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Designing wearable capacitive pressure sensors with arrangement of porous pyramidal microstructures

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Abstract

Capacitive pressure sensors are essential for advanced applications like wearable medical devices, electronic skins, and biological signal detection systems. Enhancing sensitivity in these sensors is achieved by incorporating porous microstructures into the dielectric layer. The present research focuses on designing a capacitive pressure sensor comprising a porous micro-pyramidal dielectric layer featuring diagonally arranged pyramids. The effects of geometric parameters and material properties such as dielectric constant, porosity, base length, tip width, height, and the distance between the pyramidal microstructures were examined using the three-dimensional finite element simulations. A comparative analysis was conducted to evaluate the accuracy of the numerical solution. The simulation results were compared to experimental measurements, and the findings revealed a high level of agreement. The optimal quantity of data for this analysis was determined using the design of the experiment method, specifically the response surface model. The results show that arranging microstructures diagonally or laterally can impact sensitivity and initial capacitance. Specifically, employing a diagonal arrangement enhanced sensor sensitivity by up to 1.65 times while maintaining the initial capacitance relatively unaffected. Ultimately, this study derived mathematical equations from the collected data to estimate the initial capacitance and sensitivity of the sensor. The model predictions were compared to simulation results, and it was found that the models performed effectively.

Keywords Porous capacitive pressure sensor, Micro pyramid, Diagonal arrangement, High sensitivity, Flexible wearable pressure sensor

Introduction

Flexible pressure sensors, which are capable of detecting and monitoring variations in pressure, serve as the fundamental components for a wide range of advanced applications. These cutting-edge sensors play a crucial role in meeting the requirements of wearable medical devices [1–3], electronic skins [4, 5], and biological signal detection systems [6, 7], empowering them to accurately sense the surrounding information and convert it into an electrical signal. For instance, Electronic skin (e-skin) technology has transformed human-machine interaction. E-skin with integrated pressure sensors replicate the flexibility and sensitivity of human skin and enables precise and intuitive interaction with electronic devices [8]. Given the significant potential of flexible pressure sensors in medical applications, extensive research has been dedicated to enhancing their sensitivity [9]. One of these research fields is employing microelectromechanical system (MEMS) technology in flexible pressure sensors, which has garnered significant interest owing to its array of benefits when compared to conventional pressure sensing methods [10]. The utilization of MEMS

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in pressure sensors has not only enhanced their performance but also made them more cost-effective and versatile [11]. MEMS-based pressure sensors employ microstructures and electronic components to measure pressure variations accurately [12].

Flexible pressure sensors come in various types with different mechanisms, including piezoelectric [13–15], piezoresistive [16–18], and capacitive sensors [19–21]. Among these options, capacitive pressure sensors have gained widespread popularity. The advantages of using capacitive pressure sensors are notable. Firstly, they exhibit low energy consumption, making them suitable for battery-operated devices and applications where power efficiency is critical [22]. Secondly, capacitive sensors offer high repeatability, ensuring consistent and reliable measurements over time [23]. Additionally, they maintain constant sensitivity even in the presence of environmental changes, providing stability and accuracy in various operating conditions. These characteristics make capacitive pressure sensors a preferred choice for many applications where precision, durability, and efficiency are paramount [24]. A capacitive pressure sensor typically consists of two parallel plates separated by a thin, flexible dielectric layer. The bottom plate is fixed, while the top plate is flexible and moves in response to applied pressure. The space between the plates forms a variable capacitor. When pressure is applied, the dielectric layer deflects, altering the distance between the plates and thus changing the capacitance. This change in capacitance is directly proportional to the applied pressure. Hence, the measurement of pressure in this type of sensor is based on changes in the capacitance of the capacitor [25].

