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From Silicon to PCB: A Comparative Study of Fabrication Routes and Performance of Capacitive Pressure Sensors

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Abstract: This article presents a comparative study of fabrication routes and performance of capacitive pressure sensors, emphasizing the transition from conventional silicon-based platforms to low-cost printed circuit board (PCB) substrates. The proposed method employs sputtered tantalum (Ta) and chromium (Cr) electrodes deposited directly onto the PCB solder mask using a Kapton shadow mask, eliminating the need for photolithography. This simplified process enables scalable and cost-effective sensor manufacturing. Experimental results are evaluated against conventional Si MEMS-based and ceramic capacitive sensors reported in the literature, focusing on sensitivity, hysteresis, linearity, and fabrication complexity. The PCB-based sensors exhibited a clear capacitive response in the 0–5 bar pressure range, with competitive performance and excellent mechanical stability, particularly for Ta electrodes. This work provides an analysis of the advantages and limitations of different fabrication routes and performance metrics, supporting the development of accessible pressure sensors for industrial monitoring, environmental sensing, and emerging IoT applications.

Keywords: Capacitive pressure sensors, PCB technology, MEMS fabrication, Sputtered electrodes, Sensor performance.

1. Introduction

Capacitive pressure sensors have long been essential tools for measuring and controlling parameters in diverse areas such as industrial automation, environmental monitoring, biomedical applications, and automotive systems [1]. Their working principle is based on changes in capacitance between two conductive electrodes under applied pressure, resulting in high sensitivity, low energy consumption, and excellent compatibility with miniaturized electronic circuits [2]. Over the past few decades, the increasing demand for compact and high-performance sensing systems has driven significant advances in the fabrication of capacitive pressure sensors, particularly through microelectromechanical systems (MEMS) technologies [3]. These silicon-based devices offer excellent sensitivity, repeatability, and stability under harsh conditions, making them the dominant choice in high-precision applications [4].

However, despite their advantages, silicon MEMS fabrication typically requires cleanroom facilities, photolithography steps, chemical processing, and specialized equipment [5]. These factors substantially increase production costs, limit accessibility, and reduce scalability for applications that do not necessarily require miniaturization and high precision associated with silicon devices.

In parallel, the rapid development of the Internet of Things (IoT) has driven a growing demand for low-cost, robust, and scalable sensor platforms that can be integrated into distributed monitoring networks [6]. These applications include smart manufacturing, predictive maintenance, environmental monitoring, and agricultural sensing, where cost and simplicity are often prioritized over high precision.

In this context, alternative fabrication strategies have emerged to reduce complexity and cost while maintaining adequate performance for practical applications. One promising approach is the use of printed circuit board (PCB) substrates as the structural platform for pressure sensors [7]. PCBs are inherently low-cost, mechanically robust, and compatible with standard electronics, which facilitates integration with signal conditioning and wireless communication circuits. Moreover, PCB manufacturing is already widely established at an industrial scale, enabling rapid prototyping and large-volume production at a fraction of the cost of MEMS processing.

Recent studies have demonstrated the feasibility of PCB-based sensors for different applications [8, 9]. In their review article, Perdigones and Quero (2022) describe the structure and development of sensors based on PCBs, mainly capacitive sensors with metal electrodes [10].

Metallic films such as gold, copper, aluminum, and chromium have been used as electrode materials due to their good electrical conductivity and adhesion properties [11]. However, challenges remain regarding film uniformity, mechanical stability, oxidation resistance, and adhesion to polymeric or composite PCB surfaces. Moreover, fabrication methods often rely on wet processing steps or photolithography, which may partially undermine the low-cost advantage of PCB platforms.

To address these challenges, recent research has explored alternative patterning and deposition techniques. Among them, magnetron sputtering combined with mechanical shadow masking represents a desirable solution [12, 13]. This method allows the deposition of thin metallic films with well-defined geometries directly onto PCB solder masks, without the need for photolithography or chemical etching. It is compatible with room-temperature processing, which preserves the integrity of the solder mask on PCB substrates, and it can be easily scaled up. The selection of the electrode material also plays a crucial role in determining the sensor's final performance. Chromium (Cr) is widely used due to its good adhesion and electrical properties, whereas tantalum (Ta) has been less explored but offers high corrosion resistance, strong adhesion, and excellent mechanical stability [12].

