

Preliminary Analysis on Novel PDMS Based Capacitive Pressure Sensor for Wearable Application

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Abstract—A novel fabric-based capacitive pressure sensor is presented, employing a partial curing process combined with (3-mercaptopropyl)trimethoxy silane (MPTMS) silanization to enable robust integration of a polydimethylsiloxane (PDMS) dielectric layer with conductive electrodes. Silver nanoparticle-based top and bottom electrodes are fabricated via screen printing on thermoplastic polyurethane (TPU) substrates and subsequently bonded to textile layers through a heat lamination process, ensuring mechanical stability and flexibility. The fabricated sensors are characterized under applied loads ranging from 0 to 115 N, exhibiting relative capacitance variations of 4.6%, 3.9%, and 1.3% across low (0–30 N), medium (30–80 N), and high (80–115 N) load regimes, respectively, for a pressure area of 154 mm². Consistent behavior is observed across multiple devices, demonstrating good repeatability. Cyclic loading tests over 50 cycles show excellent stability, with a capacitance drift of 0.9% and a standard deviation of ± 0.01 pF. These results highlight the effectiveness of the proposed fabrication strategy for developing reliable and flexible textile-based pressure sensors, making them suitable for wearable applications and force monitoring in diverse scenarios.

Keywords—PDMS, fabric electrode, capacitive pressure sensor, silanization

I. INTRODUCTION

In recent years, wearable pressure sensors have attracted significant attention due to their potential in next-generation technologies. Advanced pressure sensing systems are essential in wearable electronics for real-time monitoring of human motion and physiological signals [1], as well as in medical diagnostics for applications such as pulse detection, rehabilitation monitoring, and early disease identification [2]. In electronic skin and soft robotics, pressure sensors enable tactile perception, human–machine interaction, and adaptive control, while in prosthetic devices they enhance sensory feedback and user comfort [3].

Motorcycle and bicycle riding are widely practiced activities that provide both utility and recreation, but they are also associated with a high risk of accidents, with a significant proportion attributed to rider error and limitations in human perception and decision-making [4]. Riders continuously rely on precise hand control for steering, braking, clutching, and throttle or handlebar operation, where even small variations in applied force can significantly affect vehicle stability and safety. Consequently, assessing hand force and dexterity during riding provides valuable biomechanical insight for improving control performance and reducing accident risk [5]. In this context, glove-based

wearable sensing systems have gained considerable attention for monitoring hand interactions in more natural environments. Among various sensing modalities, flexible tactile and force sensors are particularly suitable due to their thin, lightweight, and compliant nature, enabling seamless integration into wearable gloves. Such systems have been widely explored for measuring grip forces, evaluating tool handling, and analyzing hand–object interactions in realistic conditions [6]. Therefore, extending these concepts to cycling and motorcycling applications offers a promising approach for real-time monitoring of rider behavior, improving safety, and enhancing human–machine interaction in personal mobility systems. Consequently, significant research efforts have focused on developing pressure sensors with high sensitivity, mechanical flexibility, durability, and low power consumption [7,8].

Based on the sensing mechanisms, pressure sensors are generally classified into capacitive, piezoresistive, triboelectric, and piezoelectric [9–12]. Among these, capacitive pressure sensors have gained considerable attention due to their simple structure, low cost, and high sensitivity. A typical capacitive sensor consists of two conductive electrodes separated by a compressible dielectric layer, where applied pressure induces a change in capacitance [13]. The sensor performance is strongly influenced by the dielectric material properties, such as dielectric constant, thickness, and mechanical compliance. In this context, polydimethylsiloxane (PDMS) has been widely adopted as a dielectric material due to its excellent flexibility, stretchability, biocompatibility, and ease of fabrication [14–18].

Despite these advantages, PDMS presents critical challenges related to its intrinsic hydrophobicity and chemical inertness, which hinder the direct deposition and stable integration of conductive materials such as silver nanoparticle inks [19]. This often results in weak interfacial adhesion, leading to cracking, delamination, and unreliable electrode performance under mechanical deformation [20]. Various approaches have been explored to address this issue, including chemical surface treatments, physical deposition techniques, printing methods, and lithographic processes [21–23]. However, achieving robust and durable bonding between PDMS and conductive electrodes remains a major challenge, particularly for flexible and wearable applications [24].

