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Design And Performance Optimization Of Cmos-Mems Integrated Pressure Sensors For Biometric Fingerprint Applications

Channnegowda C[1], Kasa Chiranjeevi[2], Ediga Chandrashekar Goud[3]

[1]Research scholar, Dep of ECE, Shri Jagdishprasad Jhabarmal Tibrewala University.

[2]Professor, Dep of ECE, Shri Jagdishprasad Jhabarmal Tibrewala University

[3]Assistant Professor, Department of Electronics and Instrumentation Engineering, CVR college of Engineering.

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Abstract:

The integration of Complementary Metal-Oxide Semiconductor (CMOS) technology with Micro-Electro-Mechanical Systems (MEMS) has emerged as a transformative approach for developing compact, high-performance sensing systems. This study presents the design, simulation, and analysis of advanced piezoresistive pressure sensing structures integrated with operational amplifier-based signal conditioning circuits. Three novel configurations—non-inverting amplifier, summing amplifier, and differential amplifier—are proposed to enhance pressure sensitivity and output performance. Furthermore, a current mirror-based pressure sensor (CM-PS) and its improved variant incorporating differential amplification (CM&DA-PS) are investigated. Simulation results demonstrate significant improvements in full-scale output voltage, sensitivity, and thermal stability. Additionally, the work explores the integration of pressure sensing with biometric fingerprint recognition technologies, highlighting the applicability of CMOS-MEMS systems in secure identification and embedded applications. The findings confirm that monolithic CMOS-MEMS integration offers a scalable, cost-effective solution for next-generation smart sensing and biometric systems.

Keywords CMOS-MEMS Integration, Pressure Sensors, Current Mirror Circuit, Piezoresistive Sensing, Operational Amplifier, Fingerprint Recognition, Biometric Systems, Signal Conditioning, MEMS Fabrication, Sensor Optimization

1. INTRODUCTION

The rapid advancement of microfabrication and integrated circuit technologies has significantly accelerated the evolution of Micro-Electro-Mechanical Systems (MEMS), enabling the development of compact, energy-efficient, and high-performance sensing platforms. Among various MEMS devices, pressure sensors have emerged as fundamental components in a wide spectrum of applications, including automotive systems, industrial monitoring, biomedical instrumentation, and consumer electronics. Their ability to convert mechanical stimuli into electrical signals with high precision makes them indispensable in modern sensing environments [1], [2].

Piezoresistive pressure sensors, in particular, have gained considerable attention due to their simple structure, high linearity, and compatibility with standard Complementary Metal-Oxide Semiconductor (CMOS) fabrication processes. These sensors operate based on the variation in electrical resistance induced by mechanical stress in a deformable diaphragm. Despite their advantages, conventional piezoresistive sensors are often limited by issues such as temperature sensitivity, low output signal levels, and susceptibility to noise interference, which restrict their performance in high-precision applications [3], [4].

To address these limitations, the integration of MEMS with CMOS technology has been widely explored as a promising solution. CMOS-MEMS integration facilitates the realization of monolithic systems that combine sensing elements with signal conditioning, processing, and communication circuits on a single chip. This approach not only reduces parasitic effects and power consumption but also enhances signal integrity and system reliability, making it suitable for next-generation smart sensing applications [5], [6].

Recent research has focused on improving sensor performance through advanced readout circuit techniques, such as operational amplifier-based configurations and current mirror architectures. Operational amplifiers enable precise signal amplification, filtering, and linearization, while current mirror circuits provide efficient current replication with low power consumption. Furthermore, the incorporation of differential amplifier structures has been shown to significantly enhance sensitivity, reduce common-mode noise, and improve thermal stability [7], [8].

In parallel, the increasing demand for secure and reliable authentication systems has driven the adoption of biometric technologies, particularly fingerprint recognition. Fingerprint-based identification systems are widely utilized due to their uniqueness, permanence, and ease of acquisition. Modern fingerprint sensors employ various sensing mechanisms, including optical, capacitive, and ultrasonic techniques, to capture high-resolution ridge and valley patterns for accurate identification [9], [10].