When selecting a pressure sensor that aligns with the desired application and performance requirements, sensitivity serves as a crucial criterion. It indicates the sensor's capability to convert applied pressure into discernible signal changes [26]. A high-sensitivity pressure sensor is able to exhibit imperceptible changes in pressure. The significance of flexibility and compatibility with the movements of human skin in capacitive pressure sensor applications, particularly wearable devices, imposes limitations on the thickness of the sensor [24]. Consequently, the range of dielectric layer alterations is also restricted to a small extent, thereby posing challenges for the sensor in measuring minor pressure changes accurately. Because making the dielectric layer more deformable is the key to improving the sensor's sensitivity, various studies have been reported to explore solutions that can enhance the dielectric layer compressibility. One way to improve the sensitivity of a pressure sensor is by incorporating microstructures into the dielectric layer, thus increasing its flexibility and reducing the modulus of elasticity [27]. Fabrication of hierarchical microstructured dielectric layer also enhances the sensor's performance [28]. The dielectric constant of the dielectric layer also affects the sensor's sensitivity. Polydimethylsiloxane (PDMS) has been extensively employed as the dielectric layer of a capacitive pressure sensor because of its low Young's modulus, flexibility, biocompatibility, and good dielectric properties [29]. Utilizing a composite material with nanoparticles as the dielectric layer, which demonstrates a high dielectric permittivity, is another approach to adjust sensitivity [30]. Jeong et al. [31] describes the creation of a flexible wearable pressure sensor utilizing a micro-structured conductive nanocomposite film composed of polyimide/carbon nanotubes (PI/CNT).Its sensor has a wide pressure sensing range of approximately 0–3000 kPa and improved sensitivity. In the work conducted by Mitrakos et al. [32], an investigation is made into pressure sensors based on nanocomposite-infused micro truncated pyramids, specifically designed for measuring low-pressure ranges. Their study involves the utilization of two distinct composite materials in these sensors: a composite consisting of Multiwalled Carbon Nanotubes (MWCNT) and elastomer, and a Quantum Tunneling Composite (QTC). In their work, Peng et al. [33] showcase the efficacy of a cost-effective elastomeric nanocomposite referred to as porous fluororubber-thermoplastic urethanes nanocomposites (PFTNs). Notably, these composites exhibit the highest intrinsic sensitivity to pressure among existing porous nanocomposites. Hsieh et al. [34] introduce a flexible wearable capacitive pressure sensor that employs a porous polydimethylsiloxane elastomer embedded zinc oxide nanowires as its nanocomposite dielectric layer. Their sensor is ultra-sensitive to subtle low pressure and can detect gentle touch and verbal stimulation. Additionally, a micro-porous dielectric layer easily deforms under applied pressure, consequently enhancing the overall sensitivity of the pressure sensor [35, 36]. To improve the sensor's sensitivity, a combination of these methods can be used [37].

Designing the dielectric layer with types of microstructures such as microcone [38], microdome [39], micropillars [40, 41], and micropyramid [42, 43] is recognized as an effective way to improve the properties of the flexible pressure sensor to decrease the compression stiffness and increase the sensor's effective surface area. Hua et al. [44] have investigated dielectric layers with nine different microstructures, which include shapes with and without ladder structure, experimentally and numerically by using finite element method. The results of their study indicate that the pressure sensor with a cylindrical ladder microstructure dielectric layer provides the highest sensitivity. Yin et al. [45] have adopted micropatterned dielectric layer to fabricate the capacitive pressure sensor.

The effects of micropillars' width on sensitivity have been considered in their work. Luo et al. [46] have employed tilted micropillars which can withstand bending to enhance the flexibility of the elastomer layer. Various geometric parameters that affect the sensor's sensitivity when the micro pyramid-shaped microstructure has been added to the dielectric layer has been studied [47]. A numerical study using finite element software COMSOL Multiphysics on capacitive pressure sensors focuses on the influence of microstructured dielectric layer arrangement, including monolayer, tip-to-tip bilayer, and bilayer with dislocation on sensitivity [48]. Xia et al. [49] have numerically studied different hollow and solid microstructures to investigate the sensor's performance. They have reported that flexible hollow structure exhibits the highest sensitivity. Employing mathematical models to analyze the parameters affecting the performance of flexible pressure sensors is regarded as an innovative and highly advantageous solution, allowing for a more tailored approach that aligns precisely with the specific requirements of the intended application.

