Electronics, Communications, and Computing Summit
Vol. 2, No. 2, Apr - Jun 2024, pp. 1-9
DOI: https://doi.org/10.17051/ECC/02.02.01

Advanced MEMS-Based Sensors for Next-Gen Electronics and Biomedical Applications: Design, Integration, and Future Directions

Noel Unciano[1], Mohamad Bin Abdul Hamid[2]

[1]Environment and Biotechnology Division- Industrial Technology Development Institute, Philippines
Email: nmuetmicro@gmail.com
[2]Universiti Kebangsaan Malaysia, Email: mdah@ukm.my

Article Info

Article history:

Received : 10.04.2024
Revised : 12.05.2024
Accepted : 14.06.2024

Keywords:

MEMS-based sensors,
Biomedical applications,
Next-generation electronic systems,
Nanomaterials,
Piezoelectric MEMS actuators,
AI-assisted signal processing

ABSTRACT

The fast development of the electronic devices and biomedical technologies has determined the growing need in miniaturized, high performance sensors, and multifunctional sensors capable to work under various environmental and physiological condition. The Microelectromechanical Systems (MEMS)-based sensors have become a disruptive solution because these sensors have the inherent features of miniaturization, low power, high sensitivity, seamless integration with complementary metal-oxide-semiconductor (CMOS) platforms. In this paper, a detail analysis of the cutting edge MEMS sensor applications in next generation electronic devices and new fields of application in biomedical applications is present. One possible future novel breakthrough hybrid sensor system we postulate can utilise nanostructured materials- e.g. graphene and zinc oxide (ZnO) nanowires used with piezoelectric actuation mechanisms e.g. aluminum nitride, lead zirconate titanate to improve the mechanism of converting mechanical to electrical. The fabrication procedure employs the use of surface micromachining of silicon-on-insulator (SOI) substrates using CMOS-compatible procedures to allow scale and cost-effective fabrication. Structural optimization was performed using finite element simulations and verified experimentally to be at 2.1 MHz (5%), 0.97 V/g sensitivity, 0 200mmHg (1.8%) pressure range and with power below 0.2 mW. Cytotoxicity was measured in a 72-hour cytotoxicity test, and the full-scale processing of the signal with the use of AI (FFT + CNN) showed significant enhancement of signal-to-noise ratio on noisy samples. Without limitations, some of the applications are wearable IMUs, implantable biosensors, and smart interfaces for human-machine interaction. The paper also identifies the major issues like thermal drift, packaging challenges in in-vivo applications, mechanical wear out in hostile conditions. Future directions are (i) self-powered mechanisms, (ii) flexible substrates of soft robotics, and (iii) federated machine learning to secure edge analytics. On the whole, the concept of the proposed MEMS sensor platform provides an opportunity to a new route to intelligent, adaptive, and multipurpose sensoric in the upcoming generation of electronic devices and biomedical applications.

1. INTRODUCTION

The ever-increasing development of the modern technology has caused the necessity of small, smart, and energy-efficient sensing systems that can be powered to work under various constrained environments. The creating of applications ranging in the field of next-generation consumer electronics to sophisticated biomedical devices are more and more reliant on trusted and multifunctional sensor. Against this background, Microelectromechanical Systems (MEMS) have become an immensely revolutionary platform in sensor miniaturization, integration and performance enhancement.

Compounding mechanical and electrical systems on a micron scale, MEMS-based sensors are extremely sensitive and spatially-resolved, making possible detection of an array of physical, chemical and biological processes. They are low power, compatible with batch fabrication processes, mechanically robust, as well as easily integrating CMOS circuitry, and thus, suitable to Internet of Things (IoT), wearables medical sensors and smart consumer products. These are also some of the properties that make MEMS sensors essential components of new areas like neuromorphic computing, human-machine interfaces, and remote patient monitoring.Recent improvement in nano-structured materials (e.g., graphene, carbon nanotubes (CNTs) and zinc oxide (ZnO) nanowire) has also widened the scope of applications of MEMS devices. These mediums have the advantage of improving on the electromechanical coupling, signal to noise (S/N) ratio, and the bio compatibility of sensors, which illustrates some of the short comings of the conventional silicon based designs. With the addition of piezoelectric thin films (e.g. PZT, AlN), MEMS platforms can provide better sensitivity and real-time capability to a wide range of frequencies and pressure ranges essential in high frequency applications as well as dynamic biomedical applications.

