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Structural engineering approach for designing foil-based flexible capacitive pressure sensors

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Abstract—**Structural engineering plays an essential role in designing, improving, and optimizing an electromechanical system, instinctively affecting its performance. In this study, design optimization, finite element analysis, and experimental evaluation of capacitive pressure sensors were conducted. The air pressure sensing application was demonstrated to characterize different sensors, which include a combination of multiple rectangular cantilevers and diaphragms (square and circular-shaped). After the design improvement, we found that the square and circular diaphragms each with two trapezoidal cantilevers exhibited highest sensitivity to air pressure monitoring among the different investigated designs which combine the square and circular diaphragms with cantilevers. These designs were then selected for further analysis for acoustic pressure monitoring. The sensors were fabricated using the do-it-yourself technique with household materials such as post-it paper, posted tape, and foil. Our approach offers an alternative to the conventional cleanroom fabrication technique and uses easily available materials to fabricate affordable sensors. Therefore, this is the first step toward the development of democratized and sustainable electronic devices that are affordable and available to everyone on the internet.**

Index Terms—**Capacitive sensing, air pressure sensing, acoustic pressure sensing, paper electronics, democratized electronics, affordable electronics, structural engineering.**
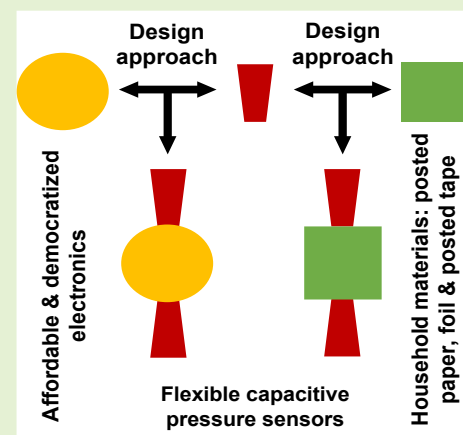
I. [1]Introduction

CONVENTIONAL solid-state electronic devices are mostly rigid in nature, and hence, are not very compatible with curvilinear, deformable, flexible, and stretchable surfaces [1]–[6]. However, these electronic devices form part of the current internet of everything (IoE) because of their excellent performance and batch fabrication as a result of revolutionary development in the semiconductor industry [3], [7], [8]. Moreover, advancement in fabrication strategies has resulted in democratized, personalized, and sustainable electronic devices that are flexible, stretchable, reconfigurable, and cost-effective, focusing on fulfilling the customer's needs [1], [4]–[6], [9]–[13]. The technology for flexible and stretchable electronics for biomedical, automation, and automobile industries has significantly improved; however, the affordability and accessibility of electronics for everyone has not materialized, which is a very basic requirement of customers to enable smart living on a large scale [6], [10], [12].

Carbon printing on paper is one of the affordable and frequently used methods for fabricating flexible pressure sensors. Piezoresistive pressure sensors are fabricated from screen printing using a carbon resistor on paper cantilevers [14]. Paper cantilevers are potentially utilized to fabricate a weighing machine with a weight of 0–12 g. The cantilevers are modified into wedge-shaped cantilevers to enhance the sensitivity and force monitoring range [14]. In another affordable and paper-based sensing approach, thin and highly sensitive capacitive touchpads are fabricated using aluminized paper [15]. The capacitive sensory pad is connected to a smaller cube and consists of six sensors connected to Arduino, demultiplexers, and light emitting diodes (LEDs) on a breadboard. When a side of the cube is touched, the corresponding linked LED glows. A square-shaped capacitive pressure sensor has been proposed for heart rate monitoring using a smart watch [16]. The sensor offers nonintimate interface with the skin as it is fabricated using recyclable materials (such as Al foil, post-it paper, double-sided tape, and microfiber wipes). A multisensory electronic skin can be designed from the same household materials, which has potential applications in robotics, healthcare, and

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agricultural monitoring [17]. The flexible and wearable capacitive pressure sensory skin is fabricated and uses paper, polyimide, and polyester conductive tape for human activity and healthcare monitoring with a minimum detection limit and response time of 3 Pa and 41 ms, respectively [18]. Another approach involves dipping paper in carbon and connecting it with electrodes, which is a smart and straightforward technique for designing a pressure sensor. The sensor is characterized for a pressure range of 0–50 kPa [19]. The electronic skin fabricated based on the same approach and materials can be applied to continuous real-time monitoring of human activity [19].

Structural engineering plays a very important role in innovative design and optimization of various electronic components or devices in terms of their fabrication techniques. It has a wide area of application in different science and technology fields, including flexible/stretchable electronics, soft robotics, human–computer interaction, biomedical, energy storage, building science, and structural health monitoring [4], [8], [9], [13], [18], [20]–[24]. To improve the performance of complex electromechanical system designs, the mechanical components can be categorized into three simple structural elements, namely, line, surface, and volume. Furthermore, the most common parts of mechanical components are the cantilever/beam and diaphragm/plate, which act as the line and surface elements, respectively [7], [8], [25], [26].