Recently, microstructured flexible pressure sensors have been of great importance in the practical applications of wearable medical devices and electronic-skin applications. One of the main goals in this field is to improve the sensitivity of the pressure sensor. In the current study, a capacitive pressure sensor is developed with a porous micro-pyramidal dielectric layer with diagonally arranged pyramids. We have investigated the influence of geometric parameters and material properties, including dielectric constant, porosity, base length, tip width, height, and interstructural separation of pyramidal microstructures using the three-dimensional finite element method. Additionally, a comparative analysis was performed to assess the effects of employing diagonally arranged microstructures within the dielectric layer. This study involved analyzing the data to develop mathematical equations that could estimate the initial capacitance and sensitivity of the sensor. Response surface methodology was used as an effective tool in this analysis. Finally, these equations were compared with simulation results to validate their accuracy.

Material and method

Numerical simulation

A capacitive pressure sensor consists of a flexible dielectric layer and two conductive electrodes. When pressure is applied to the sensor, it undergoes deformation, causing a change in the gap distance between the plates. According to the governing equation of a simple capacitive sensor $\left(C = \frac{\epsilon_r \epsilon_0 A}{d}\right)$, ($\epsilon_0$ signifies the vacuum dielectric constant, while ϵ_r represents the relative permittivity. The area between the conductive plates is denoted as A, and the separation between the parallel electrodes is indicated by d) when the distance between the parallel plates is reduced, the capacitance of the sensor is changed. By measuring the capacitance variation, the pressure exerted on the sensor can be determined. The sensor is designed to convert the capacitance change into a corresponding output signal that can be further processed and interpreted.

Sensitivity which is defined by the slope of the pressure-response curve, is an important performance parameter that must be considered when selecting a sensor for a particular application because it affects the accuracy and precision of the sensor's measurements [50].

$$S = \frac{\Delta C / C_0}{\Delta P} \tag{1}$$

where S, ΔC and C_0 are sensitivity, capacitance change and initial capacitance of the pressure sensor, respectively. The sensor sensitivity for pressures below 100 Pa has been calculated. When small changes in pressure need to be measured accurately, this is particularly important to increase sensitivity to produce a larger change in output signal for a given change in pressure. A microstructured dielectric layer can increase the sensor's effective surface area, which can increase capacitance and sensitivity. In the present study, the dielectric layer of the capacitive pressure sensor incorporates diagonally arranged porous microstructures to increase its flexibility and reduce stiffness. Figure 1 shows the geometry of the capacitive pressure sensor and the schematic configuration of the microstructures. The geometric parameters that will be investigated in this paper, including pyramid base length (a), height (t), tip width (b), and interstructural separation (d) are depicted in this figure.

The mechanical response of structures relies on a set of governing equations to describe the behavior of materials under various external forces and deformation conditions. These equations encompass three fundamental principles: equilibrium, compatibility, and constitutive relations. Equilibrium equations ensure that forces and moments acting on a structure are balanced. These equations are stemmed from Newton's laws and expressed in Eq. (2). Where $\mathbf{f}$ is a force per unit volume, ρ is the mass density, and $\boldsymbol{u}$ is the displacement vector. Compatibility equations govern the consistent and interconnected deformations of structures, ensuring the integrity of the entire system. Constitutive relations determine the relationship between stress and strain, providing insights into material behavior. By incorporating these governing equations, solid mechanics enables the analysis and prediction of the response of solid materials to external forces, facilitating the design and optimization of structures in various engineering applications. Herein, the