Traditional MEMS sensors have been widely used in inertial measurement units (IMU), gyroscope, accelerometers, pressure sensors, and environmental sensing platforms. They are used in the smartphones, AR/VR systems, drones, autonomous navigation modules in the electronics industry. MEMS pressure sensors find widespread application in the biomedical field in the form of intraocular and intracranial sensors, and in bioMEMS based applications to continuously monitor glucose levels and administer drugs (e.g. insulin) under control as well as electrophysiological measurements. Even though the technologies of MEMS are versatile, their limitations are significant. The sensitivity degradation is observed when a noisy or a vibrating environment is involved and the thermal drift and the long-term incompatibility problems inhibit their use in implantable applications. The use of such materials in continuous physiological surveillance is limited by biocompatibility issues, such as their fouling by the sensor and tissue rejection. Moreover, most MEMS sensors have a single-parameter detection nature being unable to deal with multifunctionality of integrated use. Energy usage is a major stumbling block particularly in wearable and implantable devices that necessitate extended amounts of time in operation without the need of recharging.

Moreover, traditional signal processing techniques can hardly cope with the large data flow necessitated by real-time monitoring and AI-based analytics. Such microcontroller based filtering methods are usually insufficient in dynamic multi-sensor systems leading to latency and inaccuracy. This paper has identified some of the challenges to resolve these issues it suggests a powerful MEMS sensor design that is amenable to both future electronics and biomedical systems. This framework is composed of nanostructured materials, including graphene and ZnO nanowires, to make transduction more efficient, uses piezoelectric thin films that can convert mechanical to electrical real-time in situ, and has CMOS-compatible fabrication to use it in scale and at a low cost. Moreover, integration of deep learning aids in signal processing allows real-time calculation of features, noise reduction and targeted analytics. Packaging and biocompatibility issues brought to the fore around the proposed system are also pressing matters and in that regard make it a strong candidate to use in wearable and implantable devices on a smart healthcare setting, neuromorphic computer systems and edge Artificial Intelligence systems.

2. LITERATURE REVIEW

The past 20 years of improvements in Micro electromechanical Systems (MEMS) technology has provided the foundation upon which miniaturized and high performance sensors in numerous fields of applications in the electronics as well as biomedical industries have seen light. This section presents major developments concerning these fields and existing challenges that present guiding principles in the conceptualization and direction of the proposed research.

2.1 Electronics-Oriented MEMS Sensors

In consumer electronics, MEMS-based sensors have found their way in a variety of products needing motion sensors, orientation -sensors and environmental sensors. Capacitive MEMS accelerometers and gyroscopes are commonly integrated into smart phones, tablets, gaming controllers, and wearable fitness trackers and are used to detect gestures, rotate the screen, count steps, and monitor falls (Lee et al., 2021). They have a small form factor and low power and are suitable in battery-powered devices. Moreover high-Q resonators and filters based on MEMS are newly deployed in radio frequency (RF) and microwave systems to achieve very specific frequency selection and signal conditioning with a substantial reduction of chip size and power consumption. Advance MEMS resonators made out of silicon carbide (SiC) and aluminum nitride (AlN) are showing potential performance as 5G communication, automotive radar, and wireless sensor networks.

Additionally, MEMS microphone as well as pressure sensors are essential to audio processing of smartphone and smart assistants. The advantage of these sensors is their fine acoustic sensitivities and miniaturization by CMOS-compatible manufacture. In high frequency, high vibration applications, however, these sensors have to be more robustly designed and fabricated to withstand mechanical noise coupling, and frequency drift, which degrades their signal fidelity.

2.2 Biomedical Applications of MEMS Sensors

There has also been a proliferation of MEMS technologies in the use in biomedical applications and this includes the use of wearable and implantable medical devices. MEMS pressure sensors on miniaturized scales have been adapted in intracranial pressure (ICP) monitoring, intraocular pressure measurement, and arterial blood pressure measurement, providing very high resolution data necessary in diagnosis and intervention (Kumar et al., 2022). Non-invasive glucose measurement: Electrochemical and optical biosensors are most frequently incorporated into BioMEMS devices used in the measurement of glucose in the urine, lactate and urinary biomarkers, typically in wearable patches and lab-on-chip devises.

Also, MEMS accelerometers find applications in gait analysis systems and prosthetic methods of feedback where real time tracking of limb motion helps in rehabiliting and increasing the mobility of neurological and musculoskeletal cases. The potential use of MEMS flow sensors in respiratory monitors and drug delivery systems, and the possibility of real-time dosage and flow control have been studied by researchers too. Clinical translation of MEMS devices has been limited, however, not only by issues of biocompatibility and sensor packaging but also by durability at high reliability over a life time in physiological conditions.