Cantilevers and diaphragms are the basic and predominant elements of any mechanical structure that undergoes deformation or bending after force or pressure has been applied [27]. Subsequently, both elements are frequently utilized in the design of sensors and actuators in microelectromechanical systems (MEMS), soft robots, and flexible and stretchable electronic devices. Many existing studies have compared different diaphragm shapes [8], [25], [28]–[32] for designing capacitive pressure sensors for MEMS and paper electronic applications. When the surface area is fixed for different diaphragm shapes with the same thickness (i.e., circular, square, elliptical, rectangular, and pentagonal) in the design of a capacitive pressure sensor, the circular diaphragm exhibits the highest deflection among the different diaphragm shapes. Therefore, the circular capacitive pressure sensor has the best sensitivity among other sensors; however, it's response is non-linear compared with other responses. Therefore, a specific shape of this diaphragm can be selected for the design of capacitive pressure sensors based on the requirements of the pressure range, sensitivity, and linearity. As the applied pressure increases, the diaphragm starts touching the bottom electrode. This technique is used in single [8], [33], [34] and double [8], [35], [36] touch-mode capacitive pressure sensing methods to monitor a wide pressure range with a linear response; however, this method does not improve the sensitivity of sensors in low-pressure monitoring of sensors. The cantilever is another mechanical component that has received significant research interest for low-pressure monitoring such as acoustic pressure sensing [8], [26], [37]. The aspect ratio of a cantilever plays a very important role in the design of capacitive pressure sensors, which affects the sensitivity and resonant frequency of the sensor [26]. A cantilever pressure sensor with the highest aspect

ratio is the most sensitive for acoustic pressure sensing and resonates at a low frequency; however, a sensor with the lowest aspect ratio resonates at a high frequency [26].

In this study, we combined cantilevers and a diaphragm to analyze the effect on the sensitivity of capacitive pressure sensors for pressure sensing using the structural engineering approach. The design, finite element simulations, fabrication and experimental characterization of foil-based flexible capacitive pressure sensor for air and acoustic pressure sensing is conducted. The capacitive pressure sensors were fabricated using the garage fabrication strategy (laser scribing) with affordable and household materials such that aluminum-coated polyimide film, double-sided tape, and paper as a flexible substrate.

II. BASIC PRINCIPLE OF SENSORS

A parallel plate capacitor consists of two conductive parallel plate electrodes of overlapping area, A, separated by distance, d, through a medium of permittivity, ϵ. Therefore, the capacitance of the parallel plate capacitor can be expressed as:

$$C_b = \frac{\epsilon A}{d} \qquad (1)$$

In most capacitive pressure sensors, one conductive electrode is fixed and the other is mechanically sensitive or deformable when pressure is applied. The deformation (w) in a mechanically sensitive electrode produces a change in the separation gap between the electrodes, which changes the capacitance of the sensor. The change in the capacitance is given by:

$$C_w = \iint \frac{\varepsilon\, dA}{d - w} \qquad (2)$$

The analytical solution of the deflection in any diaphragm shape is obtained based on either small or large deflection theory. Small/thin deflection theory is applied when the diaphragm deflection is less than $1/5^{th}$ of the diaphragm thickness. The theory mostly follows Hooke's law of deflection, which states that the diaphragm deflection is directly proportional to the applied pressure. Large/thick plate theory is applied when the diaphragm deflection is less than three times the diaphragm thickness. Subsequently, Hooke's deflection law is not valid for large deflection theory and the relationship between diaphragm deflection and applied pressure is not linear [38]. Since the sensor designs proposed in this study can be used for both air and acoustic pressure sensing, both large and small deflection theories were used to define the deflection in the diaphragm when air and acoustic pressure are applied.