Moreover, the integration of fabric-based electrodes with PDMS dielectric layers typically requires intermediate adhesive layers. While commercial adhesives improve

bonding, they introduce several drawbacks, including reduced sensor sensitivity, altered dielectric properties, increased signal offset, and potential biocompatibility concerns for wearable applications [25,26]. Therefore, developing adhesive-free integration strategies is critical for preserving device performance and reliability.

In this work, we propose a novel glue-free fabrication strategy for fabric-based capacitive pressure sensors, based on the combination of partial curing of the PDMS dielectric layer and (3-mercaptopropyl)trimethoxysilane (MPTMS) surface functionalization of silver nanoparticle electrodes. Unlike conventional approaches relying on adhesive layers, the proposed method enables direct and robust integration between the PDMS and the electrode layer. The partial curing process promotes intimate interfacial contact and mechanical interlocking, while MPTMS functionalization enhances chemical bonding through thiol–metal interactions and silane-mediated coupling.

The main novelty of this work lies in the synergistic combination of partial PDMS curing and MPTMS surface activation to achieve strong, adhesive-free bonding between textile electrodes and a PDMS dielectric layer, preserving the intrinsic dielectric properties of the material while improving mechanical stability and device reliability. This approach provides a scalable and effective pathway for the development of high-performance wearable pressure sensors.

II. EXPERIMENTAL

Chemicals and Materials

Sylgard 184 silicone elastomer kit (base and curing agent, Dow Corning) was used as the primary material for the fabrication of the dielectric layer. For silanization, MPTMS was purchased from Sigma-Aldrich (Italy). For the fabrication of the top and bottom electrodes, polyester textile was used as the substrate. Thermoplastic polyurethane (TPU) thin film (Intexar TE-11C, DuPont), consisting of a high-recovery TPU base film, a melt adhesion TPU layer, and a temperature-stable carrier film was used to enhance mechanical robustness and uniformity of the electrode structure. The conductive circular patterns were printed using silver nanoparticle paste (DuPont PE874). Polylactic acid (PLA, Sigma-Aldrich, Italy) was used to prepare a mold for the preparation of a PDMS thin film.

Fabrication Process

The capacitive pressure sensor was fabricated through a multistep process integrating textile-based electrode fabrication and adhesive-free bonding with a PDMS dielectric layer. The proposed approach builds upon the methodology reported in [27], with key modifications enabling direct integration between electrodes and dielectric without the use of intermediate adhesives.

A TPU thin film was first laminated onto the textile substrate using a household iron at 110–120 °C for 45 s to provide a uniform and mechanically stable surface for printing. The top and bottom electrodes were then patterned via screen printing (AUREL C920, printing pressure: 2 kg, mesh: 145) using silver nanoparticle paste. After deposition, the printed electrodes were thermally sintered at 120 °C for 15 min to enhance electrical conductivity through nanoparticle necking. The electrodes were subsequently

laser-cut to achieve precise geometries and alignment. Both electrodes were circular with a diameter of 16 mm, while the conductive tracks measured 14 mm × 4 mm, corresponding to an effective area of 154 mm².

The dielectric layer was prepared using PDMS via a controlled molding process. A circular mold (diameter: 16 mm, depth: 0.5 mm) was fabricated using fused filament fabrication (FFF) with PLA. The base and curing agent of PDMS were mixed at a weight ratio of 10:1 for 5 min and then degassed under vacuum in a vacuum desiccator for 30 min to remove trapped air bubbles. The mixture was then poured into the mold and partially cured at 70 °C for 20 min, yielding a mechanically stable yet tacky film. The partially cured PDMS layer was carefully removed from the mold and sandwiched between the pre-fabricated top and bottom electrodes, ensuring proper alignment and intimate interfacial contact. The assembled device was then fully cured at 70 °C for 3 h to complete crosslinking and enhance mechanical integrity.

The sensor dimensions were selected to enable effective integration into wearable gloves for finger pressure monitoring, ensuring high flexibility, conformability, and reliable electrical performance. The thickness of the sensing layers was optimized to maintain mechanical durability while allowing sufficient deformation under finger for sensitive detection. Similarly, the lateral dimensions were designed to match the finger geometry, promoting uniform pressure distribution across the active area. These parameters were refined through preliminary experiments to achieve stable, repeatable, and application-relevant sensor responses. A schematic representation of the device structure and layer thicknesses is shown in Fig. 1, while the complete fabrication process is illustrated in Fig. 2.

