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Diaphragm shape effect on the performance of foil-based capacitive pressure sensors

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ABSTRACT

We present detailed shape-based analyses to compare the performance of metal foil-based capacitive pressure sensors based on the shape of the diaphragm (top electrode). We perform a detailed analysis on the use of new material and deflection in various shaped diaphragms to act as a performance indicator for pressure-based capacitive sensors. A low-cost, recyclable, and readily available material is used to present an alternative to the expensive materials used in conventional pressure sensors. Diaphragms of five different shapes (circle, ellipse, pentagon, square, and rectangle) are fabricated and analyzed. Mathematical, FEM, and experimental tests are performed for capacitive sensors fabricated in five different shapes. The mathematically calculated deflection for each shaped diaphragm is compared with the results of the corresponding FEM simulations. Two different experiments are performed to verify the performance of pressure sensors.

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Pressure sensors are commonly used in biomedical, robotics, aerospace, automobile, and portable and consumer electronics applications. Among them, microelectromechanical system (MEMS) pressure sensors have found use in a diverse range of applications due to their compact size and superior performance. MEMS-based pressure sensors consist of a moveable mechanical element in the shape of a micrometer-sized diaphragm or a cantilever that deflects under the force of external pressure. The deflection of microstructures is measured by monitoring capacitance or resonance frequency variation in a capacitive structure. Alternatively, piezoresistive elements are used to detect diaphragm deflections to measure the absolute, gauge, and/or differential pressure. Such MEMS-based inertial devices are being used as commercial accelerometers, gyroscopes, and microphones that follow either the piezoresistive or capacitive sensing principle. They can be fabricated using surface and bulk micromachining process. The advantages of a capacitive sensing technique for pressure measurement over other types of measurement methods are low power consumption, less temperature drift, and high-pressure sensitivity. In various studies, circular-, square-, and rectangular-shaped diaphragms have been mathematically modeled, numerically simulated, fabricated, and characterized to evaluate the effect of shape on the sensor/transducer performance (increasing sensitivity or reducing non-linearity), ease of fabrication, and amount of material wasted. The square capacitive pressure sensor is easy to fabricate using a standard wet-etching process, which presents the advantages of high stress at the edges besides less deflection at the center of the diaphragm. This principle is utilized for piezoresistive sensing. However, the circular shape diaphragm provides less stress at the edges and large deflection at the center, which can be a more desirable option for capacitive sensing techniques. As the aspect ratio of the capacitive pressure sensor increases (from circular- to square-shaped diaphragms), the response of the sensor becomes more linear while the sensitivity decreases.
With advancements in technology and the need for sensors in unconventional places, there is a strong desire for flexible pressure sensors that can be used in electronic skins,²⁴,²⁵ wearable/implantable health monitoring,²⁶,²⁷ soft robotics,²⁸,²⁹ energy harvesting, automobiles,³¹ and aerospace applications.³² In recent years, paper has gained attention as an alternative material to make flexible pressure sensors for both the piezoresistive and capacitive sensing structures since it is easily available, low-cost, lightweight, and biodegradable.⁴,³³ Additionally, paper-based pressure sensors can be fabricated using fewer and simpler methods such as cutting, etching, printing, and laser treatment. Whitesides et al. have shown a piezoresistive pressure sensor fabricated on a cantilever made out of paper, carbon, and silver ink.³³ The associated signal processing circuitry is monolithically integrated on the paper for measuring the resistance change due to pressure application. Aluminum (Al) foil has also been used as a sensing material to make flexible pressure sensors owing to the similar advantages it presents as a paper does.⁴,³³ In a foil based capacitive pressure sensor, air or a microfiber wipe/foam can be used as the dielectric depending on the applications. To create air gap, a double sided tape is used to clamp the edges of the diaphragm. Air has a higher compressibility, which makes it a suitable choice for higher sensitivity than a sponge or microfiber wipe. Alternatively, a microfiber wipe/foam will have a linear and wider range of sensing.⁴ Mechanical and material based testing of paper and foil based sensors has shown the viability of such sensors as a low-cost and green alternative to conventional sensors.³² In most studies, square- and rectangular-shaped aluminum foils were used to make the parallel plate capacitive structure.