While many studies have focused on MEMS or PCB sensors independently, there is a lack of systematic comparative analyses between traditional silicon-based fabrication routes and emerging low-cost PCB-based alternatives. Such a comparison is critical to understanding the differences between fabrication complexity, cost, and sensor performance, particularly in terms of sensitivity, hysteresis, linearity, and long-term stability. By evaluating PCB sensors and established MEMS and ceramic pressure sensor technologies, it is possible to assess their practical deployment potential for industrial and environmental monitoring. Table 1 compares the characteristics of these technologies.

Table 1. Overview of typical fabrication characteristics of capacitive pressure sensors on different substrates.

Feature	Silicon (MEMS)	Ceramic	PCB (our work)
Typical fabrication steps	Photolithography, oxidation, deep etching	High-temperature sintering, metal deposition	Sputtering, shadow masking
Fabrication complexity	High (cleanroom facilities)	Medium	Low (only sputtering system)
Minimum size	Micrometric	Sub-millimetric	Millimetric
Integration with electronics	Indirect	Limited	Direct
Sensitivity (typical range)	High	Medium	Medium to high

This article addresses this gap by presenting a comparative study of fabrication routes and performance of capacitive pressure sensors based on different substrate technologies. We focus on the transition from silicon-based platforms, which rely on complex cleanroom processes, to PCB-based platforms fabricated through sputtering and shadow masking. Tantalum and chromium thin films are investigated as electrode materials deposited directly onto PCB solder masks [12]. The resulting devices are evaluated under controlled pressure conditions in the 0-5 bar range, and their performance is compared with values reported for conventional MEMS and ceramic capacitive sensors in the literature.

The contributions of this work are: (i) an updated review of fabrication routes for capacitive pressure sensors, highlighting their main characteristics, advantages, and limitations, and (ii) a comparison of our obtained results for PCB technology against established silicon technology, providing an overview in terms of sensitivity, linearity, hysteresis, fabrication complexity and demonstrating the feasibility of photolithography-free fabrication of PCB-based sensors using sputtered metallic electrodes.

This comparative perspective is particularly relevant in the current context of rapidly expanding IoT and Industry 4.0 applications, where the ability to deploy large numbers of cost-effective, reliable sensors is more important than ever. By exploring how PCB-based fabrication can complement or even replace traditional silicon fabrication in specific applications, this work supports the development of scalable, accessible sensing platforms.

This article is organized as follows. Section 2 provides an overview of the state of the art in capacitive pressure sensor technologies, covering silicon-based, ceramic, and PCB-based fabrication approaches. Section 3 details the fabrication process of the proposed PCB sensors and the experimental methodology used to evaluate their performance. Section 4 presents and discusses the results, including an analysis in relation to literature data. Section 5 concludes the article by outlining future research directions and potential applications of PCB-based capacitive pressure sensors in industrial and environmental monitoring systems.

2. Overview of the State of the Art in Capacitive Pressure Sensor Technologies

Capacitive pressure sensors have evolved significantly over the past decades, driven by advances in materials science, microfabrication, and system integration [3, 11]. Their basic principle relies on the change in capacitance between two conductive plates separated by a dielectric layer when an external pressure induces mechanical deformation [12]. This simple mechanism enables high sensitivity, low power consumption, and good linearity over a wide pressure range. Depending on the application requirements, these sensors can be fabricated on various substrates, including silicon, ceramic, and polymeric materials [11]. Each approach presents distinct advantages and challenges in terms of fabrication cost, scalability, mechanical robustness, and integration potential. The following subsections summarize the main features of two major fabrication technologies, silicon-based MEMS and ceramic-based, compared to our proposal of PCB-based capacitive pressure sensors.

2.1. Silicon-based MEMS Capacitive Sensors

Silicon-based capacitive pressure sensors are the most mature and widely adopted technology [14]. They form one of the main types of industrial and biomedical devices, from automotive manifold pressure monitors to blood pressure sensors and barometers in consumer electronics. These sensors are typically fabricated using microelectromechanical systems (MEMS) processes, which hold the same infrastructure as integrated circuit manufacturing. The sensor structure generally consists of a thin silicon diaphragm that deflects under pressure, forming one plate of a parallel-plate capacitor, with a fixed counter-electrode underneath, as shown in Fig. 1 [15].