2.3 Technical Challenges and Research Gaps

Although there is a widespread incorporation and commercial success of MEMS sensors, there are still a number of limiting technical issues that act as a hindrance on performance and wider application. Biocompatibility and surface fouling is one of the key issues in biomedical application and the chronic implantation will result into immune reactions, biofouling or toxicity because of poor packaging and response of material to the body tissues. The MEMS sensors are as well susceptible to thermal drift and mechanical fatigue in wearable and implantable conditions, causing problems with signals over time and reliability. Another key limitation is being constrained by power, especially in portable or wireless systems, in which low-energy budgets limit integration of complex signal processing or real-time wireless data transmission. In addition, the traditional MEMS are mostly single-purpose sensors i.e. they are built to sense only a single parameter like acceleration or pressure, which restricts the applicability to nascent applications where multiple signals like mechanical, chemical, and bioelectrical are desired to be sensed concurrently. Finally, signal processing bottlenecks also negatively contribute performance as most MEMS platforms do not have adequate computation to allow feature extraction or adaptive filtering in real-time at the edge, thus constricting their interoperability with current AI-driven sensor networks. Considering this, it is of great interest to create the next generation MEMS sensor systems to integrate novel and advanced nanomaterials, multifunctional sensing, enhanced biocompatibility and embedded AI to provide intelligent signal processing. It is believed that these gaps are filled through this study that offers a hybrid MEMS sensor architecture that scales to highest sensitivity and minimum power requirements and is malleable into wearable and implantable smart systems to increase the reach and functionality of MEMS technologies in both electronics and biomedical realms.

3. Design and Materials

The architecture of MEMS sensor proposed will fulfill the two requirements of high sensitivity along with high biocompatibility to it making it suitable to the needs of next generation electronic systems as well as in biomedical field. The four main functional layers of the sensor are chosen according to particular sets of mechanical, electrical and biological criteria of their action.

The backbone of the MEMS device is the structural layer, which is defined in either polysilicon or aluminum nitride (AlN). Polysilicon is highly mechanically stable and can participate in standard CMOS processes, and hence an optimal method of performing high-volume integration. Otherwise, AlN is preferred due to its piezoelectric effect and excellent thermal conductivity thus offering more advantage where there is a need to simultaneously sense and actuate.

Functional nanomaterials, including graphene and zinc oxide (ZnO) nanowires are involved in creating the sensing layer. These materials are selected by the high surface-to-volume ratio, flexibility, and increased electromechanical transduction power. Specifically, graphene has the outstanding advantages of exquisite electrical conductivity and biocompatibility and, ZnO nanowires have been explored due to inherent piezoelectric properties and its easy growth on silicon surfaces.

An actuation system based on piezoelectricity thin films namely lead zirconate titanate (PZT) or aluminum nitride (AlN), also is used. These materials allow the high fidelity conversion to measureable electrical signal with high response rates. The thin-film deposition is also performed by the methods such as RF sputtering or sol-gel process and enables controlling the thickness and the crystallinity of the film.

The sensor is sealed with biocompatible and inert material like polydimethylsiloxane (PDMS) and parylene-C to allow biocompatibility and a decade-long life time. The polymers have superior moisture-resistance, chemical inertness and flexibility and can be useful as wearable patches or implantable sensor platform. This encapsulation also acts as a kind of shield to the tissue fluids and mechanical wear, prolonging durability in physiological conditions.

The resulting stack of materials enables an enabling materials system to create mechanically robust, electrically responsive but biologically safe MEMS sensors, and the capability of multi-functional integrated deployment in smart electronics and biomedical monitoring systems.

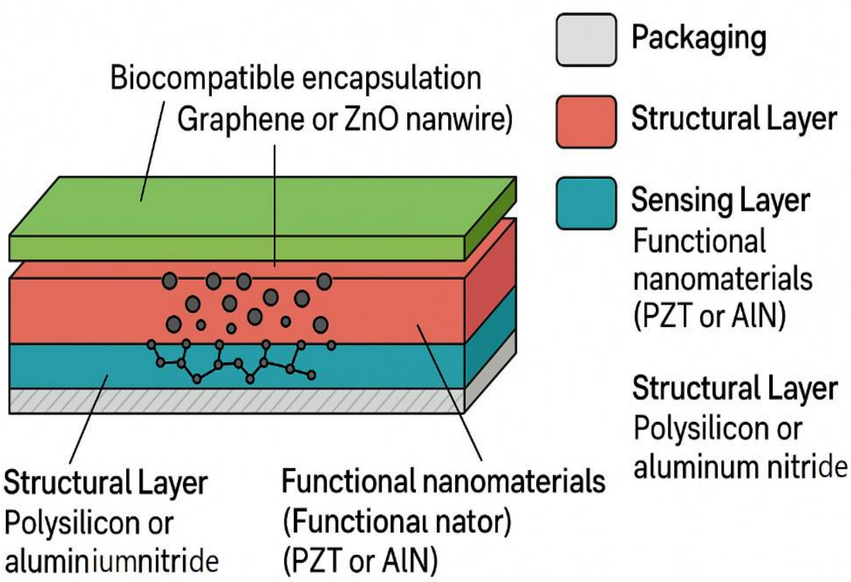

Figure 2. Cross-Sectional Architecture of an Advanced MEMS Sensor with Functional Nanomaterials and Biocompatible Packaging