III. DESIGN APPROACH

In this study, we investigated the effect of different diaphragm shapes on the sensitivity of capacitive pressure sensors based on combinations of diaphragms with different number of cantilevers [Fig. 1]. First, we clamped all the edges of the square-shaped diaphragm (design S1) with an edge length (2A) of 13.3 mm. Next, instead of clamping all the edges, we
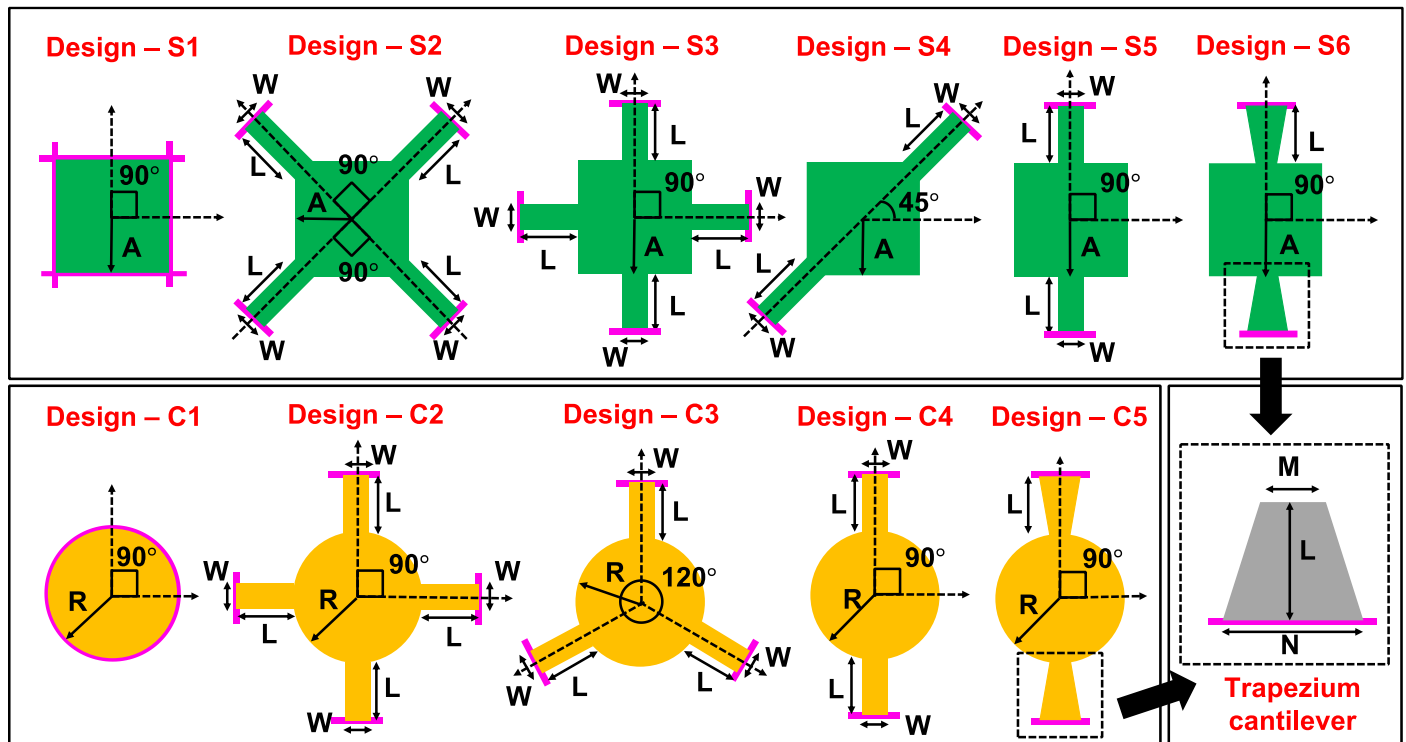
Fig. 1. Structural engineering approach based on possible multiple designs of a capacitive pressure sensor. The different designs were derived from combinations of square and circular-shaped diaphragms with multiple rectangular and trapezium-shaped cantilevers to examine the sensitivity improvements of air and acoustic pressure sensing. The pink colored bold lines in the images indicate the clamped edges of different sensors.

clamped the significant edge length using different number of cantilevers [length (L) of 8 mm and width (W) of 5 mm]. In design S2, four cantilevers were combined in such a way that each cantilevers clamps two edges of the square-shaped diaphragm. In design S3, the same number of cantilevers were combined with a diaphragm so that each cantilever acts to clamp only one edge of the diaphragm. Similarly, two cantilevers act to clamp all the four and two edges of the diaphragms in designs S4 and S5, respectively.

The normal pressure on the trapezium-shaped cantilever increases the deflection and resonant frequency compared with rectangular cantilevers of the same surface area [39], which is useful for designing more sensitive capacitive pressure sensors, particularly for ultra-low-pressure monitoring. Next, we introduced the trapezoidal cantilever to decrease the amount of area that participates in clamping the edge. Here, we ensured that the length of the trapezoidal cantilever is the same as that of the rectangular cantilever, namely L = 8 mm. Moreover, the small and large bases are kept M = 3 mm and N = 7 mm, respectively.

We followed the same procedure to clamp the edges of circular-shaped diaphragms [diameter (2R) = 15 mm] with different number of cantilevers (from design C1 to design C5), while maintaining the symmetry. The surface areas of the circular and square-shaped diaphragms were also kept constant.

IV. FINITE ELEMENT ANALYSIS (FEA)

Before the fabrication, we performed FEA using COMSOL Multiphysics® to examine the response trends of different sensor designs. During the simulation, we considered 25 μm thick Al-diaphragms to avoid complex mesh generations, which cause problems with linearized simulation because of numerical discretization of partial differential equations [40]–[43]. Other paraments such as the radius of the circular-shaped diaphragms, edge length of the square diaphragm, and length and width of the rectangular and trapezoidal cantilevers were kept the same as mentioned in the design approach section and Fig. 1. To perform the numerical simulation for diaphragm deflection, we applied a uniformly distributed normal pressure of 1 Pa on mechanically sensitive diaphragms. Finite element simulations of all the designs were performed, and the results are shown in Fig. 2. The deflections due to the applied pressure in all the sensor designs with square-shaped (from S1 to S6) and circular-shaped diaphragms (from C1 to C5) are shown in Fig. 2 (a) and Fig. 2(b), respectively. Design S6 exhibited the highest mechanical sensitivity among all the square-shaped diaphragm designs; however, C5 is the most sensitive of all the designs. The 3D-plots of the finite element simulation results of the mechanical sensitivity of S6 and C5 are shown in Fig. 2(c) and Fig. 2(d), respectively.