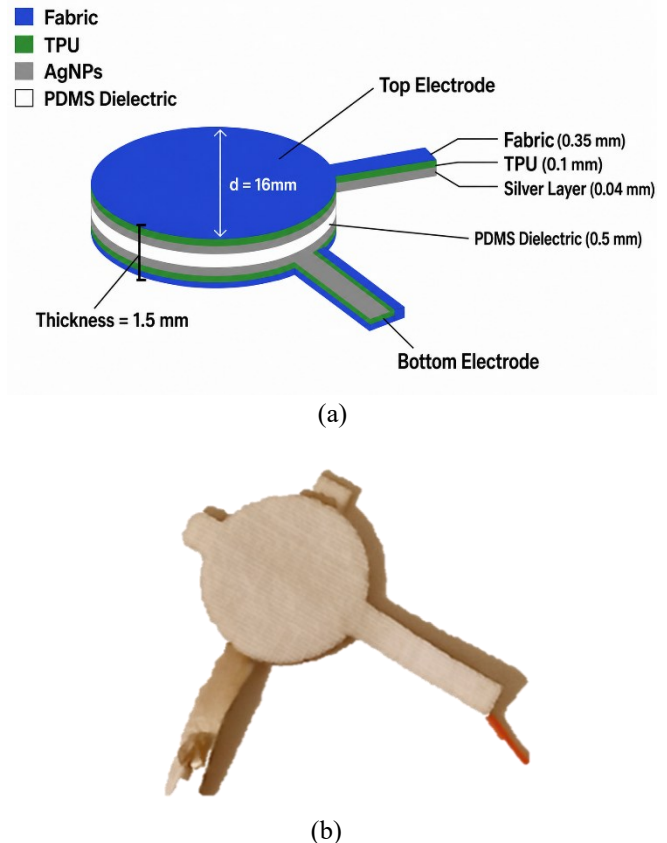


Fig. 1. a) Schematic illustration of the different layers and their thickness and b) real picture of the sensor 1.

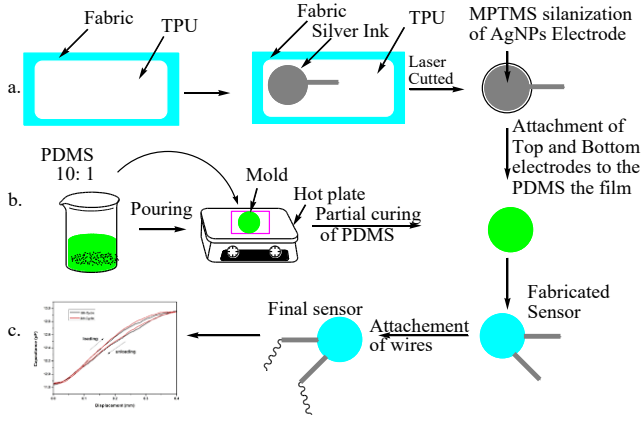


Fig. 2. Fabrication procedure of the capacitive pressure sensor, where a, b, and c show the sequence of the fabrication process.

Experimental Setup and Procedure

The electrical and electromechanical characterization of the as-fabricated pressure sensors was carried out using a tensile testing machine (Mark-10) equipped with a 250 N load cell, in combination with an MFIA impedance analyzer (500 kHz) for real-time electrical measurements. For measurements, each sensor was placed between two flat contacts, and compressive force was applied normal to the active sensing area using the testing machine, ensuring uniform pressure distribution. Electrical connections to the top and bottom electrodes were established using conductive leads, and the impedance analyzer was interfaced with a personal computer running MATLAB for continuous and synchronized data acquisition. The setup ensured stable mechanical alignment and minimized contact resistance and external noise during measurements. For each test, the load and crosshead displacement curves were recorded using the tensile system, while capacitance was measured by the MFIA 500 kHz Impedance Analyzer every 0.02 s.