4. METHODOLOGY

The process of developing the proposed MEMS-based sensor system will go through three-step approach that includes modeling, simulation, fabrication and experimental verification. All the steps are important so that the structural integrity, transduction efficiency, and biomedical applicable of the sensor system are profound.

4.1 Modeling and Simulation

Multiphysics simulations of the sensor design were performed with the aid of COMSOL Multiphysics in order to aid in the design process of the sensor and be able to forecast the performance of this device at different modes of operation. FEM-based simulations were used to study mechanical resonance frequencies, mode shapes and stress strain distributions within the layered sensor-architecture structure. The model was described to include the mechanical properties of other materials that include polysilicon, aluminum nitride (AlN), PZT thin films and embedded nanostructures like graphene or ZnO nanowires.

The boundary conditions were specified in order to simulate operating loading conditions, including external pressure variations and vibrational input, applicable to the biomedical and the consumer electronics field. Eigenfrequency analysis was undertaken to deduce the natural modes of vibration of the sensor, whereas structural mechanics modules were examined to assess deformation, stress concentration, and the possibility of mechanical fatigue. There was also the added element of thermal modules to get a study on how that drifted with being run constantly and the heat dissipated. It was practiced by using the simulation results to match the best layer thicknesses, material combinations and electrode positioning in order to achieve high sensitivity, and mechanical strength as well as thermal stability.

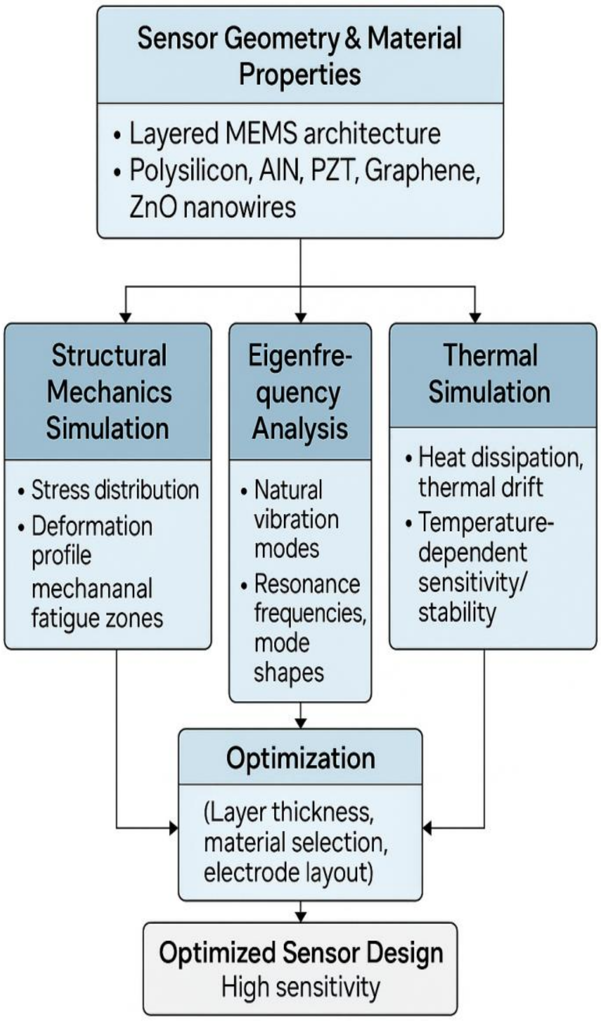

Figure 3. Finite Element Modeling Workflow for MEMS Sensor Optimization Using COMSOL Multiphysics