V. FABRICATION OF SENSORS

We initially investigated household materials, Al-foil for electrodes, in accordance with our fabrication approach; however, handling the diaphragms of Al foils is quite challenging because of their extremely low mechanical strength. Therefore, we used a commercially available, flexible, linear elastic, and light-weight aluminum (Al)-coated polyimide (PI) foil (Liren's LR-PI 100AM of 200 nm aluminum-coated 25 μm polyimide) to fabricate eleven different designs of capacitive pressure sensors. The polyimide provides mechanical strength
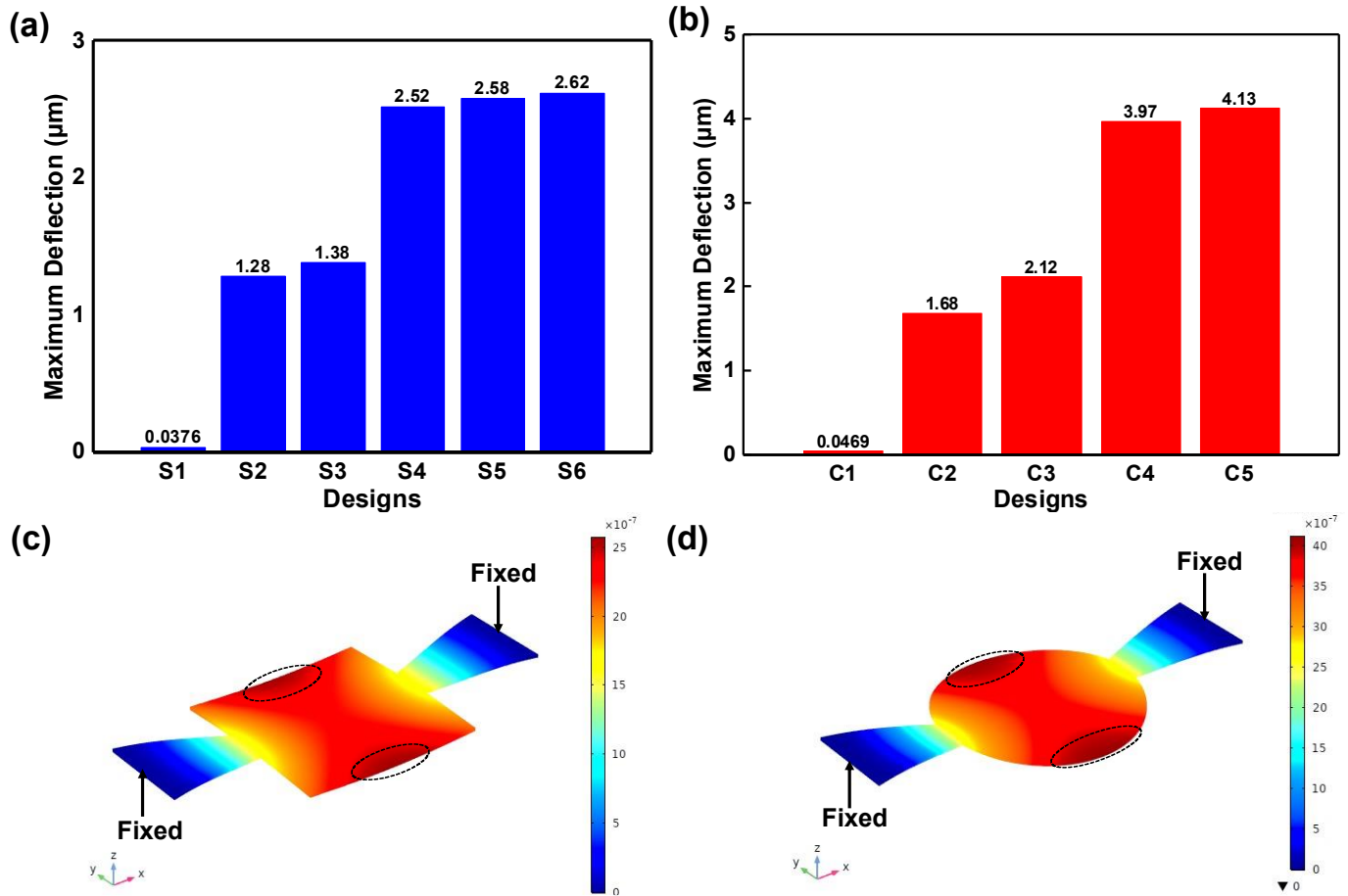
Fig. 2. Finite element analysis: Deflection due to the application of a uniformly distributed normal pressure of 1 Pa on mechanically sensitive diaphragms for different sensor designs – (a). from S1 to S6 and (b). from C1 to C5. 3D view of diaphragm deflections in: (c). S6 and (d). C5 sensor designs at 1 Pa uniformly distributed normal pressure. The highlighted area in the FEM-simulations of designs S6 and C5 is under the maximum deflection due to the application of 1 Pa uniform pressure.

to the aluminum foil, which acts as conductive electrodes of the capacitor. The other materials such as post-it paper and scotch posted tape (adhesive from both sides) are easily available household materials and are used for sensor fabrication. Material selection for sensor fabrication allows us to reduce the overall cost, making it widely acceptable in the current industry 4.0. We used the garage fabrication approach for the sensor fabrication, which offers a simple and rapid fabrication of sensors and further democratizes electronic devices, making them available for all.