Several mechanical testing protocols were employed to evaluate sensor performance. In Test 1, ten quasi-static load-unload cycles were applied from 0 N to 115 N at a crosshead speed of 0.2 mm/min, with a 10 s dwell time between consecutive cycles to allow partial recovery. Test 2 involved a stress relaxation experiment, in which the sensor was loaded to 30, 80, and 115 N with the same crosshead speed and then held at these force levels, while the force decay was recorded for 5 minutes. In Test 3, fifty load-unload cycles were performed between 0 N and 80 N at a crosshead speed of 10 mm/min to assess high force sensitivity and repeatability. A total of five sensors were fabricated and tested under identical conditions to ensure reproducibility; one representative device is discussed in detail, while an additional device is presented for comparison.

The sensing mechanism is governed by the compression of the PDMS dielectric layer, which induces a variation in capacitance. The applied pressure (the load is uniformly applied on the electrode area A), induces a reduction in dielectric thickness d , and thus the electrical capacitance of the sensor. Indeed, the sensor behavior can be described by the parallel-plate capacitor model [28]:

$$C = \frac{\epsilon_0 \epsilon_r A}{d} \quad (1)$$

where ϵ_0 is the vacuum permittivity, and ϵ_r is the relative permittivity of PDMS. Accordingly, d dominates the capacitive response, while the electrode area can be considered approximately constant within the investigated load range. A. Nonlinear response observed at higher loads is primarily attributed to the viscoelastic compression of PDMS and the progressive reduction of its effective stiffness.

III. RESULTS AND DISCUSSIONS

The electrical response of the fabricated sensors was first analyzed through impedance spectroscopy in the frequency range of 100–510 kHz. The measured behavior was well described by an equivalent parallel $R_p - C_p$ circuit, as shown in Fig. 3. Although minor device-to-device variations were observed, both sensors closely followed the expected electrical model. The resistance remained consistently above 1 M Ω and exhibited negligible dependence on the applied load, confirming that the capacitive component dominates the sensing mechanism.

The cyclic compression tests demonstrated a hysteresis of approximately 23% in the mechanical response of the sensors, which is mainly attributed to the viscoelastic nature of the elastomeric dielectric layer, as illustrated in Fig. 4. From the compression data, the Young's modulus of the dielectric material was estimated to be approximately 2,785 kPa. While viscoelasticity is an intrinsic characteristic of PDMS, it does not significantly affect the repeatability of the sensor output when adequate relaxation time is allowed between cycles. In this study, a slow loading protocol was employed, with each compression-release cycle lasting 350 s, thereby accentuating viscoelastic effects. The extent of hysteresis is strain-dependent, with minimal hysteresis in the low-displacement region due to predominantly elastic deformation, increased hysteresis in the intermediate region where significant viscoelastic chain reorientation occurs, and reduced hysteresis at higher displacements as a result of strain-stiffening and molecular alignment. Notably, the near overlap of the fourth and fifth loading–unloading cycles indicates that the material reaches a stable mechanical response after initial conditioning, demonstrating good repeatability and mechanical reliability of the elastomer under cyclic compression. The data shown correspond to sensor 1, though similar behavior was consistently observed for the second device. At a displacement of 0.15 mm, equivalent to approximately 10% compressive strain, the hysteresis reached nearly 23% of the maximum applied load.

The capacitance–displacement relationship (Fig. 5) exhibited a maximum capacitance variation of approximately 12% for a compressive strain of 27%. In contrast to the mechanical response, the capacitive hysteresis remained significantly lower, with a maximum value of 0.69% at ~60 N (17% strain), and below 0.1% at lower and higher loads. This behavior suggests that capacitance is less affected by viscoelastic relaxation compared to force measurements, making it a more reliable sensing parameter. Similarly, to evaluate the sensitivity of the sensor, the relative change in capacitance as a function of applied load was plotted, as shown in Fig. 6.

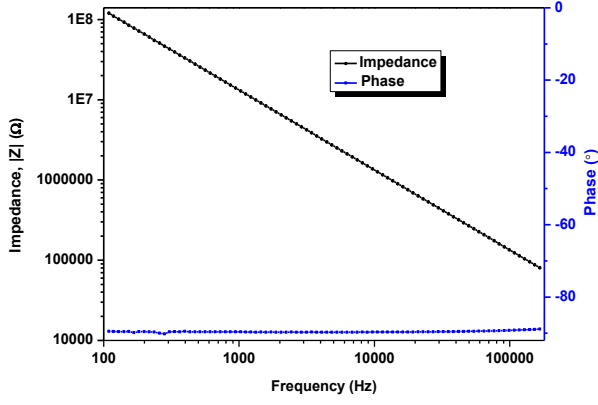


Fig. 3. Impedance response of sensor 1 without applied load.