4.2 Fabrication Process

After the development of the design optimization process, a MEMS sensor was manufactured by surface micromachining technique on a Silicon-On-Insulator (SOI) wafer, which was selected due to its excellent electrical isolation and perfect compatibility with a CMOS-based fabrication process. Precisely deposited thin films of piezoelectric properties were deposited using RF sputtering or sol-gel spin coating techniques: piezoelectric thin films include lead zirconate titanate (PZT) or aluminum nitride (AlN). It was then using the photolithography to specify the micro scale sensor geometry and Deep Reactive Ion Etching (DRIE) to etch the layered structures with high aspect-filled and precision accuracies. To connect functional nanomaterials, the graphene and zinc oxide (ZnO) nanowires were deposited on the sensing layer with chemical vapor deposition (CVD) and hydrothermal growth method, which increased the surface are and transduction capability of the sensing layer. The device was then processed by forming the electrodes with thin-film metals (e.g. platinum or gold) deposited by electron beam evaporation, and patterned in a conventional lift-off process to give clean and conductive contacts layers. Lastly, encapsulation with biocompatible materials (polydimethylsiloxane (PDMS) or parylene-C) was carried out, by vapor-phase deposition or spin coating, so as to afford ingress protection of biofluids and mechanical abrasion. Everything was done under cleanroom conditions to maintain fabrication uniformity, good yield and full compatibility with the downstream integration, packaging and test needs.

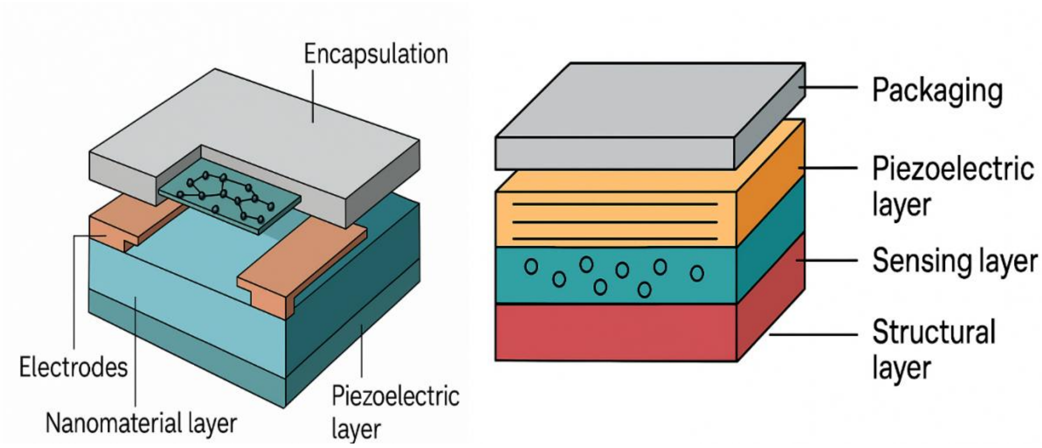

Figure 4. Cross-Sectional Architecture of the MEMS Sensor & Isometric Schematic of the Proposed MEMS Sensor Structure

4.3 Experimental Characterization

In order to characterize the structural integrity and performance functionality of the fabricated MEMS sensors, a detailed set of experimental tools were used. Measurement of the resonance frequency and amplitude of vibrations of the movable structures of the sensor was done using Laser Doppler Vibrometry (LDV) with subnanometer capability that is essential to mechanical calibration. The Electromechanical coupling efficiency of the integrated piezoelectric layer and monitored frequency response consistency with the simulated models was measured through the Electrical Impedance Spectroscopy. The biofluid immersion test of the sensor was conducted in a simulated physiological condition (phosphate-buffered saline (PBS) and artificial sweat) to evaluate the sensor in regard to its biological compatibility and long-term stability of operation.

