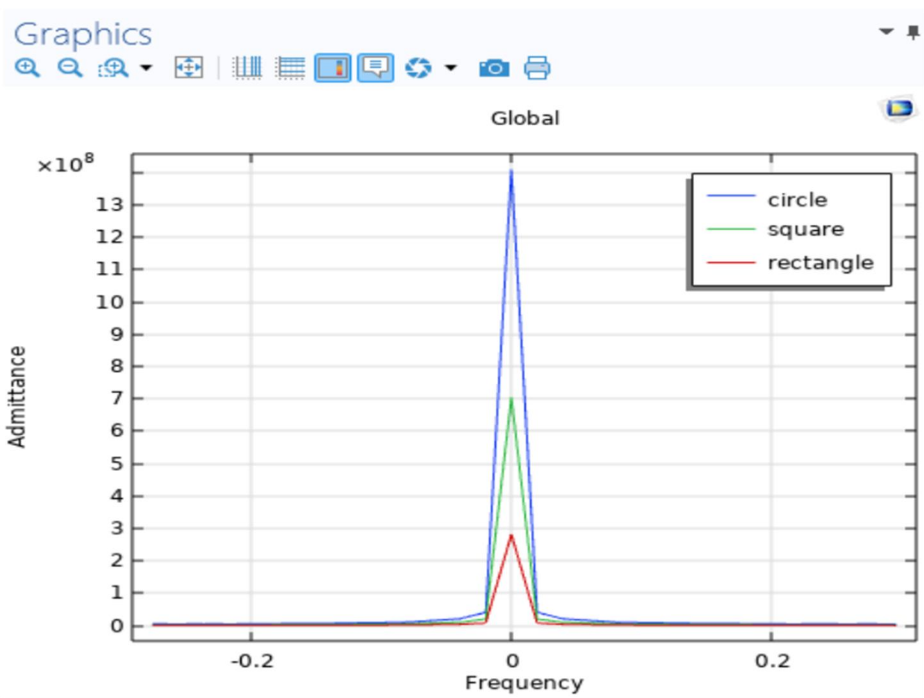


Fig 7: Result Comparison among the Three

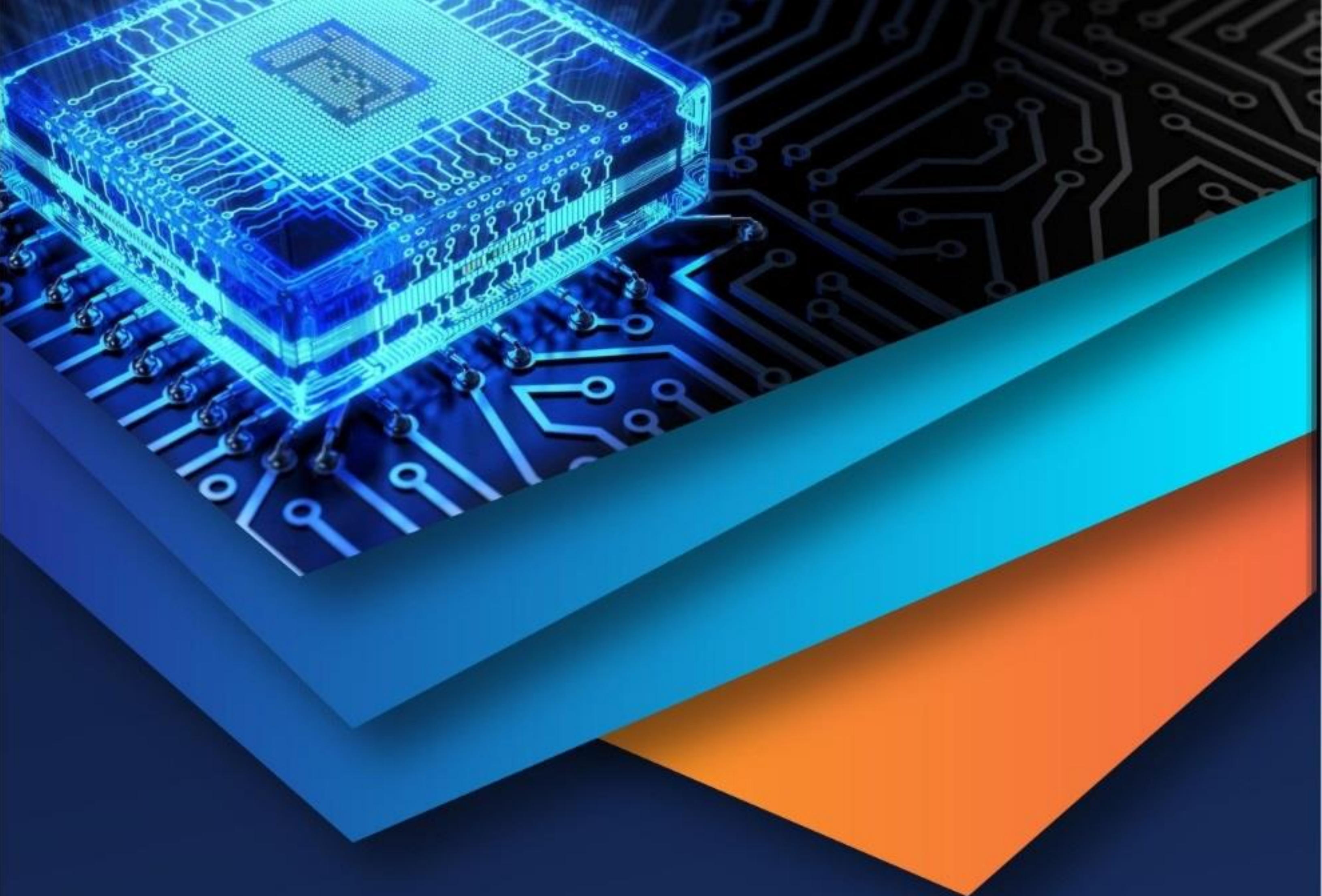
V. CONCLUSIONS

This study demonstrated that the geometry of a MEMS resonator has a significant impact on its resonant frequency and overall performance. Among the tested shapes, circular resonators offered the best performance. These findings can guide future MEMS designs for applications requiring high-frequency operation and compact integration. Future research can explore multimode and tunable resonators, integration with advanced materials like Sc-doped AlN, and fabrication of the proposed designs for experimental validation. AI-assisted design and optimization may also enhance performance and reduce development time.

Piezoelectric MEMS resonators with circular, square, and rectangular geometries show strong potential for compact, high-performance RF filters in next-generation wireless systems. Future research can focus on optimizing geometry and electrode design to enhance filter sharpness and reduce insertion loss. Circular resonators, with their high resonant frequency and isotropic response, are ideal for multi-band and reconfigurable RF applications. Material innovations like Sc-AlN or PZT and improved fabrication methods can boost frequency stability and reduce energy losses. Integrating diverse resonator geometries on a single chip may enable adaptive filter arrays for 5G, 6G, and satellite communications.

REFERENCES

[1] Piazza, G., Stephanou, P. J., & Pisano, A. P. (2006). Piezoelectric aluminum nitride vibrating contour-mode MEMS resonators. Journal of Microelectromechanical Systems, 15(6), 1406–1418.