The advantages of MEMS technology include excellent sensitivity, stability, and repeatability, as well as the ability to achieve sub-micrometer precision in device dimensions. Silicon's mechanical strength, thermal stability, and well-understood processing characteristics make it an ideal substrate for precise and miniaturized sensors. Moreover, the compatibility of MEMS fabrication with CMOS processes enables the monolithic integration of sensing elements with signal-conditioning electronics [16].

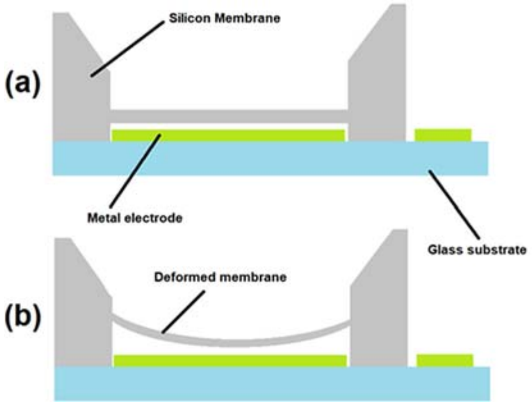

Fig. 1. Mechanism of silicon MEMS capacitive pressure sensors: (a) No pressure applied; (b) Deformation of the silicon membrane in response to applied pressure. Reproduced from [15].

Despite these strengths, MEMS-based fabrication has inherent limitations. It requires cleanroom facilities, photolithography, chemical etching, thin-film deposition, and wafer bonding, all of which contribute to high operational costs. Furthermore, MEMS devices often require specialized packaging to protect delicate diaphragms from mechanical or environmental stress, which can account for a significant portion of the final product cost [17]. For applications requiring massive production, such as automotive and mobile devices, these costs can be justified. However, for small- and medium-scale manufacturing, research prototypes, or custom applications, the high entry barrier makes MEMS fabrication less attractive.

Recent developments have focused on enhancing MEMS pressure sensor performance through advanced materials (e.g., silicon carbide, graphene, or polymer composites) [18], novel packaging techniques, and improved thermal stability. Nevertheless, the fundamental cost and complexity of silicon-based processing remain a key motivation for exploring alternative fabrication approaches.

2.2. Ceramic-based Capacitive Sensors

Ceramic materials have also been widely used for capacitive pressure sensors, particularly in applications that require operation in harsh environments, such as high temperatures, high pressures, or corrosive media [19]. Alumina and zirconia are common substrate materials, offering high mechanical strength, excellent thermal stability, and good chemical resistance [20, 21]. The basic structure of a ceramic capacitive pressure sensor consists of two parallel electrodes deposited on ceramic plates, separated by a precise spacer ring or a sealed cavity that defines the capacitance gap, as shown in Fig. 2 [22].

The main advantage of ceramic sensors lies in their robustness. They can withstand aggressive environments where silicon sensors would fail due to mechanical or chemical degradation. Moreover, ceramic substrates are compatible with thick-film and screen-printing technologies, enabling relatively simple, scalable electrode deposition without the need for cleanroom processing. As a result, ceramic capacitive sensors are widely employed in industrial process control, fluid monitoring, and environmental sensing [22].

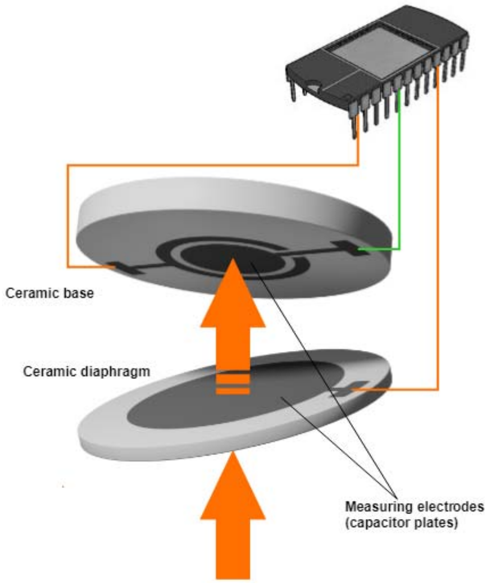

Fig. 2. Commercial alumina ceramic capacitive pressure sensor. Reproduced from IFM [22].

However, ceramic-based sensors also present drawbacks. Their fabrication generally involves high-temperature sintering steps that limit the choice of electrode materials and increase production time. The mechanical rigidity of ceramics can reduce sensitivity compared to silicon or polymeric substrates, as the diaphragm deflection under pressure is smaller. Additionally, integrating ceramic sensors with standard electronic circuits often requires additional interconnection layers or separate packaging, increasing the total system cost.