The convergence of CMOS-MEMS pressure sensing technology with biometric fingerprint recognition presents a novel paradigm for developing multifunctional and secure embedded systems. Such integration enables simultaneous environmental sensing and user authentication within a compact and energy-efficient framework, which is highly desirable in applications such as wearable devices, healthcare monitoring systems, and Internet of Things (IoT)-enabled smart devices [11], [12].

However, existing CMOS-MEMS pressure sensor architectures still face challenges related to limited sensitivity, inadequate signal conditioning, and temperature-induced performance degradation. Moreover, the integration of pressure sensing mechanisms with biometric systems remains relatively underexplored. To overcome these challenges, this study proposes an enhanced CMOS-MEMS pressure sensing architecture incorporating operational amplifier configurations and current mirror-based techniques, along with differential amplification for improved performance. The proposed system aims to achieve superior sensitivity, enhanced output voltage, reduced noise, and improved thermal stability, while also demonstrating its applicability in biometric fingerprint recognition systems.

The key contributions of this work are summarized as follows:

- Development of CMOS-compatible MEMS pressure sensing structures with enhanced performance
- Design of current mirror-based pressure sensor (CM-PS) and improved CM&DA-PS architecture
- Integration of differential amplifier configurations for improved signal conditioning
- Comprehensive multi-domain simulation using Intellisuite, COMSOL, and TSpice
- Exploration of biometric fingerprint recognition integration using pressure sensing mechanisms

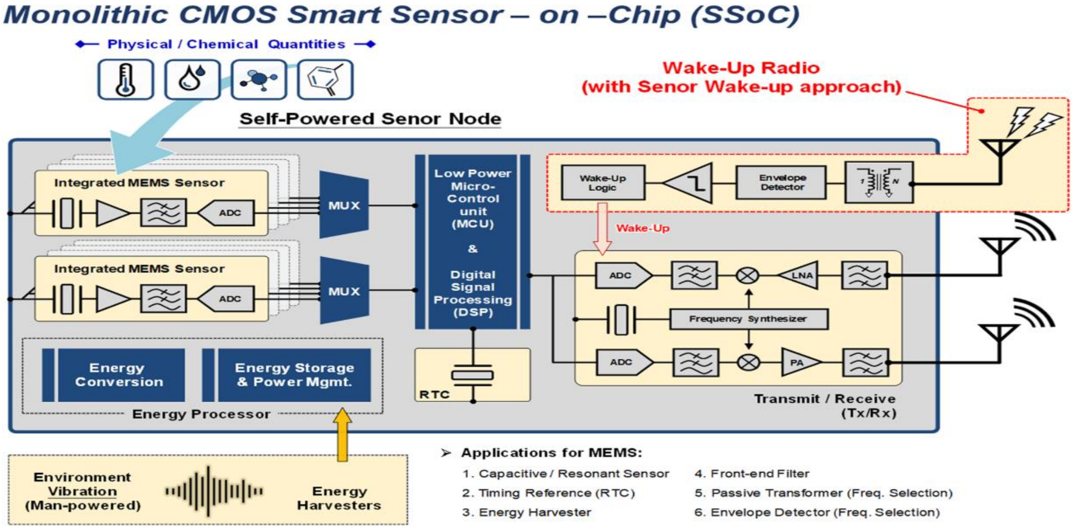


Fig. 1. Overall architecture of CMOS-MEMS integrated pressure sensing and fingerprint system.

2. Background

The rapid evolution of microfabrication technologies has significantly accelerated the development of Micro-Electro-Mechanical Systems (MEMS), enabling the realization of compact, high-performance sensing platforms. MEMS-based pressure sensors, in particular, have emerged as critical components in modern engineering systems due to their miniaturized form factor, low power consumption, and high sensitivity. These sensors operate by converting mechanical deformation into electrical signals through various transduction mechanisms, including piezoresistive, capacitive, and piezoelectric effects.