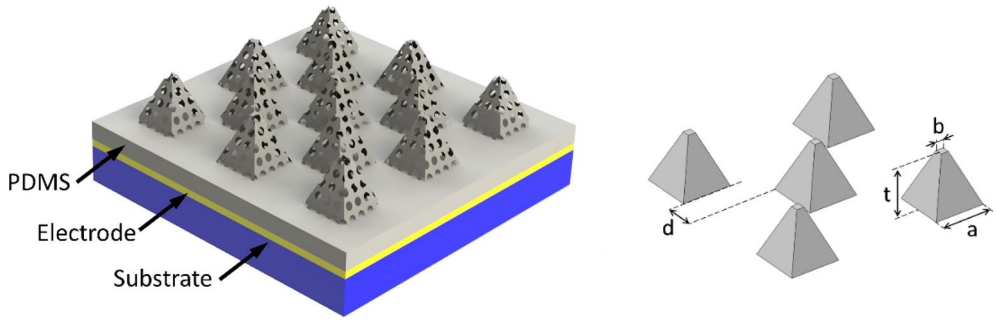

Fig. 1 Schematic illustration of the diagonal arrangement of pyramidal microstructures in a porous dielectric layer of a capacitive pressure sensor

dielectric material for the porous pyramid microstructures has been selected as PDMS. This choice is motivated by PDMS's desirable characteristics, including a low Young's modulus, flexibility, biocompatibility, and excellent dielectric properties. To accurately capture the behavior of the dielectric layer, which exhibits large deformations and a nonlinear stress-strain relationship, the Neo-Hookean model, a hyperelastic constitutive equation, has been employed. Equation (3) defines the strain energy density function (W) for the dielectric layer.

$$\nabla \cdot \sigma + \mathbf{f} = \rho \frac{\partial^2 \boldsymbol{u}}{\partial t^2} \tag{2}$$

$$W_s = C_{10}\left(\overline{I_1} - 3\right) \tag{3}$$

where C_{10} is the material constant and $\overline{I_1}$ is the first invariant of the left Cauchy-Green deformation tensor [51].

The governing equations for the electric field in the capacitive pressure sensor can be described by Gauss's law.

$$\nabla \cdot (\epsilon_0 \epsilon_r \nabla V) = \rho_v \tag{4}$$

In this equation, ϵ_r represents the relative dielectric constant of the domain, V represents the electric potential, and ρ_v represents the volumetric free charge density. The vacuum dielectric constant, denoted as ϵ_0, has a value of 8.8542×10^{-12} F/m. The correlation between the intensity of the electric field (E) and the electric potential (V) can be expressed as follows:

$$\overrightarrow{E} = -\nabla V \tag{5}$$

In this research, a comprehensive three-dimensional computational model was proposed to analyze the performance of a capacitive pressure sensor. The flexible pressure sensor consisted of two parallel electrodes with a microstructured elastomer layer featuring porous frustum-shaped pyramid microstructures arranged diagonally. To study the effects of geometrical parameters and material properties of the dielectric layer on capacitance variation and sensor's sensitivity, simulations were performed using the finite element method (FEM). The governing equations, including equilibrium, compatibility, and constitutive equations and the conservation of electric charge, were solved through COMSOL Multiphysics software. The electrostatic interface in the AC/DC module was utilized to obtain the electric field by solving the charge conservation equation. The solid mechanics and moving mesh interfaces were employed to determine the deflection of the elastomer layer under the applied pressure. The terminal boundary condition with a fixed potential was applied to the top electrode. This electrode was considered a rigid part and was allowed to move only in the z-direction. The boundary load was applied to this electrode to compress the dielectric layer. The dielectric layer, incorporating the pyramid microstructures, was modeled as a hyperelastic material using the Neo-Hookean model. The bottom electrode was grounded and considered a fixed boundary, while other boundaries were designated electrically insulating. Seven parameters, including the pyramids' shape, porosity, and material properties, were chosen to optimize the pressure sensor's sensitivity and initial capacitance. The response surface methodology was used to determine the best set of parameters for simulations.