Nevertheless, ongoing research seeks to improve the performance of ceramic capacitive sensors through multilayer architectures, composite ceramics, and co-fired technologies (LTCC/HTCC), which allow for integrated electrical routing and embedded cavities [19]. These developments make ceramics an enduringly relevant substrate for applications requiring high reliability and environmental endurance.

2.3. PCB-based Capacitive Sensors

In recent years, the use of printed circuit board (PCB) substrates has emerged as an innovative and cost-effective alternative for fabricating capacitive pressure sensors [8-10]. PCBs offer several unique advantages: they are low-cost, mechanically robust, and inherently compatible with electronic circuitry. The ubiquity of PCB manufacturing infrastructure allows for rapid prototyping and large-scale production without the need for cleanroom environments.

The typical PCB-based capacitive pressure sensor consists of two conductive electrodes patterned on separate PCB layers and bonded together with a dielectric spacer (Fig. 3). The pressure-induced deflection of the upper layer or the compression of the adhesive spacer alters the electrode separation, leading to a measurable change in capacitance. Metallic films such as gold, chromium, aluminum, and, more recently, tantalum have been explored as electrode materials [12, 13]. Deposition can be achieved by sputtering, electroplating, or printing, among other methods.

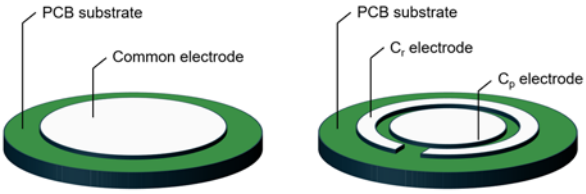

Fig. 3. Structure of the capacitive pressure sensor: PCB substrates, reference capacitance (Cr), and process capacitance (Cp). Reproduced from [12].

Compared to MEMS or ceramic technologies, PCB-based sensors stand out for their simplicity and scalability. They can be fabricated using standard, low-temperature processes and can integrate sensing, signal conditioning, and communication circuits on the same substrate. This makes them particularly attractive for distributed sensor networks, IoT applications, and innovative industrial systems. However, challenges remain in achieving the same level of miniaturization and precision as silicon sensors. Issues such as film adhesion, surface roughness, and long-term mechanical stability must be carefully addressed to ensure reliable performance [12].

Current research trends focus on optimizing thin-film deposition parameters, exploring new polymeric dielectrics, and implementing photolithography-free patterning techniques to simplify the process further. The comparative performance between PCB-based and traditional sensors suggests that, while PCB devices may not reach MEMS-level accuracy, they offer a compelling balance between cost, sensitivity, and manufacturability. Table 2 compares PCB and MEMS technologies.

In summary, the ongoing diversification of substrate technologies for capacitive pressure sensors reflects the growing need for tailored solutions across different application domains. Silicon-based sensors remain dominant in precision markets, ceramic sensors excel in harsh environments, and PCB-based sensors are emerging as a versatile, economical alternative for scalable, integrated sensing systems.

Table 2. Economic comparison between silicon-based and PCB-based fabrication approaches.

Technology	Silicon (MEMS)	PCB-based (our work)
Initial investment (CAPEX)	Very high (cleanroom infrastructure, lithography equipment, cleanroom maintenance)	Very low (standard infrastructure, simpler deposition tools)
Unit cost (high volume)	Low (fixed costs are diluted over large-scale production)	Moderate (reduced, but not as low as silicon at very high volumes)
Unit cost (low volume)	High (high fixed costs spread over a small number of devices)	Low (minimal setup costs)
Design flexibility	Low (any design change requires new masks and process adjustments)	High (easy and inexpensive to adjust layouts and processes)
Development time	Long (complex fabrication cycles)	Short (fast fabrication)
Packaging cost	High (often requires specialized encapsulation)	Low to moderate can be integrated directly into the PCB
Scalability	Excellent (ideal for mass production, thousands to millions of units)	Good (more advantageous for small- and medium-scale production
Integration with electronics	Indirect (requires interconnection with external boards)	Direct (sensor and electronics can be fabricated on the same PCB)
Total project cost (R&D + production)	High (justified only for large-volume applications)	Low (ideal for custom, small-scale, or IoT applications)