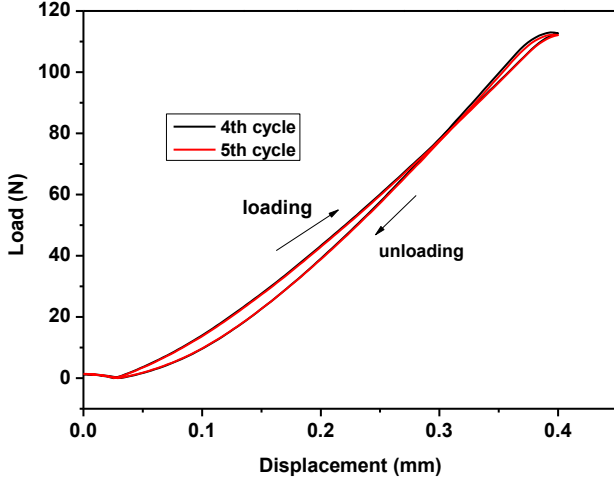


Fig. 4. Load-displacement curve of sensor 1, loading/unloading for two cycles.

The relationship between the percent relative capacitance change ($\Delta C/C_0$ (%)) and the applied load (Fig. 6) is inherently non-linear; however, it can be approximated as linear by dividing the response into three distinct force ranges. In this study, sensitivity is defined as the slope of the percent relative capacitance change with respect to force ($\Delta C/C_0/\Delta F$, expressed in %/N, to enable consistent comparison across different ranges. In the low-force range (0–30 N), the sensor exhibits a relative capacitance change of 4.6%, corresponding to a sensitivity of 0.14 %/N with good linearity ($R^2 = 0.989$). In the intermediate range (30–80 N), the relative change decreases to ~3.9%, yielding a sensitivity of **0.07 %/N** ($R^2 = 0.994$). At higher forces (80–115 N), the response further reduces to 1.3%, with a sensitivity of **0.04 %/N** ($R^2 = 0.950$). The performance parameters of Sensor 1 across different force ranges are summarized in Table I. This behavior is attributed to the nonlinear compression of PDMS, where the effective stiffness increases with strain, limiting further thickness reduction of the dielectric layer.

TABLE I. RELATIVE CAPACITANCE CHANGES AND SENSITIVITY IN DIFFERENT FORCE RANGES OF SENSOR 1.

Force Range (N)	$\Delta C/C_0$ (%)	Sensitivity (%/N)	R^2
0–30	4.6	0.14	0.989
30–80	3.9	0.07	0.994
80–115	1.3	0.04	0.950

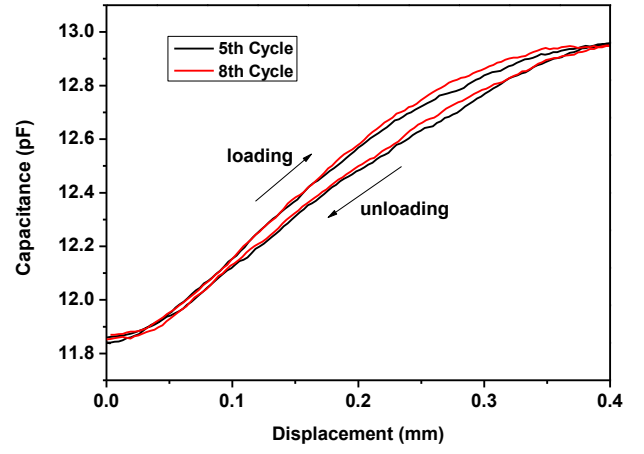


Fig. 5. Capacitance-displacement curve of pressure sensor 1.