The Versa 2000 carbon dioxide (CO_2) laser cutter was used to cut the Al-coated PI foil to ensure accuracy of the designs. The fabrication starts with adhering the Al-coated PI foil on the glass carrier ($7.5 \times 5 \times 1$ mm^3). Then, the desired eleven designs were scribed one by one. We opstimized the different laser parameters (power: 10 %, speed of laser beam: 18%, speed: 1000 ppm, and separation between laser outlet and sample: 2.3 mm) before scribing the sensor designs, which yields effective scribing, does not burn the sides of the designs, and provides better accuracy. The designs were scribed by maintaining the same size (length and width of 3 mm and thickness of 1.5 mm) of clamping materials, that is, scotch posted tape, for all the designs.

During the fabrication of the sensors, we used a laser cutter to maintain the design accuracy, ensuring a precise and professional output suitable for industrialization. However,

paper cutters or scissors can also be used to cut the shapes of sensors.

The detailed fabrication steps of the sensors are shown in Fig. 3. Given that the bottom electrode of the sensors is fixed, we adhered one piece of each sensor design to post-it papers with a size of 7.5×7.5 mm^2 using a double-sided tape with a thickness of 0.1 mm [Fig. 3(a) and Fig. 3(b)]. The post-it paper offers flexibility and helps to fix the bottom electrode of the sensor. Next, the clamping material was placed based on the size and shape of the sensor design. The fabrication steps of design S1 are shown in Fig. 3(c) and Fig. 3(d) in which all the edges of the square diaphragm were clamped. Another piece of the sensor design was then placed on top of the clamping material [Fig. 3(d)], which provides the final sensor design used for experimental validation [Fig. 3(e)]. The clapping material provides the separation gap between the electrodes. Air and PI act as a dielectric material and the separation gap between the electrodes was 1.525 mm (i.e., 1.5 mm air as dielectric material + 0.025 mm PI as dielectric material) [Fig. 3(f)]. The same technique was used to clamp the edges of circular sensor design C1. However, in the other sensor designs, only the cantilever's width (w) was fixed. The optical images of sensor design S1 are shown in the Fig. 3(g), after performing all the fabrication steps. The optical images of sensor designs S1 and C5, which were
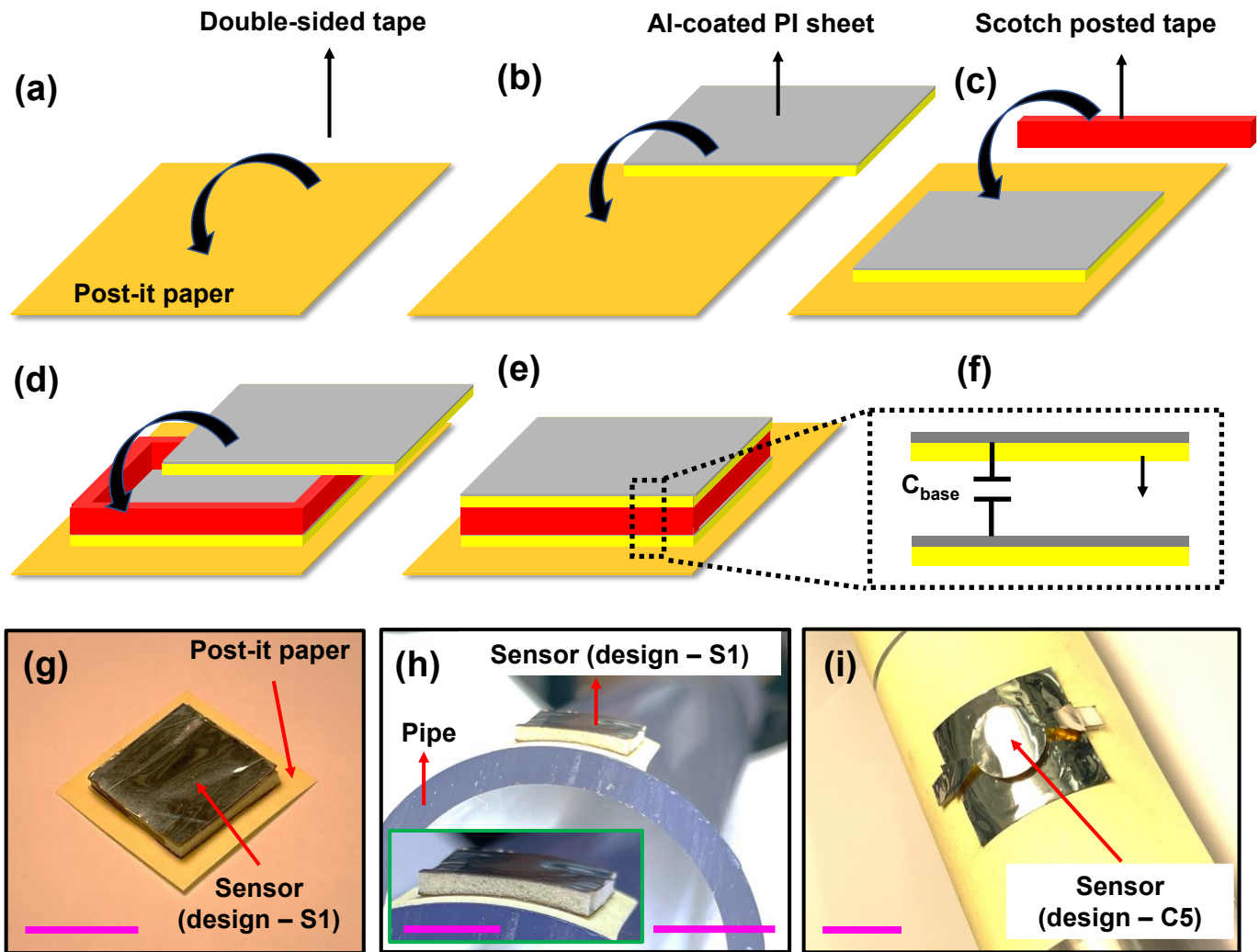
Fig. 3. Fabrication steps of sensors: (a). Double-sided tape adhered to the piece of post-it paper. Here, the post-it paper acts as a flexible substrate for the sensor. (b). Al-coated PI foil adhered to another side of the double-sided tape. (c-d). Scotch post-it tape adhered to the flexible post-it paper based on the orientation and design of the sensor. Herein, the fabrication step of square-shaped sensors is shown. (e). Placement of another Al-coated PI foil, which is a pressure-sensitive diaphragm whose structure is based on the sensor design. (f). Cross-sectional area of the flexible capacitive sensor with air and PI as the dielectric material. PI provides mechanical strength to the thin Al electrode, and air allows the diaphragm to deflect in the media. (g). Optical image of the fabricated sensor. Scale bar = 1.5 cm. (h). Optical image of sensor S1, which was placed on a transparent pipe with a radius of 3.5 cm. Scale bar = 1.5 cm. The inset image shows the zoomed version of the sensor placed on the pipe. Scale bar of 2 cm. (i). Optical image of sensor C5, which was placed on the same pipe. The sensor was placed on the pipe to determine its flexibility. The scale bars are 1.5 cm long.