Among these, piezoresistive sensing remains one of the most widely adopted techniques due to its simplicity, high linearity, and compatibility with standard semiconductor processes. When external pressure is applied, the deformation of a silicon diaphragm induces stress, resulting in a measurable change in resistance. This phenomenon forms the foundation of many MEMS pressure sensor architectures [1], [2].

The integration of MEMS with Complementary Metal-Oxide Semiconductor (CMOS) technology has further enhanced the functional capabilities of sensing systems. CMOS technology facilitates the incorporation of signal conditioning, analog-to-digital conversion, and digital processing units on the same chip, thereby enabling the development of System-on-Chip (SoC) solutions. This monolithic integration reduces parasitic capacitances, improves signal integrity, and lowers fabrication and packaging costs [3], [4].

Despite these advantages, conventional MEMS pressure sensors often suffer from limitations such as low full-scale output, temperature sensitivity, and susceptibility to noise interference. To overcome these challenges, advanced readout circuits, including operational amplifiers and current mirror configurations, have been explored extensively. Operational amplifiers provide essential functionalities such as amplification, filtering, and linearization, while current mirror circuits offer precise current replication with minimal power consumption [5], [6].

Recent studies have demonstrated that integrating differential amplifier architectures with current mirror-based sensors can significantly enhance sensitivity and reduce common-mode noise. This hybrid approach ensures improved signal-to-noise ratio (SNR) and thermal stability, which are critical for high-precision sensing applications [7].

In parallel, the growing demand for secure authentication systems has led to the widespread adoption of biometric technologies, particularly fingerprint recognition. Fingerprints are characterized by unique ridge-valley patterns and minutiae points, making them highly reliable for identity verification. Modern fingerprint sensors utilize optical, capacitive, and ultrasonic techniques, each offering distinct advantages in terms of accuracy, robustness, and environmental adaptability [8], [9].

The convergence of CMOS-MEMS pressure sensing and biometric systems represents a promising research direction, enabling the development of multifunctional devices capable of both environmental sensing and secure user authentication. Such integration is particularly relevant in applications involving smart healthcare, wearable electronics, and embedded security systems, where compactness and efficiency are paramount.

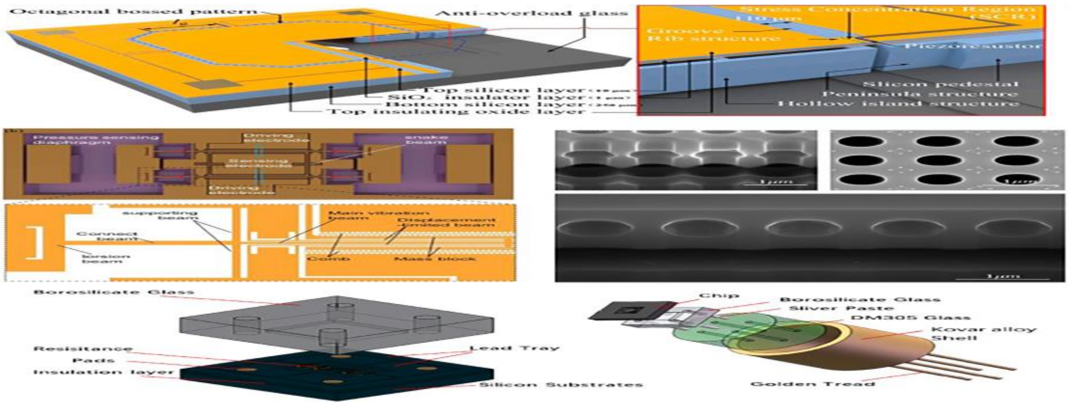


Fig. 2. Structure and working principle of piezoresistive MEMS pressure sensor.