Design of experiments

Design of Experiment (DoE) is an efficient methodology utilized across diverse disciplines to study and improve processes. It involves strategically planning and executing experiments to gather data and derive valuable insights. By manipulating variables and carefully controlling experimental conditions, DoE enables researchers to explore the cause-and-effect relationships between these variables. Through data analysis, DoE helps identify significant factors that impact the outcome of interest and determine the optimal settings for achieving desired results. The response surface method (RSM) is

Table 1 The range of independent variables for the central composite design

Parameter	Symbol	Unit	Range
Base length	*a*	µm	20–300
Height	*t*	µm	20–200
Interstructural separation	*d*	µm	20–300
Tip length	*b*	µm	0.01–20
Dielectric constant	ϵ	–	2–60
Modulus of elasticity	*E*	kPa	120–3000
Dielectric layer porosity	*v*	–	0–1

a DoE model that utilizes statistical approaches to efficiently navigate the design space, providing insights into the parameters that influence the response. The primary advantage of employing RSM is its ability to reduce the number of experiments required while still providing valuable information about the influence and interaction of input variables. In this article, we aimed to optimize the geometrical parameters and material properties of the capacitive pressure sensor with diagonally arranged microstructures. Hence, a central composite rotational design (CCRD) model of RSM has been utilized to simplify the design of the capacitive pressure sensor with effective performance. Table 1 presents the dependent variables that have an impact on capacitance and the sensor's sensitivity. The effects of parameters such as pyramid tip width, base length, height, dielectric layer porosity, dielectric constant, and interstructural separation of porous micro-pyramids in the diagonal arrangement of pyramids have been investigated.

Result and discussion

To delve into the influence of geometric parameters and material properties of the dielectric layer on the sensor's sensitivity and capacitance, a three-dimensional finite element model of the capacitive pressure sensor with diagonally arranged pyramidal microstructures has been constructed using COMSOL Multiphysics software. This model serves as a tool for investigating the relationship between these parameters and the efficiency of the capacitive pressure sensor. In order to assess the performance of the model, a comparison was made with the sensitivity of the bulk [52] and porous [53] pyramid capacitive pressure sensors. The results reveal a good agreement between the experimental and numerical results, as summarized in Table 2. Additionally, the agreement between the numerical and experimental results for the capacitance variation to the initial capacitance of the pressure sensor with respect to the applied pressure was examined

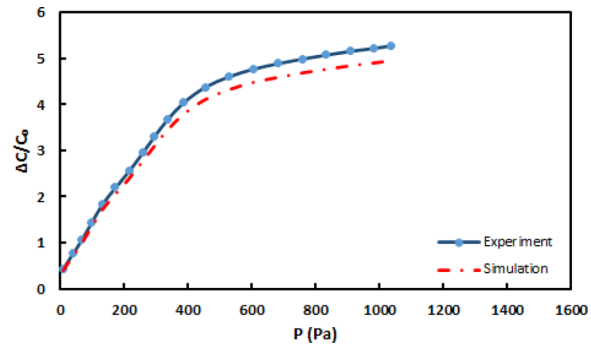

Fig. 2 Relative change in capacitance versus pressure of the capacitive pressure sensor based on porous pyramid dielectric layer

Table 2 Sensitivity assessment of the pressure sensor with bulk and porous pyramid dielectric layers by comparing the results of numerical simulations and experimental measurements

Microstructured dielectric layer	Sensitivity [kPa^{-1}]	References
Bulk pyramid	0.42	Experiment [52]
	0.417	Simulation
Bulk pyramid	4.30	Experiment [53]
	4.26	Simulation
Porous pyramid	14.6	Experiment [53]
	14.5	Simulation

Table 3 Difference in sensitivity of the capacitive pressure sensor for different pore sizes

Simulation	2 µm [53]	2 µm	4 µm	6 µm
Sensitivity [kPa^{-1}]	14.6	14.5	14.63	14.7

and represented in Fig. 2. This confirms a satisfactory level of agreement.