3. Fabrication Process of the Proposed Capacitive Sensors on PCB and Their Performance

The fabrication of the proposed capacitive pressure sensors was designed to demonstrate a simple, low-cost, and scalable approach compatible with printed circuit board (PCB) technology [12, 13]. The process integrates thin metallic electrodes deposited by direct current (DC) magnetron sputtering onto the polymeric solder mask of standard PCB substrates. The use of mechanical shadow masking during deposition eliminates the need for photolithography, enabling photolithography-free fabrication suitable for laboratory or industrial settings without cleanroom infrastructure. Two metals, tantalum (Ta) and chromium (Cr), were selected as electrode materials to investigate the influence of intrinsic film properties on the electrical and mechanical performance of the sensors. Fig. 4 compares this proposed fabrication process with the traditional silicon fabrication process.

3.1. Substrate Preparation and Electrode Deposition

Commercial PCB substrates with solder mask were used as the base platform for both sensor types (Fig. 5(a)). The solder mask acted as an insulating layer. The PCB substrates were cleaned with isopropyl alcohol and dried under ambient conditions before deposition. No additional surface treatment was applied to evaluate the intrinsic adhesion behavior of the metallic films on the polymeric layer.

To define the electrode geometry without photolithography, Kapton shadow masks were used (Fig. 5(b)). These flexible masks were cut using precision metal molds corresponding to the circular layout of the sensor design. The use of Kapton provided excellent thermal and mechanical stability during sputtering, allowing for accurate pattern definition.

The electrode deposition was carried out using a DC magnetron sputtering system equipped with a high-purity Ta (99.99 %) sheet and a Cr (99.5 %) target (Fig. 5(c)). Deposition parameters were carefully optimized to achieve uniform coverage while maintaining low substrate temperatures, ensuring compatibility with the polymer-based solder mask. The main parameters are summarized for Ta films. A sputtering power of 30 W, base pressure of 2×10^{-5} Torr, and argon partial pressure of 4×10^{-2} Torr were employed. For Cr films, the power was increased to 100 W with a base pressure of 1.6×10^{-5} Torr and an argon partial pressure of 7.5×10^{-3} Torr.

Each deposition lasted 60 minutes, yielding films with an average thickness of ~1.3 µm as measured by atomic force microscopy (AFM) [13]. Scanning electron microscopy (SEM) confirmed that both Ta and Cr films formed continuous, uniform coatings without visible cracking or delamination (Fig. 5(d)).

The choice of Ta and Cr was motivated by their distinct mechanical and chemical properties. Chromium is known for its excellent adhesion to polymeric substrates and high electrical conductivity.

At the same time, tantalum exhibits outstanding corrosion resistance and mechanical stability, forming a native oxide layer that can improve long-term performance (Fig. 5(e)). The comparative study of these two materials provides insights into how the electrode composition affects the sensor's sensitivity, hysteresis, and durability.

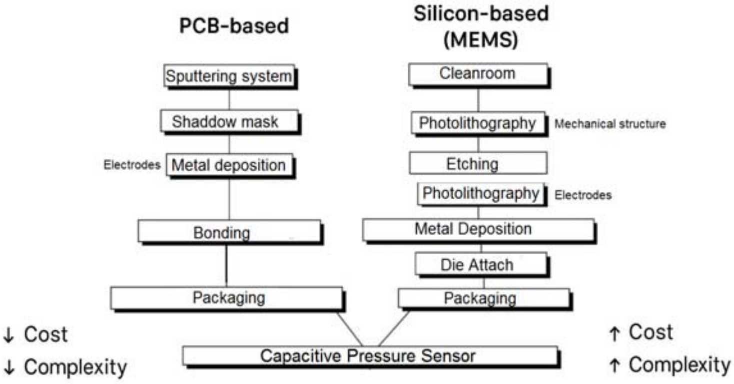

Fig. 4. Comparison between the fabrication of the proposed PCB-based sensor and the silicon-based sensor.