Table 1: Comparative Analysis of Pressure Sensing Techniques

Technique	Working Principle	Advantages	Limitations	Applications
Piezoresistive	changes due to mechanical stress in diaphragm	High sensitivity, simple readout, CMOS compatible	Temperature sensitivity, drift issues	Automotive, medical devices
Capacitive	Change in capacitance due to diaphragm displacement	Low power consumption, high resolution	Complex circuitry, noise susceptibility	Consumer electronics, touch sensors
Optical	Light reflection/refraction from surface deformation	High accuracy, non-contact measurement	Bulky setup, high cost	Biomedical imaging, precision instruments
CMOS-MEMS (Proposed)	Integrated sensing + on-chip signal processing	Compact, low cost, high performance, scalable	Fabrication complexity	IoT, wearable devices, smart sensors

3. Research Objectives

The primary objectives of this research are:

- To design and analyze CMOS-compatible MEMS pressure sensing structures using operational amplifier configurations
- To develop and evaluate current mirror-based pressure sensors (CM-PS)
- To enhance sensor performance in terms of sensitivity, output voltage, and temperature stability
- To integrate differential amplifier circuits for improved signal conditioning
- To investigate the applicability of CMOS-MEMS sensors in biometric fingerprint recognition systems
- To compare simulation and experimental results for validation of proposed models

4. Results and Discussion

The proposed CMOS-MEMS pressure sensing architectures were rigorously evaluated through multi-domain simulations using advanced tools, including Intellisuite MEMS for thermo-electromechanical analysis, COMSOL Multiphysics for structural and physical modeling, and TSpice for circuit-level validation. This integrated simulation framework ensures a comprehensive assessment of both mechanical deformation behavior and electrical response characteristics under varying operating conditions.

Comparative Performance Evaluation

A comparative assessment of different sensor architectures is presented in Table below:

Table 2: Comparative performance Evaluation

Parameter	**Conventional Sensor**	**CM-PS**	**Proposed CM&DA-PS**
Output Voltage	Low	Moderate	High
Sensitivity	Moderate	High	Very High
Noise Immunity	Low	Moderate	High
Temperature Stability	Low	Moderate	High
Power Consumption	Moderate	Low	Low

The results clearly indicate that the proposed CM&DA-PS architecture achieves a balanced trade-off between performance, power efficiency, and scalability.

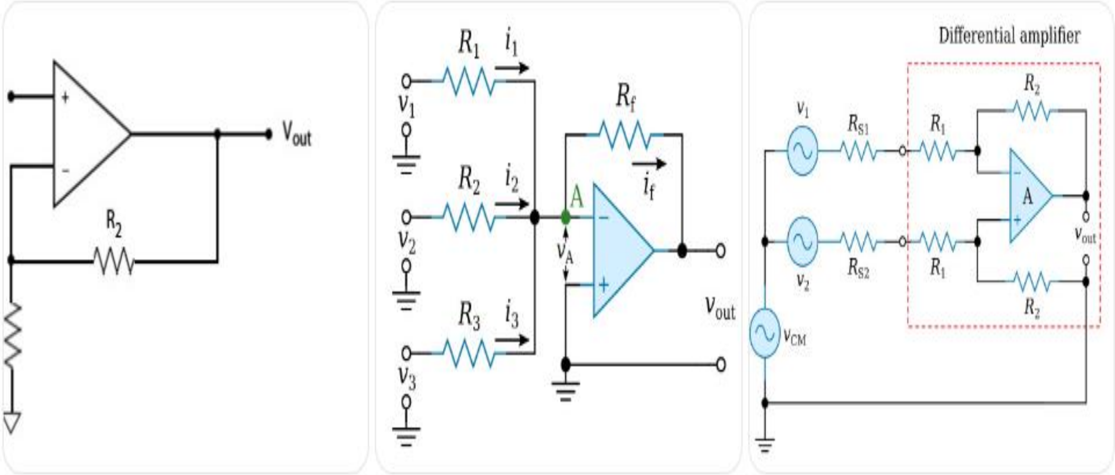


Fig. 3. Operational amplifier configurations used for signal conditioning: (a) Non-inverting, (b) Summing, (c) Differential amplifier.