In Table 3, the sensitivity of the capacitive pressure sensor has been calculated for a pore size of 2 µm based on the [53], as well as for sizes of 2, 6, and 10 µm while keeping the volume fraction constant, using finite element modeling at low pressures. As seen in Table 3, the difference in sensitivity obtained at low pressure with same volume fraction for different pore sizes is less than 1%. Therefore, the results have been investigated based on the variation in volume fraction. The pores considered in the simulation are assumed to be spherical with a diameter of 6 µm.

The pressure and electric field distribution of the micro-pyramid in the diagonal arrangement were simulated through the visualization of two-dimensional

contour plots, as depicted in Fig 3. As can be seen in Fig. 4, three-dimensional contour revealed that when external pressure is applied to the sensor, the apex of the micro-pyramid experiences significantly heightened stress. Additionally, the analysis unveiled a notable disparity in the electric field intensity, with the pyramid's sharp points and apex exhibiting higher intensity levels compared to the surrounding regions.

Mathematical models play a crucial role in the analysis and optimization of flexible pressure sensors. These models allow for a comprehensive understanding of the factors that influence sensitivity and accuracy, facilitating the creation of customized sensors that meet specific design requirements. This approach enhances our comprehension of sensor behavior and enables the development of tailored solutions for achieving high-precision pressure sensing. The performance of the porous capacitive pressure sensor requires careful consideration of the materials and designs of the dielectric layer, as they can impose significant constraints. Specifically, the effects of the sensor's dielectric constant, dielectric layer porosity, base length, pyramid tip width, height, intermicrostructural spacing, and modulus of elasticity have been investigated. By thoroughly understanding the interplay between these factors, researchers can effectively design and optimize pressure sensors to fulfill the desired criteria for various specialized applications. In the analysis of parameters influencing the capacitive pressure sensor, porosity was chosen as the fundamental parameter. This is due to the fact that the sensitivity of the sensor can be easily modified by adjusting the porosity of the dielectric layer. As the sensitivity of the sensor is inversely proportional to the modulus of elasticity, an increase in porosity within the dielectric layer causes a decrease in the modulus of elasticity, subsequently leading to an increase in sensitivity.

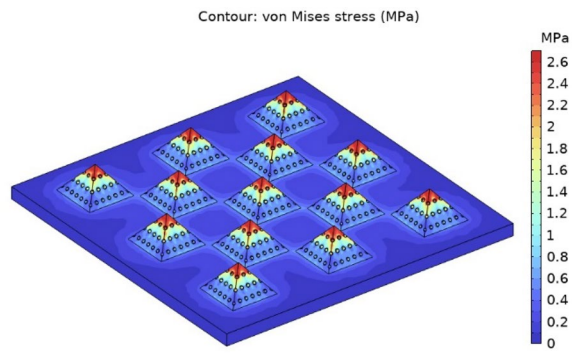

Fig. 4 Stress distribution in dielectric layer with diagonally arranged microstructures

Figure 5 presents the quantitative impacts of the inherent material property and the geometric parameter of microstructures on initial capacitance (c_0) and sensor's sensitivity. In each plot analyzing the impact of two specific parameters on the sensor's sensitivity and initial capacitance, all other parameters remain constant except for the two under investigation. The base length, the tip width, the dielectric constant, and the modulus of elasticity constant levels are set at the fixed value of 50, 0.1, 2.7, and 400 kPa, respectively. Furthermore, the height of pyramid in this study is calculated based on the Eq. (6).