placed on top of a transparent pipe (radius = 3.5 cm) to confirm their flexibility, are shown in Fig. 3(g), Fig. 3(h), and Fig. 3(i).

VI. RESULTS AND DISCUSSION

Air and acoustic pressure sensing using capacitive principle is one of the most widely used characterization techniques in MEMS, microfluidics, flexible electronics, and soft robotics. Most capacitive pressure sensors consist of either diaphragms or cantilevers, which deflect with the application of pressure. The different sensor designs characterized in this study include a combination of diaphragm and cantilevers; therefore, we developed air pressure and acoustic pressure sensing setups on a gowning room bench (temperature and relative humidity of 20 °C and 56%, respectively).

A. Air pressure sensing

The customized experimental setup for air pressure sensing was developed from an acrylic box ($15 \times 12 \times 6$ cm^3) consisting of a small hole through which the outlet of the air pressure nozzle was inserted. The inserted air pressure nozzle applies uniform pressure and was placed 1 cm above the diaphragms of the sensors. Keithley semiconductor characterization system (Model – 4200 SCS) was used for monitoring the change in the capacitance. The knob of the nozzle was calibrated for pressure values using a commercially available MEMS capacitive pressure sensor (MS5803-14BA). The accuracy of this MEMS pressure sensor is high; it measures the absolute pressure and is widely used for various applications, including operations in harsh environments.

During the sensor characterization, the commercially available sensor was replaced with our paper and metal-coated
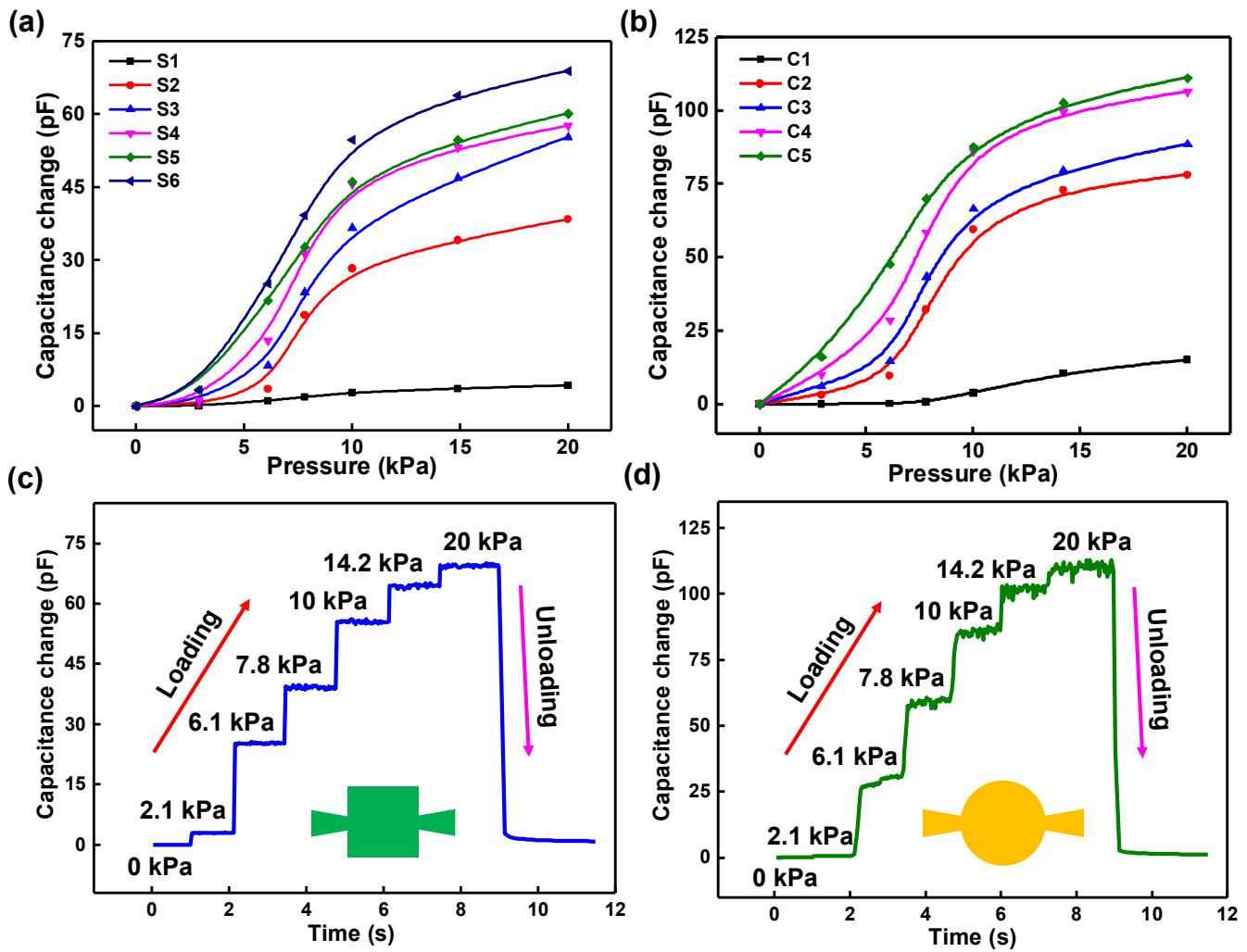
Fig. 4. Experimental verification of the capacitance change of the sensor designs after air pressure application (a). from S1 to S6 and (b). from C1 to C5. The capacitance change of sensor designs (c). S6 and (d). C5 under loading and unloading conditions of uniform application of pressure with respect to time variation.