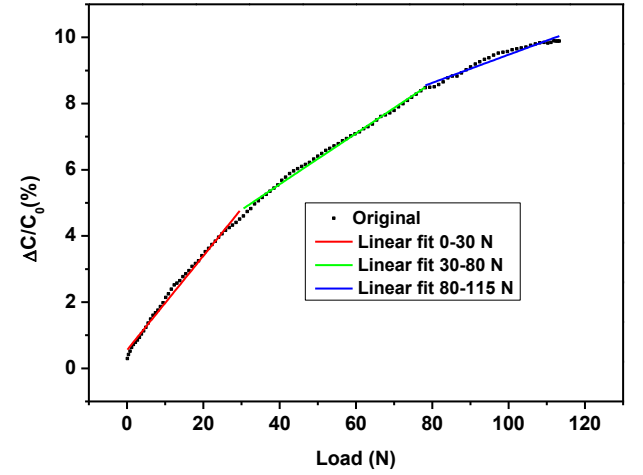


Fig. 6. Relative capacitance changes vs load for pressure sensor 1.

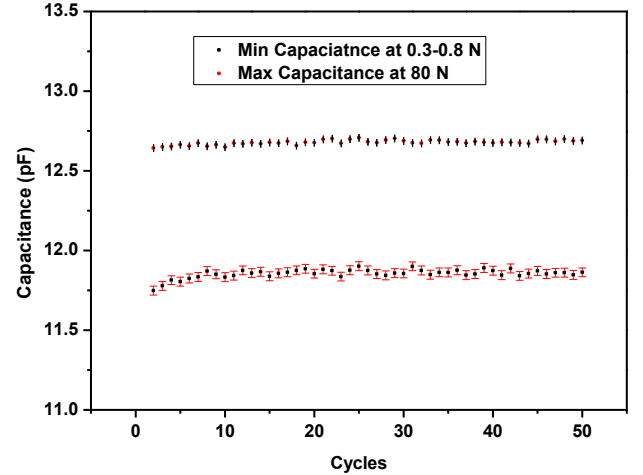


Fig. 7. Cyclic stability and capacitance drift of Sensor 1 over 50 repeated cycles.

Furthermore, the fabricated pressure sensor was subjected to 50 consecutive loading-unloading cycles (0 to 80 N) to assess its performance under repeated mechanical stress, as shown in Fig. 7. The capacitance drift for both minimum and maximum values is less than 1%, with a standard deviation of ± 0.02 pF and ± 0.01 pF, respectively, over 50 cycles, confirming the excellent operational stability and suitability for repetitive loading applications, such as wearable sensing devices [29].

The time-dependent response of the sensor under different compressions is illustrated in Fig. 8. Upon initial compression, both the applied load and capacitance rise sharply, indicating a rapid mechanical and electrical response. During the loading phase, while the displacement of 0.2 mm (Test 1), 0.3 mm (Test 2) and 0.4 mm (Test 3) are kept constant, the load gradually decreases due to viscoelastic relaxation of the PDMS dielectric layer, whereas the capacitance remains nearly constant. This behavior shows that the sensor's electrical response is largely insensitive to the time-dependent relaxation of the material. Consequently, the hysteresis in the capacitance-displacement curve is smaller than in the load-displacement curve, supporting our reported values and confirming the reliability of the sensor for accurate capacitance-based measurements.