$$t = \frac{\tan\theta}{2}(a - b) \tag{6}$$

where θ is the micro pyramid's side angle. In this study, θ has been set to 54.7° based on the microfabrication requirements. Figure 5a, which illustrates the initial capacitance of the porous capacitive pressure sensor as a function of the dielectric constant and the volume fraction, demonstrates that increasing the dielectric constant

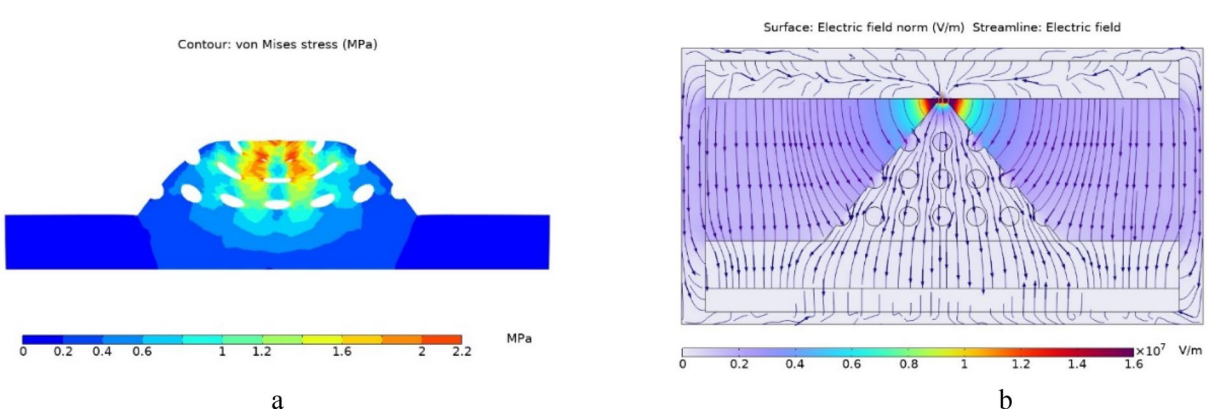

Fig. 3 2D contour plot of pressure and electric field distribution in the microporous dielectric layer, **a** stress distribution, **b** contour of the electric field and electric field lines