polymer-based flexible capacitive pressure sensors and characterized for a pressure range of 0–20 kPa. After pressure application, the sensor's diaphragm deflects and the separation gap between the electrodes decreases, thereby increasing the capacitance. This change in the capacitance reflects the amount of pressure applied. The characterization results of both the square and circular diaphragm designs are shown in Fig. 4(a) and Fig. 4(b), respectively.

It can be clearly observed from the experimental results [Fig. 4] that capacitance change increases with constant application of pressure as one moves from design S1 to S6 and C1 to C5. This gives an intuitive result that the diaphragm deflection increases from S1 to S6, as well as from C1 to C5 for constant application of pressure, which agrees with the trend of the FEA analysis [Fig. 2(a) and Fig. 2(b)].

It can be observed from the experimental results [Fig. 4] that the sensitivity of the sensor decreases if more parts of the diaphragms are clamped. The results of design S2 and S3 clearly show that the sensitivity of design S2 is lower than that of S3, even with the same number of cantilevers. This is because in design S3, each cantilever opposes the bending and moment of each side of the square-shaped diaphragm, whereas in design

S2, each cantilever opposes the bending of two sides of the square-shaped diaphragm, which resists the bending and moment in the diaphragm more than the diaphragm of design S3. Overall, as the number of cantilevers attached to the diaphragm increases, the deflection of the diaphragm decreases, decreasing the sensitivity of the sensor.

We modified the rectangular cantilever to trapezoidal cantilevers in designs S6 and C5. It is clear from the experimental results that the sensitivity of the sensor increased. The increase in the capacitance at 20 kPa is 8.81 pF and 4.58 pF for designs S6 and C5, respectively. We achieved significant improvement in the sensitivity of sensors S6 and C5 at a low pressure compared with designs S5 and C4. Therefore, we used these two designs (S6 and C5) to perform acoustic pressure sensing for further comparative analysis. Before performing acoustic pressure analysis, we applied stepped pressure to characterize the S6 and C5 sensor designs, as shown in the Fig. 4(c) and Fig. 4(d). Other characteristics of sensor designs S6 and C5 are listed in Table I.

B. Acoustic pressure sensing

We also developed a customized experimental setup for

Characteristics	Sensor design – S6	Sensor design – C5
Precision	± 1.9 %	± 2.3 %
Rise time	23.22 ms	25.67 ms
Relaxation time	123.4 ms	135.3 ms

The precision time was measured at a pressure of 2.1 kPa after repeating the tests four times in series for each sensor design.

The rise time was calculated after applying a pressure of 2.1 kPa on sensor designs S6 [Fig. 4(c)] and design C5 [Fig. 4(d)].

The relaxation time was calculated when sensor designs S6 and C5 are at rest from 20 kPa to 0 Pa for each sensor design [Fig. 4(c) and Fig. 4(d)].