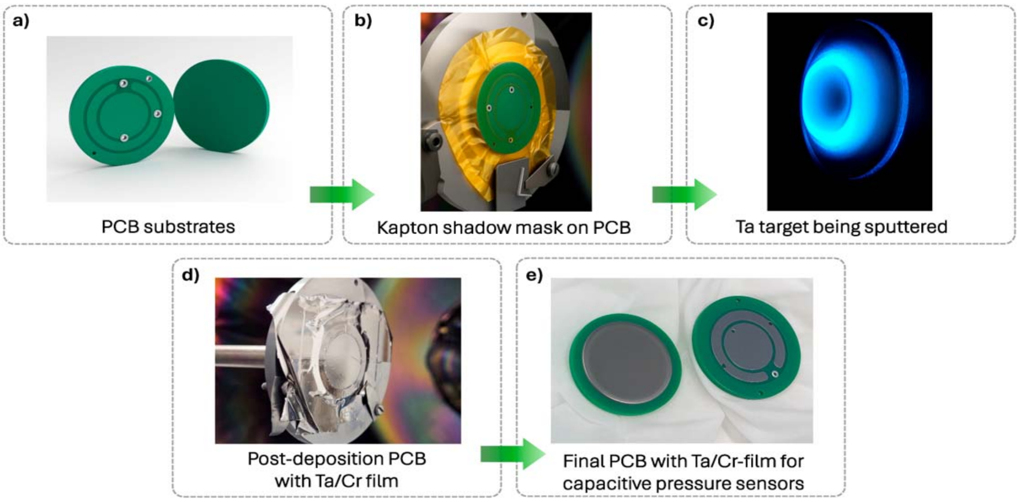

Fig. 5. Schematic illustration of the fabrication process for Ta/Cr-based capacitive pressure sensors on flexible PCB substrates, (a) preparation of the circular PCB substrates; (b) placement of a Kapton shadow mask on the PCB before sputtering; (c) tantalum (Ta) target under plasma discharge during the sputtering process; (d) PCB after Ta/Cr thin-film deposition; (e) final PCB with Ta/Cr-based electrodes for capacitive pressure sensor configuration.

3.2. Sensor Assembly

After electrode deposition, two PCB substrates were aligned face-to-face to form the capacitive structure. A thin layer of UV-curable adhesive was applied between the substrates, serving as both the mechanical bonding agent and the dielectric spacer. This approach replaced the traditional use of spacer rings or precision shims, simplifying assembly and reducing fabrication time. The bonding process was performed using mechanical clamps to ensure uniform contact while maintaining the parallel alignment of the electrodes.

The assembly was cured in a 405 nm UV curing chamber for 12 minutes. The resulting structure exhibited good mechanical stability, with minimal warping or misalignment. Electrical contacts were made by soldering fine wires to the metallic electrodes on the PCB pads, followed by encapsulation to protect against mechanical stress during testing.

The final devices had a circular active area of approximately 2 cm in diameter. The total thickness, including both PCBs and the adhesive layer, was around 1.7 mm. The flexible adhesive layer provided enough mechanical compliance to allow measurable deformation under applied pressure, thereby modulating the electrode separation and capacitance.

3.3. Measurement Setup and Procedure

The sensors were tested under controlled pressure conditions using a Beamex calibration system capable of applying pressures from 0 to 5 bar, with 1 bar increments. For each pressure step, capacitance was recorded during both pressurization (ascending) and depressurization (descending) cycles to evaluate hysteresis behavior.

Each sensor was submitted to pressure cycles to verify repeatability and mechanical robustness. Environmental conditions (temperature and humidity) were kept constant during all tests.

3.4. Results and Performance Analysis

Both Ta- and Cr-based sensors exhibited a precise and repeatable capacitive response to applied pressure, confirming the validity of the PCB-based fabrication route. The Ta sensor showed a capacitance increase from 0.052 nF at 0 bar to 0.066 nF at 5 bar, an overall variation of approximately 26 % [12]. The Cr sensor presented a larger capacitance change, from 0.081 nF to 0.116 nF, corresponding to a 43 % increase. The higher baseline capacitance and greater sensitivity observed for Cr can be attributed to its smoother surface morphology and higher electrical conductivity.

Both devices exhibited quasi-linear behavior across the pressure range studied. Slight hysteresis was observed in both cases, more pronounced in the Cr-based sensor, likely due to differences in adhesion and mechanical compliance of the metallic layer with the polymer substrate. Tantalum, with its strong interfacial bonding and stable oxide layer, demonstrated improved mechanical stability and smaller hysteresis between loading and unloading cycles.

The sensors maintained consistent responses across multiple pressure cycles, indicating good repeatability. The UV-cured adhesive layer effectively acted as a compliant dielectric spacer, ensuring structural integrity without introducing significant viscoelastic drift. These results confirm that the simplified photolithography-free approach provides reliable performance suitable for industrial monitoring and IoT applications.