The shape of electrodes, permittivity of the dielectric medium, and separation gap affect the sensitivity of the sensor. In this work, aluminum-coated polyamide foil and a double-sided tape is used to fabricate the sensors of five different shapes, which are circular, elliptical, pentagon, square, and rectangular. The foil is used as top and bottom electrodes, and a double-sided type is used to clamp the edges of the top and bottom electrodes. The basic principle of the sensor is based on change of separation between electrodes due to pressure applications. The base capacitance of the capacitive pressure sensor is given by

\[ C_b = \epsilon \frac{A}{d}. \]  

Fig. 1(a) Al-PI sheet cut to make the bottom fixed plate. (b) A layer (90 μm) with double-sided tape adhered at the edges. (c) Step “b” repeated four times to get 350 μm height. (d) The cut top sheet adhered on the double-sided tape. (e) Cross-sectional view of the fabricated sensor. (f) Actual fabricated sensor bent to show the flexibility of the sensor; the inset highlights the small gap between the two sheets in a negative and zoomed-in image. (g) Equivalent surface areas of circle-, ellipse-, pentagon-, square-, circle-, and rectangle-shaped diaphragms in terms of “a.”

Since we are using flexible yet mechanically strong sheets, the sensor can be bent to as much as 4 mm bending radius while keeping the air gap intact. The fabricated sensor is shown in the bent form in Fig. 1(f); the inset (inverted color image) highlights the small air gap.
For the sake of simplicity, this helps us to visualize how the deflection decreases as we move from the circle to square as indicated in Table I.

It is important to choose a material for the diaphragm that is both low cost and compatible with a do-it-yourself (DIY) fabrication approach. The advantage of using foil-based sensors is that they can be fabricated using simple yet large scale manufacturing compatible fabrication techniques. Aluminum foil is cheap, readily available, and responds reliably to pressure. Although it is made up of aluminum metal, aluminum foil tends to crumble and deform easily after undergoing normal wear and tear due to its plastic nature at a small thickness. Elastic modulus is a measure of the strength of a material, which is inversely proportional to the cross-sectional surface area, which means that small cross-sectional areas (thickness) have less elastic strength and thus bend easily. Therefore, we decided to use the commercially available Al metalized Polyimide (PI) film (Liren’s LR-PI 100AM; 200 nm thick Al on top of 25 μm thick PI). PI is a flexible substrate with high thermal and mechanical stability that acts as a supporting and carrier film for Al, while Al provides the relevant conductivity necessary for the formation of a capacitor. This improves the mechanical strength of the diaphragm while maintaining the useful characteristics of aluminum foil. Studies have shown that the presence of Al improves the linear elastic range compared to using only PI and using a thin diaphragm results in an increased deflection and tensile strength of the diaphragm.43,44

We verify the mathematical analysis that relates the deflection of the diaphragm to the pressure using both FEM simulations and experiments. We utilize the FEM analysis for each shape to realize the attained deflection under prescribed boundary conditions. We use a commercially available FEM tool COMSOL45 to compare the deflection of the circle-, ellipse-, square-, pentagon-, and rectangle-shaped diaphragms in order to validate the mathematical analysis findings. Pressure based sensors are predominantly used as acoustic sensors (microphones) and to monitor atmospheric pressure.

Thus, we wanted to verify the shape analysis with two experimental setups: the first setup will use sound, while the second setup will utilize air as the pressure input to monitor the extent of deflection for each diaphragm shape. Consequently, the imposed boundary conditions were taken analogous to the experimental conditions. For fair comparison, we take the equivalent surface areas for each shape, i.e., the calculated area for each of the geometrical shape is the same. The Solid-Mechanics module was used with mechanical pressures of 1 Pa and 40 Pa at the top surface to correspond to sound and air pressure experiments, respectively. Constraints were imposed at the edges of the lower surface of each diaphragm to mimic the double-sided adhesive tape clamps. We ensured that the mesh element size is fine enough to get the converged solution. Additionally, to consider large deformations, we use the geometric nonlinearity in our study.

To mimic the conditions of the acoustic sensor setup, we put all the diaphragm shapes under an equivalent sound pressure level (SPL) intensity of 94 dB, which is equivalent to a loud sound produced by human beings. In order to find the equivalent value of pressure in Pascal (Pa), we convert the value of Sound Pressure Level (SPL) into Pascal (Pa),44

\[
SPL(dB) = 20 \log_{10} \left( \frac{\text{Measured Sound Pressure}}{\text{Reference Pressure}} \right),
\]

where the reference pressure was set to 20 μPa, which is the threshold of human hearing.45 An SPL of 94 dB corresponded to 1 Pa. The FEM simulation results to visualize the deflection behavior in each diaphragm are shown in Figs. 2(a)–2(e). The deflection at the center of each diaphragm (\(w_{\text{sim}}\)) against each shape is plotted in Fig. 3(a). The mathematical values of deflection (\(w_{\text{math}}\)) in terms of “\(D^2\)” (\(w_{\text{math}} \times D\)) for each shape is plotted in the same graph to verify that the simulation results follow the same performance trend as indicated by the respective equations. The same diaphragms are then subjected to an equivalent pressure as used in the air pressure sensing experimental setup to observe the deflection response for large pressures (~40 Pa). The results of the FEM simulations along with maximum deflection are shown in the supplementary material, Fig. 1. The trend remains the same for this larger pressure albeit with a much larger deflection.