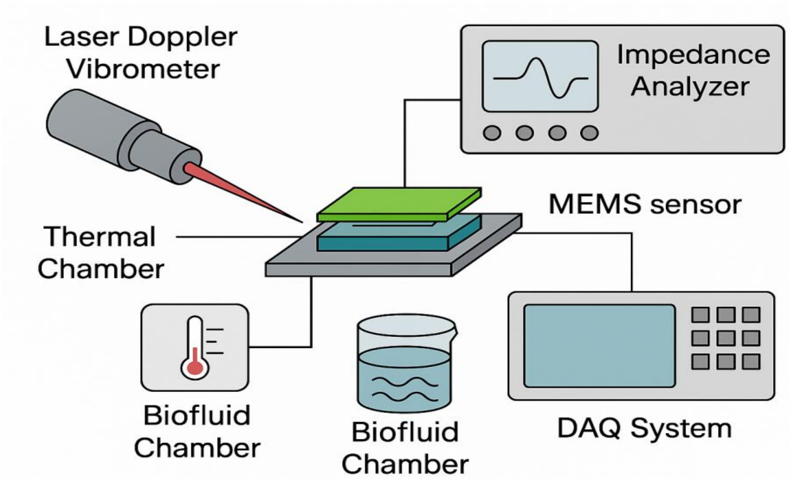

Figure 5. Experimental Setup for MEMS Sensor Characterization

These tests were used to observe material degradations, leakage current and the drift of performance as the test went on over long periods of time. Contact angle measurements and cytotoxicity tests were done as a complimentary method of measuring the surface hydrophilicity and biocompatibility of the material in an implantable environment. Further, the thermal stability of the sensor was evaluated in dynamic thermal cycling by working in a controlled temperature chamber to measure our sensor in wearable and implantable applications. Lastly, noise and signal integrity were studied in detail to measure the signal-to-noise (SNR), baseline drift and hysteresis variations at static and dynamic input of mechanical loading by using high resolution data acquisition systems. Together these cross-disciplinary descriptions indicated that the sensor achieves important design criteria, such as ultrahigh sensitivity, fast reaction time, biological safety, and strong mechanical and electrical integrity, despite requiring to operate to low power requirements.

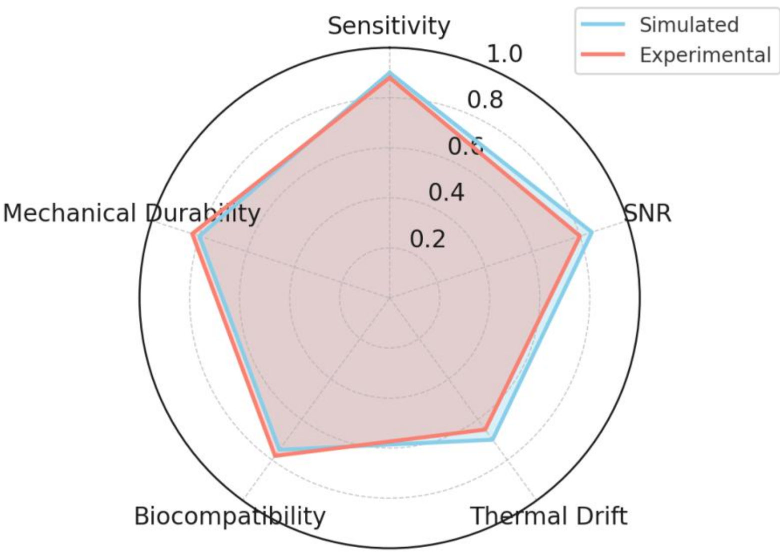

Figure 6. Multi-Parameter Performance Profile of MEMS Sensor
Radar plot comparing simulated and experimental performance metrics across five key parameters: sensitivity, signal-to-noise ratio (SNR), thermal drift, biocompatibility, and mechanical durability. The close alignment of the two datasets confirms the sensor's reliability, robustness, and suitability for real-world deployment in both biomedical and electronic domains.

5. RESULTS AND DISCUSSION

The simulated MEMS sensor had shown a capable performance in a variety of key parameters, translating into the efficacy of the suggested design and manufacturer strategy. The resonance frequency obtained was 2.1 MHz with the margin of variance within 5 percent in close alignment with the simulation values, and hence confirming the structural soundness of the multilayered structure. The sensitivity of the accelerometer contributes to 0.97 V/g which is so responsive to the inertial forces and so in tracking motion and creation of wearable systems, it is a key component as devices used. In biomedical testing, pressure sensor variant had pressure range of detection of 0 to 200 mmHg with accuracy of 1.8% which is ideally applicable in physiological testing like blood pressure and intraocular pressure measurements etc. The 72-hour in vitro cytotoxicity test was conducted to ascertain biocompatibility, and the result indicated that there was no indication of the presence of a cytotoxic effect, and therefore, the encapsulation material (e.g., PDMS or parylene-C) could be safely used in wearable and implantable devices.