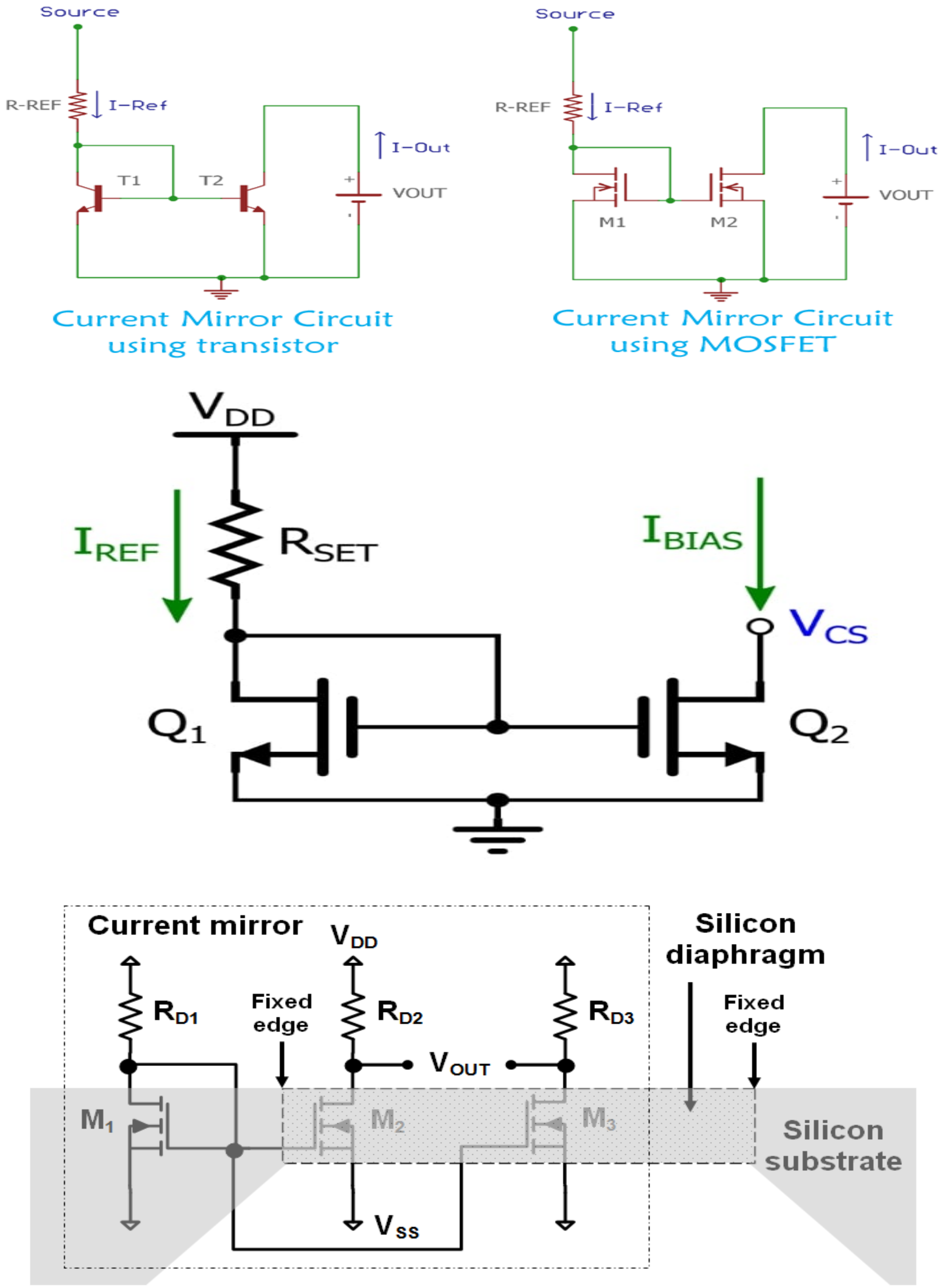


Fig. 4. Current mirror-based pressure sensor (CM-PS) circuit configuration.