The Liren's LR-PI 100AM 200 nm Al-coated 25 µm PI foil was used to design the pressure sensor for monitoring asthma [30]. The sensors made from the same foil were experimentally characterized for over 1000 cycles under a pressure of 1 MPa to evaluate the stability and durability of different sensor designs. Because the thickness of the Al is 200 nm, the brittleness and hardness of the metal electrode do not affect the sensor's flexibility up to this extent. However, 2D or 3D carbon materials can be potentially utilized to enhance the sensitivity of the sensor by maintaining the interface between PI and other potential materials.

acoustic pressure sensing. The setup consists of a small vertical test bench to place the sensors to a fixed orientation. An acoustic signal of 1 Pa (corresponding to 94 dB intensity) was applied using JBL Go, a portable wireless Bluetooth speaker. The sensor was placed on a vertical test bench, connected to the Keighley semiconductor characterization system (Model – 4200 SCS), and kept 3 cm away from the speaker. The speaker was operated from a wirelessly connected Motorola one power (P30 node) smartphone.

During the sensor characterization, a sweep of 20 Hz to 20 kHz of the acoustic pressure was applied to obtain the resonant frequency of both S6 and C5 sensor designs. The S6 sensor has a resonant frequency $(f_r|_{S6})$ of 193 Hz with a change in capacitance of ~17 fF, as shown in Fig. 5(a), whereas the C5 sensor has a resonant frequency $(f_r|_{C5})$ of 148 Hz with a capacitance change of ~44 fF, as shown in Fig. 5(b).

VII. CONCLUSION

We used the structural engineering approach to design paper and metal-coated polymer-based flexible capacitive pressure sensors. We used the garage fabrication technique and household materials, which further democratizes electronic devices, improving affordability and availability for everyone. The approach of connecting the cantilevers to square and circular-shaped diaphragms was briefly analyzed and optimized. First, all possible designs were analyzed and finite element analysis was performed. Then, all the sensor designs were fabricated and experimentally characterized for air pressure monitoring. Sensor designs S6 and C5 exhibited highest sensitivity among the same category of diaphragms. The experimental results followed the same trend as those of finite element analysis. To perform the experimental analysis, we selected air and acoustic pressure sensing applications to investigate the most sensitive sensor design for both high as well as low pressure monitoring. The air pressure sensing experiment confirmed that sensor design S6 (square diaphragm and two trapezoidal cantilevers) and sensor design C5 (circular diaphragm and two trapezoidal cantilevers) are the most sensitive among the same category of diaphragms. However, during the acoustic pressure sensing experiment, sensor design S6 exhibited a lower sensitivity (even at the resonant frequency) compared with sensor design C5. Sensor design S6 resonates at a higher frequency compared with sensor design C5, although the diaphragms of these sensors have the same surface area. Therefore, among different sensor designs, sensor C5 is the most sensitive for both high and low pressures, that is, it has a broader range of pressure applications. The dimension scaling of circular diaphragm and trapezoidal cantilevers reported in this paper yields a sensor for a specific resonant frequency.
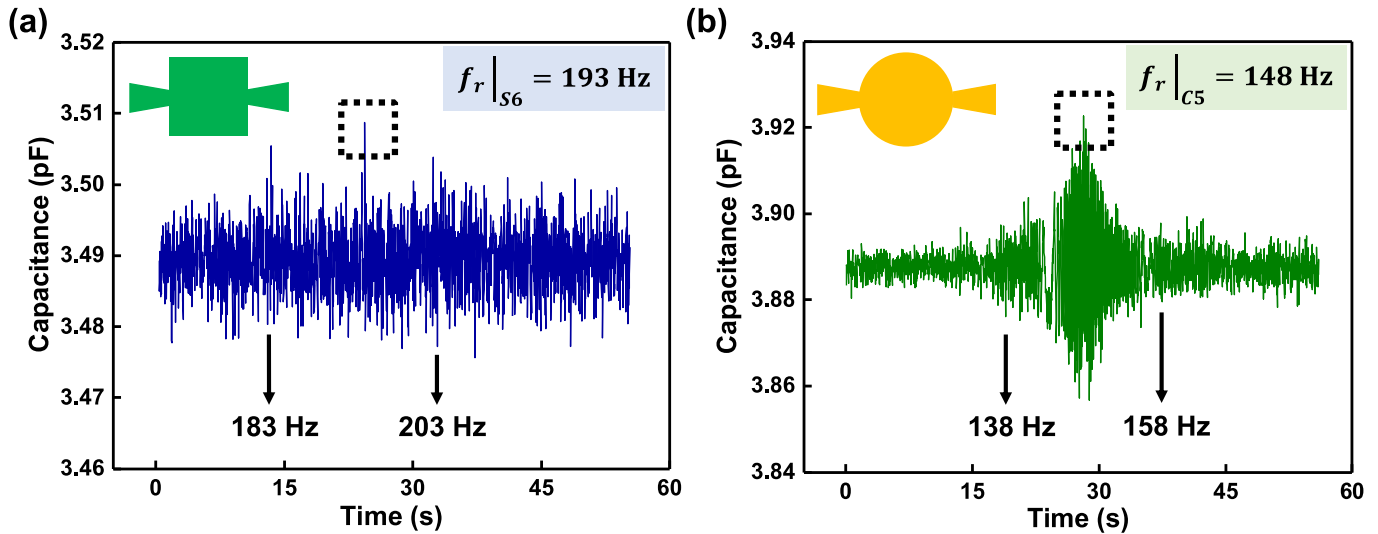
Fig. 5. Experimental investigation of capacitance change of (a). S6 and (b). C5 sensor designs after acoustic pressure application

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