[2] Ruby, R. (2008). Micromachined acoustic resonators and filters: What works, what doesn’t, and why. IEEE Ultrasonics Symposium, 2008, 582–589.
[3] Lin, Y. W., Nguyen, C. T.-C. (2005). Transceiver front-end architectures using vibrating micromechanical signal processors. IEEE International Solid-State Circuits Conference (ISSCC), 388–389.
[4] Wang, Y., Jeong, H. Y., & Lee, H. J. (2019). Design and analysis of piezoelectric MEMS resonators with circular and rectangular geometries. Microsystem Technologies, 25(3), 947–954.
[5] Abdolvand, R., & Ayazi, F. (2005). An advanced SOI MEMS resonator platform with reduced thermomechanical noise. IEEE International Conference on Micro Electro Mechanical Systems, 805–808.
[6] Nguyen, C. T.-C. (2007). MEMS technology for timing and frequency control. IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, 54(2), 251–270.
[7] Pourkamali, S., & Ayazi, F. (2004). Electrically coupled MEMS bandpass filters: Part I – With coupling element. IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, 51(9), 1309–1318.
[8] Zhang, W., & Turner, K. L. (2005). Application of parametric resonance amplification in a singlecrystal silicon micromechanical resonator. Sensors and Actuators A: Physical, 122(1), 23–30.
[9] COMSOL Multiphysics® User Guide. (2022). Piezoelectric Devices Module – Resonator Modeling Examples. COMSOL Documentation Portal.
[10] Bhugra, H., & Piazza, G. (2017). Piezoelectric MEMS Resonators. Springer Series in Advanced Microelectronics.



10.22214/IJRASET

INDEX COPERNICUS

45.98

IMPACT FACTOR: 7.129

IMPACT FACTOR: 7.429

TOGETHER WE REACH THE GOAL

INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Call : 08813907089 (24*7 Support on Whatsapp)