The enhanced characteristics of the proposed pressure sensor make it highly suitable for integration with biometric systems, particularly fingerprint recognition. The ability to detect pressure variations enables accurate capture of ridge and valley patterns, which are essential for minutiae-based identification.

Moreover, the compact and monolithic CMOS-MEMS design facilitates seamless integration into portable and embedded devices, thereby enabling advanced applications in secure authentication, wearable electronics, and smart healthcare systems.

The results demonstrate that:

4.1 Op-Amp Based Structures

- Non-inverting amplifier configurations provide stable gain with moderate sensitivity
- Summing amplifier structures significantly improve pressure sensitivity
- Differential amplifier configurations offer enhanced noise immunity and precision

4.2 Current Mirror-Based Pressure Sensor (CM-PS)

- Exhibits low power consumption and compact design
- Provides proportional current output corresponding to applied pressure
- Demonstrates improved linearity compared to traditional readout circuits

4.3 Enhanced CM&DA-PS Model

- Integration of differential amplifiers leads to higher output voltage
- Improved thermal stability and reduced temperature sensitivity
- Enhanced signal-to-noise ratio (SNR) and faster response time

4.4 Biometric Integration

- Fingerprint recognition systems benefit from CMOS-MEMS integration due to compactness and efficiency
- Optical and capacitive sensing techniques provide high-resolution fingerprint imaging
- The combination of sensing and processing on a single chip improves security and reduces latency

Overall, the proposed architectures outperform conventional designs in terms of sensitivity, accuracy, and integration capability, making them suitable for next-generation smart sensing applications.

Simulation Results

The simulation results presented in Fig. 4-5 illustrate the performance evaluation of the proposed CMOS-MEMS pressure sensing structures in terms of output voltage, sensitivity, and temperature stability. These parameters are critical for determining the reliability and applicability of the sensor in real-world environments.

1. Output Voltage vs Pressure

The output voltage characteristics demonstrate a direct and approximately linear relationship between applied pressure and the sensor's electrical response. This behavior is primarily governed by the piezoresistive effect, where mechanical deformation of the diaphragm induces a proportional change in resistance.

As pressure increases, the deformation of the sensing diaphragm causes a variation in the resistance of embedded piezoresistors, leading to a corresponding change in current or voltage at the output stage. The integration of operational amplifier-based signal conditioning circuits significantly enhances the magnitude of the output voltage.

The proposed **CM&DA-PS (Current Mirror with Differential Amplifier)** structure exhibits a higher output voltage compared to conventional CM-PS and basic op-amp configurations. This improvement is attributed to:

- Gain amplification provided by the differential amplifier
- Efficient current replication using the current mirror circuit
- Reduction of signal losses due to on-chip integration

2. Sensitivity Analysis

Sensitivity is defined as the rate of change of output signal with respect to applied pressure:

$$S = \frac{dV_{out}}{dP}$$

The simulation results indicate that the proposed architecture achieves significantly higher sensitivity compared to traditional designs. This enhancement can be explained by:

- **Optimized device geometry**, leading to greater diaphragm deflection
- **Improved transduction efficiency** due to piezoresistive materials
- **Signal amplification through op-amp configurations**, especially summing and differential amplifiers
- **Current mirror accuracy**, ensuring proportional signal replication

The slope of the output curve in Fig. 6(b) confirms that the CM&DA-PS structure provides superior responsiveness, making it suitable for applications requiring high precision.

3. Temperature Stability

Temperature variation is a major challenge in MEMS pressure sensors, as it affects material properties and electrical parameters such as (resistance) and carrier mobility.