When compared to data from silicon-based MEMS and ceramic capacitive sensors reported in the literature, the PCB devices demonstrated competitive sensitivity (in the order of 10^{-3} nF/bar) at a fraction of the fabrication cost. While MEMS sensors typically achieve higher precision and miniaturization, the PCB sensors offer superior scalability, lower production complexity, and easier integration with electronic circuits on the same substrate.

The results highlight the importance of material selection and deposition conditions in achieving high-performance PCB-based capacitive sensors. Chromium electrodes yield higher sensitivity but may exhibit greater hysteresis due to lower adhesion strength, while tantalum offers better mechanical stability at the expense of slightly reduced capacitance variation.

Overall, the combination of room-temperature sputtering, Kapton shadow masking, and UV-adhesive assembly provides a practical, reproducible method for producing capacitive pressure sensors without specialized facilities. The process can be easily adapted for different electrode geometries or pressure ranges by modifying the adhesive layer thickness and electrode dimensions. Future developments may include surface-treating the solder mask to improve film adhesion and encapsulation strategies further to enhance long-term stability in humid or corrosive environments.

4. Discussion

The proposed PCB-based sensor achieved sensitivities of 3-7 pF/bar, comparable to those of silicon MEMS-based sensors [23] and slightly higher than those of ceramic-based capacitive sensors designed for industrial applications [22]. However, the fabrication time and process complexity of the PCB devices are significantly lower, requiring no cleanroom facilities or high-temperature processing. The low sputtering temperature also enables potential integration with flexible or polymeric substrates, expanding the range of applications.

When compared with existing technologies, the results confirm that PCB-based capacitive sensors can achieve sensitivity levels comparable to those of more sophisticated silicon or ceramic devices, while offering substantial advantages in cost, scalability, and fabrication simplicity. Although MEMS sensors remain superior in precision and miniaturization, the PCB approach is desirable for applications where moderate sensitivity and robustness are enough, such as industrial monitoring, environmental sensing, or distributed IoT nodes.

Furthermore, the use of Ta electrodes demonstrates excellent stability under cyclic loading, suggesting strong potential for long-term operation in environments subject to mechanical vibration. The Cr-based sensors, on the other hand, provide higher initial capacitance and greater signal variation, which can be beneficial for detection systems that require higher sensitivity but operate under stable conditions.

The experimental results and comparative analysis validate the proposed fabrication route as a viable alternative to conventional MEMS and ceramic technologies. The method combines mechanical robustness, reproducibility, and low-cost manufacturing while maintaining competitive performance metrics. These characteristics make PCB-based capacitive pressure sensors an attractive solution for scalable and accessible sensing systems that bridge the gap between advanced MEMS devices and traditional low-cost pressure sensors.

5. Conclusions

This work presented the development, fabrication, and characterization of capacitive pressure sensors implemented on printed circuit board (PCB) substrates using sputtered tantalum (Ta) and chromium (Cr) thin films as electrodes. The proposed approach combines simplicity, low cost, and scalability, providing an alternative to conventional silicon and ceramic technologies. By employing a Kapton shadow mask during metal deposition and a UV-curable adhesive as a dielectric spacer, the entire fabrication process was achieved without the need for photolithography or cleanroom facilities.

The experimental results demonstrated that both Ta- and Cr-based sensors exhibited clear capacitive responses in the 0-5 bar pressure range, with nearly linear behavior and good repeatability. The Cr electrode configuration yielded higher capacitance variation and sensitivity (≈7 pF/bar), while the Ta configuration offered improved mechanical stability and reduced hysteresis. These findings highlight how electrode material selection directly affects sensor performance, enabling design flexibility for different target applications.

When compared to the state-of-the-art MEMS and ceramic capacitive sensors reported in the literature, the PCB-based devices showed comparable sensitivity and reliability, despite being fabricated using a much more straightforward, lower-cost process. The proposed route thus demonstrates strong potential for developing accessible, scalable pressure-sensing solutions that can be readily integrated into electronic systems. The inherent compatibility of PCB technology also enables the integration of signal conditioning circuits, wireless modules, and embedded processing, paving the way for compact, multifunctional sensor platforms.