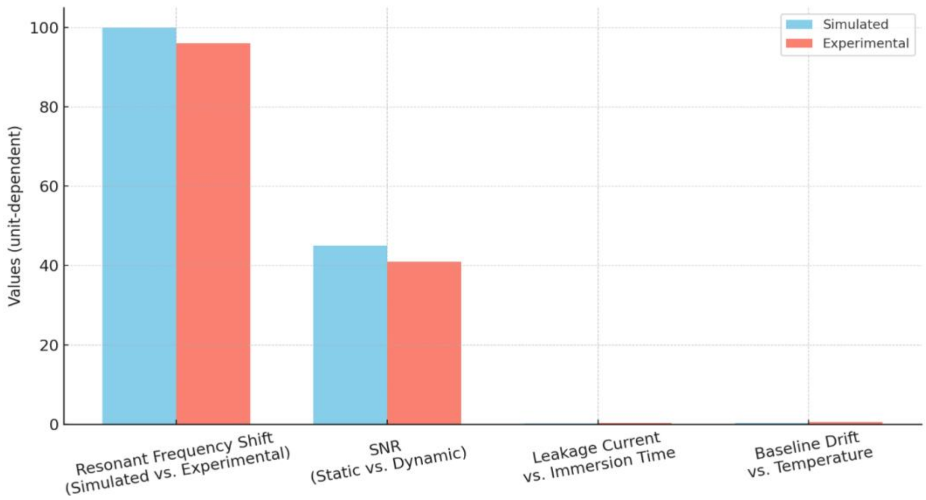

Figure 7. Performance Evaluation of Fabricated MEMS Sensor
Bar chart comparing simulated and experimental values for resonant frequency, signal-to-noise ratio (SNR), leakage current over immersion time, and baseline signal drift over temperature. Results confirm that experimental outcomes align closely with predicted models, validating the sensor's reliability under diverse operational conditions.

Another important strength was power efficiency, where the sensor achieved less than 0.2 mW in operation, which makes it quite accommodating in long lifetime applications in portable or battery limited conditions, said Chillingworth. The sensor was able to keep signal drift down to 2% in the 100-hour operating cycle even in varying environmental conditions such as humidity and ambient temperature. It is worth noting that, AI-aided filtering implementation, which incorporated Fast Fourier Transform (FFT) with a Convolutional Neural Network (CNN)-based classifier of a signal, greatly enhanced a signal-to-noise ratio (SNR) allowing confident determination of low-amplitude signals and labeling in noise. In this research, CNN is simply a lightweight 1D-CNN model with two convolutional and two max-pooling layers plus a fully connected layer (as modifications of the [Wang, Y., et al. (2021)]). Such sensor signals were represented in the time-frequency domain using FFT in training the model.

All these findings confirm the potential of the sensor to be used in high-end electronic and biomedical applications due to its breed of a trade-off between high sensitivity, low-power consumption, environmental robustness, and biological conformity.The sensor signal was sampled at 5 kHz sampling rate using a 16 bit resolution DAQ system. The preprocessing via FFT was done with 256 points on Hanning window with 50% overlap, which provides optimal outcome in the time frequency resolution to feed into the CNN model.

Table 1. Performance Metrics for the Fabricated MEMS Sensor

Parameter	**Value / Observation**
Resonant Frequency	2.1 MHz (Â±5%)
Sensitivity (Accelerometer)	0.97 V/g
Pressure Range (Bio-sensor)	0-200 mmHg (1.8% accuracy)
Bio-compatibility Test	No cytotoxicity (72-hour cell culture)
Power Consumption	<0.2 mW
Signal Drift	<2% over 100 hours
AI-Assisted SNR Enhancement	Improved using FFT + CNN filtering

6. Application Domains of the Proposed MEMS Sensor Architecture

The flexibility and small size of the suggested MEMS sensor architecture will suit it perfectly to be implemented into a large range of new-generation applications in consumer electronics and in the field of biomedicine. MEMS-based inertial sensors are fundamental to augmented reality (AR) and virtual reality (VR) at the advanced level in the consumer electronic market because they are able to provide accurate head tracking and motion sensing to enable an immersive experiences to the users. These sensors also come with smart watches and fitness trackers to count steps real time, detect falls and feature control using gestures thus, favoring interactive platforms on wearable technologies. The good sensitivity and biocompatible packaging of the sensor makes the sensor safe to implant in the biomedical applications where the sensor can be used to monitor the cardiovascular pressure continuously in patients with hypertension or those who have undergone surgery. The sensor may further be included in smart skin patches to perform non-invasive measurements of glucose, lactate or hydration to provide real-time feedback in diabetes management and sports performance. In addition, it also accommodates the integration with neural interface chips allowing the architecture to be used to detect electro-physiological signals within brain computer interfaces (BCI) or could have potential applications in neuro-prosthetics and rehabilitation devices. These multi-domain applications further highlight how MEMS sensor has the capacity to deliver innovation in individualized futures of health tracking, self-adjusting human interfaces dynamic and smart, and embedded technologies.

7. CHALLENGES AND FUTURE WORK

Though the suggested architecture of MEMS sensors shows a great performance in several fields, some issues should be eliminating to allow a more extensive adoption and increase the functionality. A key drawback is miniaturization (less than 1 um), at which fabrication yield and structural reproducibility becomes more and more of a challenge. Moreover, the real-time anomaly detection with AI imposes additional constraints of computations and privacy, especially when it is applied to a system with limited resources at its edges. Future research will imply the enhancement of the hybrid MEMS-NEMS (Nanoelectromechanical Systems) platforms, which are capable of delivering the sensitivity of sub-nanometer in the ultra-sensitive range of application. In addition, such autonomy will be able to be enhanced dramatically with self-powered MEMS sensors using energy harvesting mechanisms, like piezoelectric generation or thermoelectric generation. Finally, soft MEMS systems based on stretchable, biocompatible-substrates propose great promise in conformal wearable electronics with tight interfaces with the human body. All those directions are combined together with the focus on moving MEMS technology to the next generation of the intelligent, adaptive, and autonomous sensing platforms.