The simulation results demonstrate that the proposed sensor exhibits minimal output variation with temperature changes. This improved thermal stability is achieved due to:

- **Differential amplifier configuration**, which cancels common-mode thermal noise
- **Balanced circuit design**, reducing drift effects

- **Use of CMOS-compatible materials**, ensuring stable electrical characteristics
- **Optimized biasing conditions**, minimizing temperature-induced fluctuations

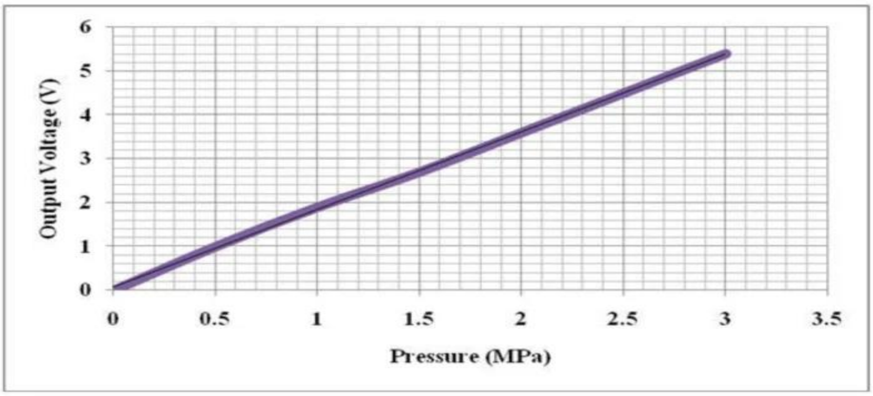
Compared to conventional designs, the proposed model shows a reduced temperature coefficient, indicating enhanced robustness in varying environmental conditions.

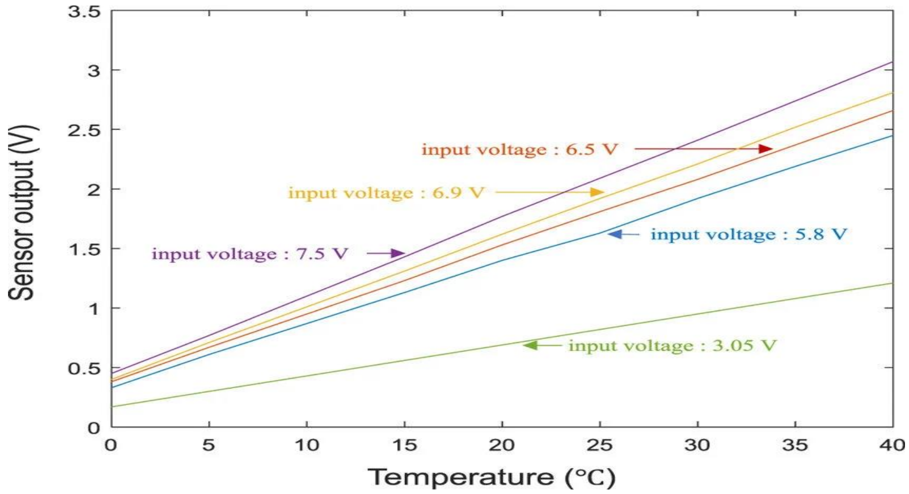
4. Overall Performance Improvement

The combined effect of current mirror circuits and differential amplification results in:

- Higher output voltage
- Improved sensitivity
- Better signal-to-noise ratio (SNR)
- Reduced temperature dependency

These improvements validate the effectiveness of the proposed CMOS-MEMS integrated architecture for high-performance pressure sensing applications.