For the acoustic sensing experiment, we set up the experiment to evaluate the performance of each diaphragm for sound detection.

| Shape   | Deflection | Deflection in term of “\(D\)” |
|---------|------------|-------------------------------|
| Circular | \(\frac{8a^3}{4D}\) | \(\frac{1}{4D}\) |
| Elliptical | \(\frac{pD}{4D} \left( \frac{4a^3}{3(4a^4+b^4)}+\frac{2b^4}{2b^4} \right)\) | \(\frac{1}{1175}\) |
| Pentagon | 0.0041 \(\frac{Pa}{D}\) | \(\frac{1}{2440}\) |
| Square  | 0.0013 \(\frac{Pa}{D}\) | \(\frac{1}{752}\) |
| Rectangle | 0.0239 \(\frac{Pa}{D}\) | \(\frac{1}{11675}\) |
We attached each of the sensors on a glass slide with the top metal plate (the diaphragm) of the sensor facing upwards and the bottom plate is fixed to the glass slide. A Bluetooth speaker (JBL Go Portable Speaker) was placed at a 2 mm distance from the top metal diaphragm. Three different frequency sound tones (200 Hz, 250 Hz, and 300 Hz) were played through the speaker and the capacitance was monitored using Keithley 4200. The sound amplitude was set to 94 dB, which corresponds to a pressure of 1 Pa that was used in the FEM simulations. The results from three different input sounds are shown in Fig. 3(b). Three different sound frequencies were chosen to make sure that the frequency of the input sound does not affect the result in any other way. Sound is inherently a sinusoidal wave.

Thus, we get a sinusoidal output capacitance response and a sample output response for the circle diaphragm at 300 Hz shown in the supplementary material, Fig. 2(a). $\Delta C$ was calculated for each diaphragm by calculating the peak-to-peak amplitude of the output observed for each sound frequency. It can be seen that the experimental results verify the mathematical and simulation results. The circle diaphragm shows the largest deflection with as much as 150 fF change in capacitance followed by the ellipse diaphragm. The results for the ellipse diaphragm and the rectangle diaphragm are close to each other because the dimensions of ellipse ($a = 2$ cm, $b = 0.5$ cm) form a shape similar to that of a rectangle.

For the air pressure experimental setup, we created a custom setup to exert pressure on the top diaphragm. A 5 mm diameter pipe was connected to an air valve. A custom scale was made on the valve with values of 0–50 such that the value is 0 for a fully closed valve and 50 for a fully opened valve. The end of the pipe was then inserted into a hole inside the top layer of an acrylic box such that the air coming out of the nozzle will apply pressure on the bottom surface of the acrylic box [see the supplementary material, Fig. 2(b)]. A commercial pressure sensor (MS5803-14BA) was then attached to the bottom surface right below the opening of the pipe. This MEMS pressure sensor measures the absolute pressure of the fluid around it, which includes air, water, and anything else that acts like a viscous fluid. The valve was opened from 0 to 50 with increments of 5, and the corresponding pressure was measured using the air pressure sensor. A linear fit of the pressure observed corresponding to the value of scale can be seen in the supplementary material, Fig. 2(c). This plot is used to convert the value of the custom scale to a pressure value in Pascal (Pa). To conduct the experiment, we placed all of the diaphragms at the same place as the pressure sensor and opened the valve from 0 to 24 (after 24, the increased pressure makes the deflection difference too large for graphical representation). The change in capacitance from the starting value for each diaphragm is plotted against the applied pressure, and the results are plotted in Fig. 3(c). The experiment further verifies that indeed the diaphragm exhibits a similar deflection response as expected from the mathematical analysis and the FEM simulations. The circle diaphragm undergoes largest deflection followed by the ellipse diaphragm. The square shape shows the least deflection.

We have thus verified the mathematical and FEM simulation results using two experimental setups. From the obtained results, it is evident that the circle provides the most amount of deflection.
among the five shapes. If sensitivity is important for a required application, a circular or elliptical shape should be chosen. We have used low-cost recyclable materials, which can result in reduced financial and environmental cost. The elliptical shaped diaphragm has less material wastage while having a comparable performance in comparison with circular-shaped diaphragms. For scalable manufacturing techniques with least material wastage, a square-shaped diaphragm is more useful. In addition, square-shaped diaphragms show a linear response. The response becomes nonlinear as we move toward circular-shaped diaphragms. Thus, this article may serve as a reference to choose the appropriate shapes as per the requirements.

See the supplementary material for images.

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