Future work will focus on long-term stability studies, environmental testing under varying temperatures and humidity, and surface modification of the solder mask to enhance metal adhesion and reduce hysteresis. Moreover, extending this fabrication method to flexible or multilayer PCB substrates could enable the design of conformable, wearable pressure sensors. Overall, the results confirm that PCB-based capacitive sensors offer a promising balance of performance, robustness, and manufacturability, advancing cost-effective sensing technologies for industrial monitoring, environmental assessment, and emerging IoT applications.

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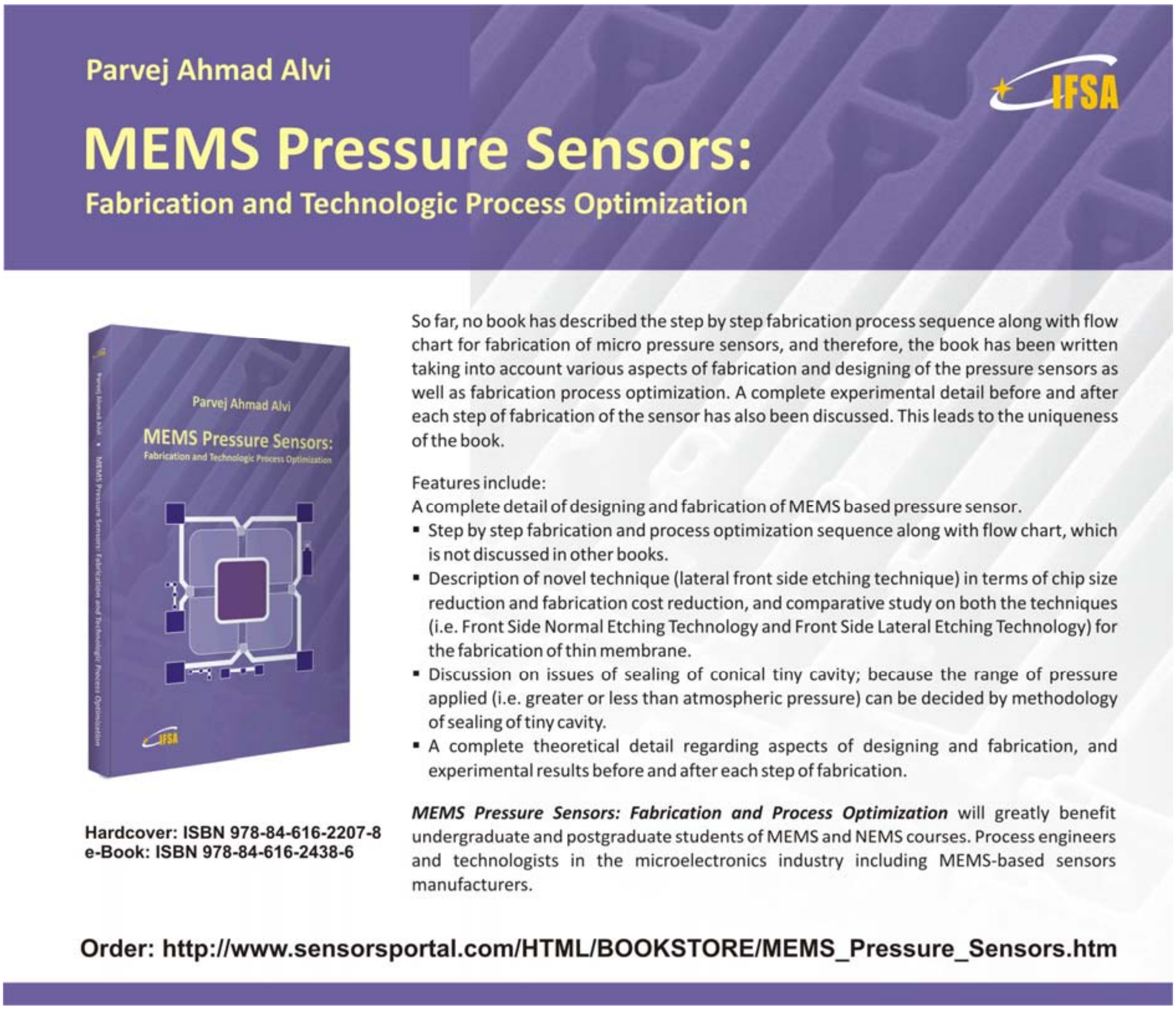

Parvej Ahmad Alvi

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