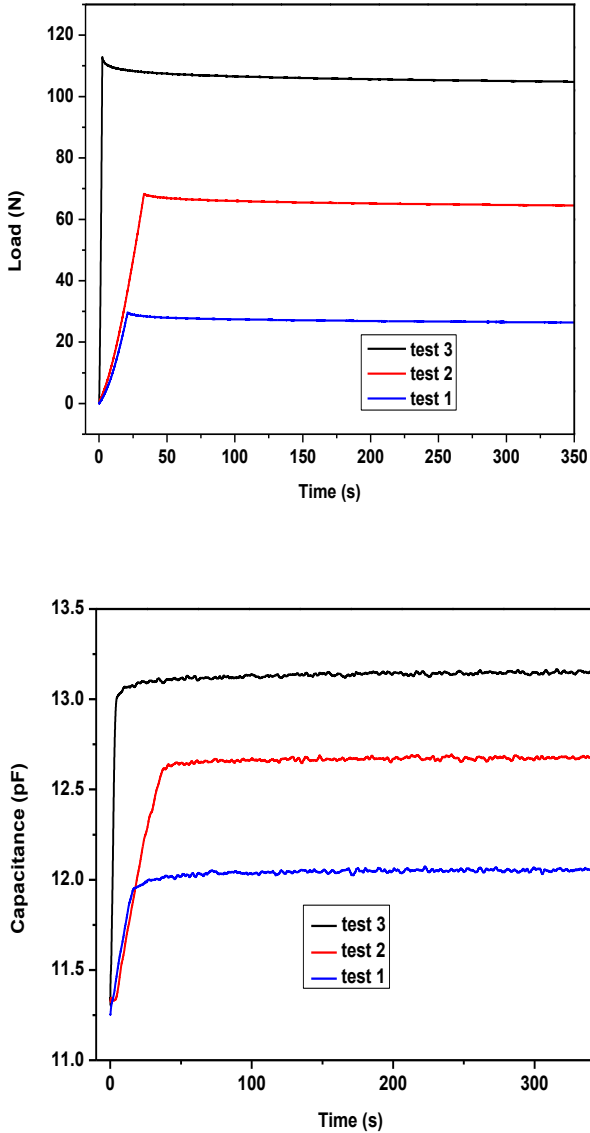


Fig. 8. Relaxation of load (top) and capacitance (bottom) over time of sensor 1.

Finally, two independently fabricated pressure sensors were compared using normalized capacitance as a function of applied load, as shown in Fig. 9. In this case, only loading values were considered, due to the target application of grasping and fingertip contact. Although the values of two sensors are not fully overlapping, their trend and sensitivities are nearly identical, with slopes of 0.08 %/N for sensor 1 and

0.07 %/N for sensor 2. The observed variations between the two sensors are attributed to device-to-device variations, such as slight difference in dielectric thickness, electrode alignment, and contact conditions during testing.

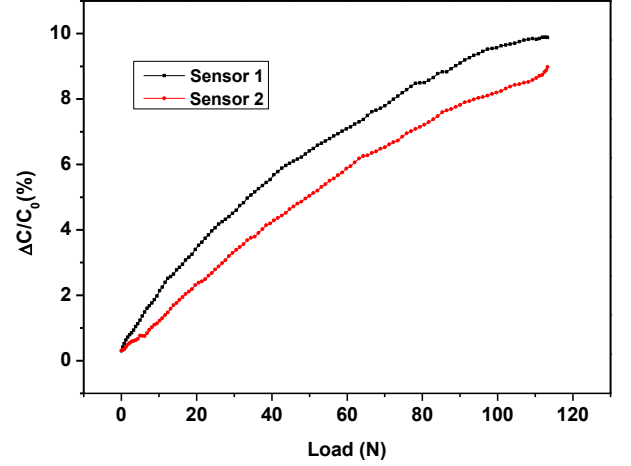


Fig. 9. Trend in relative change in capacitance vs load of sensor 1 and sensor 2.

IV. CONCLUSIONS

In this work, a novel fabrication strategy for fabric-based capacitive pressure sensors has been demonstrated, enabling robust and adhesive-free integration between a PDMS dielectric layer and silver nanoparticle electrodes. The proposed approach, based on the combination of partial PDMS curing and MPTMS surface functionalization, ensures strong interfacial bonding while preserving the intrinsic dielectric properties of the elastomer.

The fabricated sensors exhibit a nonlinear but well-defined capacitive response over a wide load range (0–115 N), with higher sensitivity at low loads and progressively reduced response at higher pressures due to the strain-dependent stiffening of the PDMS layer. The devices show low capacitive hysteresis (<0.7%) despite the intrinsic viscoelasticity of the material, confirming that capacitance-based sensing is less affected by time-dependent mechanical relaxation.

Cyclic testing over 50 loading–unloading cycles demonstrates excellent repeatability, with a capacitance drift below 1% and low signal variation, while consistent performance across multiple devices confirms the reproducibility of the fabrication process.

Overall, the developed adhesive-free integration approach offers a stable and scalable method for fabricating flexible textile-based pressure sensors suitable for wearable applications, force sensing, and human–machine interface technologies. Future studies will aim to enhance sensor sensitivity at low pressure levels and broaden the operational sensing range by optimizing the structure and properties of the dielectric layer and to investigate the sensor response under bending and multi-directional mechanical stimuli to better reflect real-world wearable conditions.

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