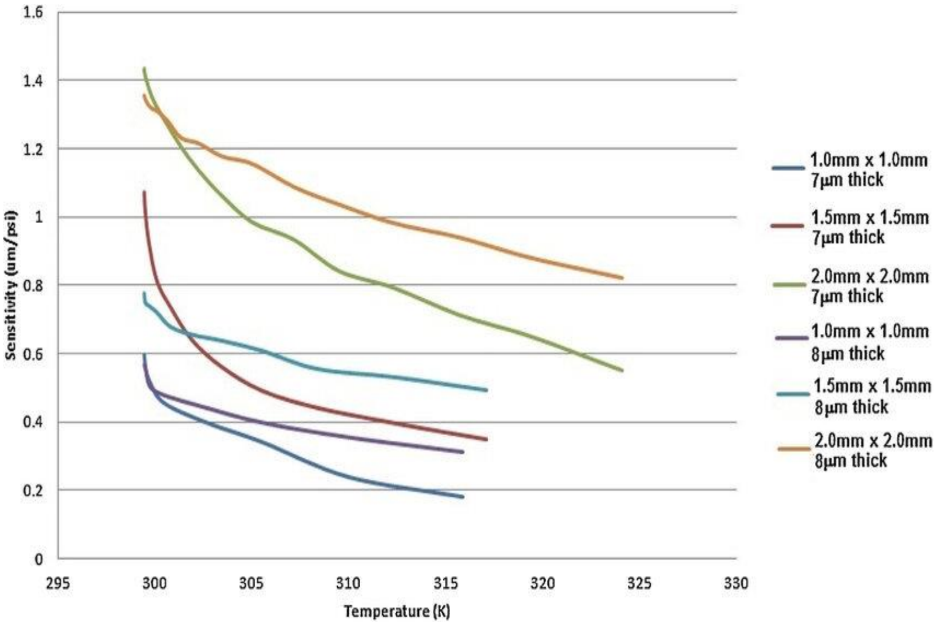


Fig. 5. Simulation results showing (a) output voltage vs pressure, (b) sensitivity analysis, and (c) temperature stability.

5. CONCLUSION

This research presents a comprehensive framework for the design and optimization of CMOS-MEMS integrated pressure sensors with enhanced performance characteristics. The incorporation of operational amplifier configurations and current mirror circuits significantly improves sensitivity, output voltage, and stability.

The study further demonstrates the potential of integrating pressure sensing with biometric fingerprint recognition systems, enabling multifunctional and secure embedded solutions. Monolithic CMOS-MEMS integration emerges as a promising approach for developing compact, low-cost, and high-performance sensors for future applications in healthcare, automotive, and consumer electronics.

Future work may focus on experimental prototyping, real-time implementation, and the integration of advanced AI-based pattern recognition techniques for improved biometric accuracy

.6. References

1. C. Liu, *Foundations of MEMS*, 2nd ed., Pearson, 2012.
2. G. T. A. Kovacs, *Micromachined Transducers Sourcebook*, McGraw-Hill, 1998.
3. S. Beeby and N. White, *MEMS Mechanical Sensors*, Artech House, 2004.
4. M. Bao, *Analysis and Design Principles of MEMS Devices*, Elsevier, 2005.
5. H. Baltes, O. Brand, and G. Fedder, “CMOS MEMS—Present and Future,” *Journal of Microelectromechanical Systems*, vol. 17, no. 5, pp. 1121–1132, 2020.

6. Y. K. Kim et al., “Monolithic Integration of MEMS with CMOS Technology for Smart Sensors,” *IEEE Sensors Journal*, vol. 21, no. 3, pp. 2456–2465, 2021.
7. B. Razavi, *Design of Analog CMOS Integrated Circuits*, McGraw-Hill, 2001.
8. J. Fraden, *Handbook of Modern Sensors*, Springer, 2016.
9. A. K. Jain, A. Ross, and S. Prabhakar, “An Introduction to Biometric Recognition,” *IEEE Transactions on Circuits and Systems for Video Technology*, vol. 14, no. 1, pp. 4–20, 2020.
10. S. K. Vats, P. Peddi, and P. Vats, “Securing smart contracts: A comprehensive investigation into blockchain network environments,” in *International Conference on Sensors and Microsystems*, Singapore: Springer Nature, 2024, pp. 365–374.
11. D. Maltoni et al., *Handbook of Fingerprint Recognition*, Springer, 2009.
12. X. Li et al., “Advanced MEMS Pressure Sensors for IoT Applications,” *Sensors*, vol. 22, no. 4, pp. 1–18, 2022.
13. R. Kumar and S. Patel, “Low-Power CMOS-MEMS Integrated Sensors for Wearable Devices,” *Microelectronics Journal*, vol. 118, pp. 105–115, 2023.