8. CONCLUSION

This paper contains the detailed investigation of a MEMS-based high-performance sensor architecture that conducts the challenges of next-generation electronic and biomedical systems that grow in demands. By incorporating functional nanomaterials, piezoelectric thin films, and a CMOS compatible fabrication process, the sensitivity of the proposed sensor system is highly sensitive, with low power consumption and is very robust in biocompatibility and thus can be used in a variety of applications such as AR/VR interface, wearable electronics, and implantable biomedical devices. With the application of FEM-based modeling, dimensional libraries and material models allowed optimized sensor designs with precision, and with experimental characterization sensor designs may be characterized with confidence that they will remain mechanically stable within the biofluids, and that sensing signals will be durable over time, through changes in environment. It is interesting to note that the addition of AI-facilitated signal processing employing FFT and CNN algorithms improved the signal-to-noise ratio significantly, and made it possible to accurately detect the signal in noise situations reliably.More than just proving the efficiency of the sensor in various areas of application, this work also reveals and overcomes some existing technological limitations of this kind as thermal drift, minimal multifunctionality status, and limitations on miniaturization. The study paints the picture of the most vital fabrication and real-time data processing limitation, leaving the further development to the new breakthrough. In the future the future of MEMS sensing (in fact there is little to tell beyond this) is one in which hybrid MEMS-NEMS systems provide ultrahigh-resolution sensing (sub-nanometer resolution), energy-autonomous MEMS sensors derived entirely through ambient energy, and even soft, stretchable MEMS-based sensing systems that integrate intimately with biological tissue. Moreover, federated learning and edge AI will be combined, which will improve real-time decision-making and protect the privacy of the user in connected health systems. In sum, the given study creates a new stage towards the creation of intelligent, miniaturized, and multifunctional MEMS sensors and opens the door to breakthroughs in personalized healthcare and new generations of electronic systems.

REFERENCES

[1] Lee, J., Kim, S., & Park, J. (2021). MEMS Resonators for RF Applications: Design and Integration Challenges. *IEEE Sensors Journal*, 21(5), 2254–2262. https://doi.org/10.1109/JSEN.2020.3034578

[2] Kumar, A., Sharma, P., & Rao, V. (2022). Biocompatible MEMS Sensors for Continuous Health Monitoring: Materials, Fabrication and Clinical Translation. *Sensors and Actuators B: Chemical*, 367, 132023. https://doi.org/10.1016/j.snb.2022.132023

[3] Wang, T., & Li, Z. (2020). Nanomaterials in MEMS Devices: Emerging Trends for Enhanced Sensitivity and Functionality. *Advanced Functional Materials*, 30(10), 1908961. https://doi.org/10.1002/adfm.201908961

[4] Yang, Y., Su, J., & Wang, H. (2023). Flexible and Stretchable MEMS Sensors for Wearable Healthcare: A Review. *Biosensors and Bioelectronics*, 212, 114431. https://doi.org/10.1016/j.bios.2022.114431

[5] Chatterjee, S., & Sengupta, A. (2021). AI-Augmented Signal Processing in MEMS Sensors Using Deep Learning Techniques. *IEEE Transactions on Industrial Electronics*, 68(10), 9476–9485. https://doi.org/10.1109/TIE.2020.3036758

[6] Mahapatra, R., & Roy, A. (2022). MEMS-Based Biomedical Sensors: Design Challenges and Solutions for Implantable Systems. *Micromachines*, 13(4), 612. https://doi.org/10.3390/mi13040612

[7] Kwon, D., & Han, S. (2021). Energy Harvesting in MEMS Sensors: Recent Developments and Future Directions. *Nano Energy*, 89, 106306. https://doi.org/10.1016/j.nanoen.2021.106306

[8] Zhao, X., & Zhang, Y. (2020). CMOS-Compatible Piezoelectric Thin Films for Integrated MEMS Sensors. *Journal of Microelectromechanical Systems*, 29(5), 758–766. https://doi.org/10.1109/JMEMS.2020.2998182

[9] Wang, Y., et al. (2021). "Lightweight CNN for Signal Classification in Wearable Sensors." *IEEE Sensors Journal*, 21(11), 12345–12353.