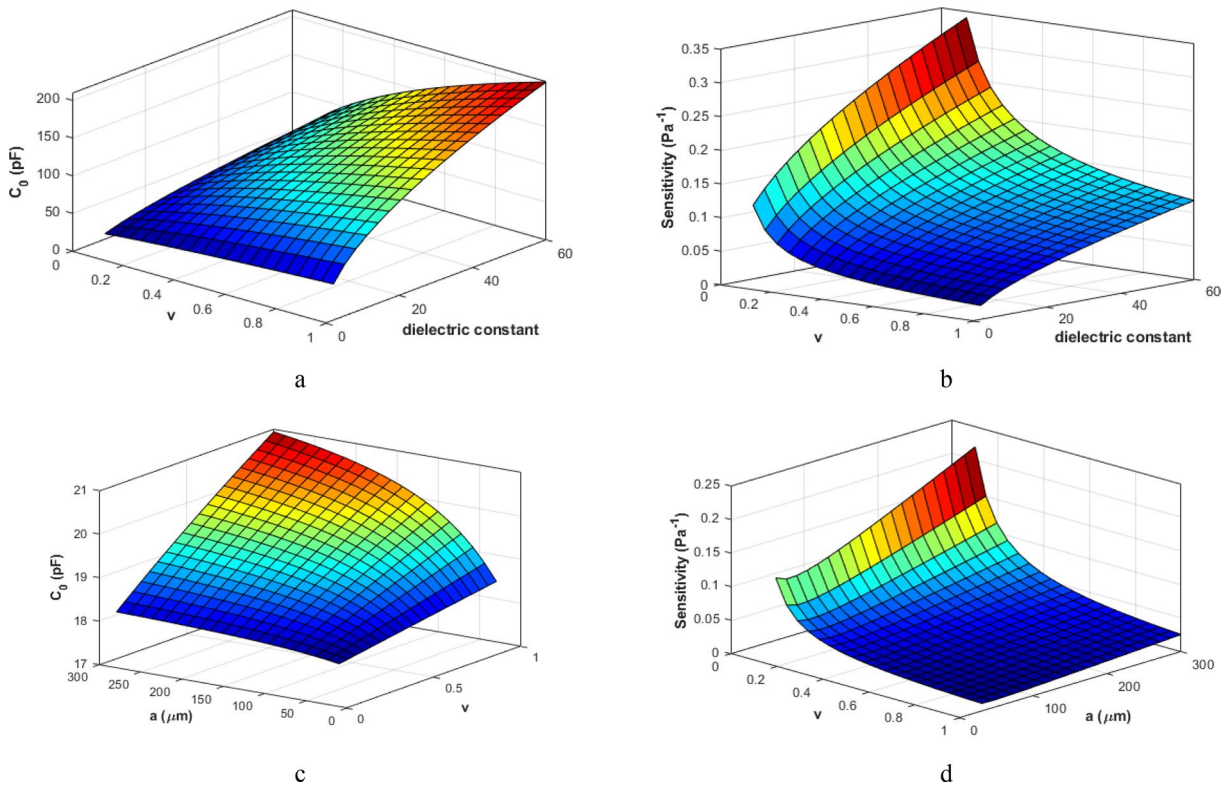

Fig. 5 A visual repetition of the initial capacitance and sensitivity of the pressure sensor with respect to characteristics of the dielectric layer, **a** influence of volume fraction and dielectric constant on initial capacitance, **b** influence of the volume fraction and dielectric constant on sensor sensitivity, **c** influence of porosity and pyramid base length on initial capacitance, **d** influence of porosity and pyramid base length on sensor sensitivity

leads to higher initial capacitance because based on the governing equation of a capacitor, capacitance is directly proportional to the dielectric constant. Similarly, raising the volume fraction of the dielectric layer also increases the initial capacitance. The dielectric constant of the elastomer is higher than that of air. Consequently, as the porosity decreases, the dielectric constant of the dielectric layer increases, resulting in an increase in the initial capacitance. The initial capacitance exhibits a steeper slope as the volume fraction and dielectric constant increase.

Figure 5b shows how the sensitivity of the capacitive pressure sensor varies with respect to the volume fraction of the dielectric layer and dielectric constant. The increase in the porosity decreases the dielectric layer's modulus of elasticity and makes the dielectric layer more flexible. As the sensitivity is inversely proportional to modulus of elasticity, it results in higher sensor's sensitivity. As discussed earlier, a greater dielectric constant result in increased capacitance within the capacitive sensor, subsequently boosting its sensitivity. The sensitivity of the sensor demonstrates a greater rate of change as the porosity and dielectric constant are increased.

The effects of the porosity of the dielectric layer and pyramidal microstructure's base length on the initial capacitance and sensitivity of the capacitance pressure sensor are shown in Fig. 5c, d. Assuming all geometric parameters remain constant and only the base length of the pyramid increases, the air-to-elastomer ratio in the dielectric layer also increases. Since the dielectric constant of the elastomer is higher than that of air, and the initial capacitance is directly related to the dielectric constant, the initial capacitance of the sensor also increases with the base length of the pyramid as it is shown in Fig. 5c. The initial capacitance reaches its peak when both the base length of the pyramids and the volume fraction of the dielectric layer are increased. The initial capacitance exhibits a steeper slope as both the volume fraction and pyramid base length increase.

As shown in Fig. 5d, the sensor's sensitivity increases with the increase in dielectric layer porosity and the base length of the pyramids. Similar to what was discussed in Fig. 5c, increasing the base length of the pyramids results in an increased capacitance, leading to enhanced sensor sensitivity. Furthermore, reducing the tip width to base length ratio in frustum-shaped pyramid increases

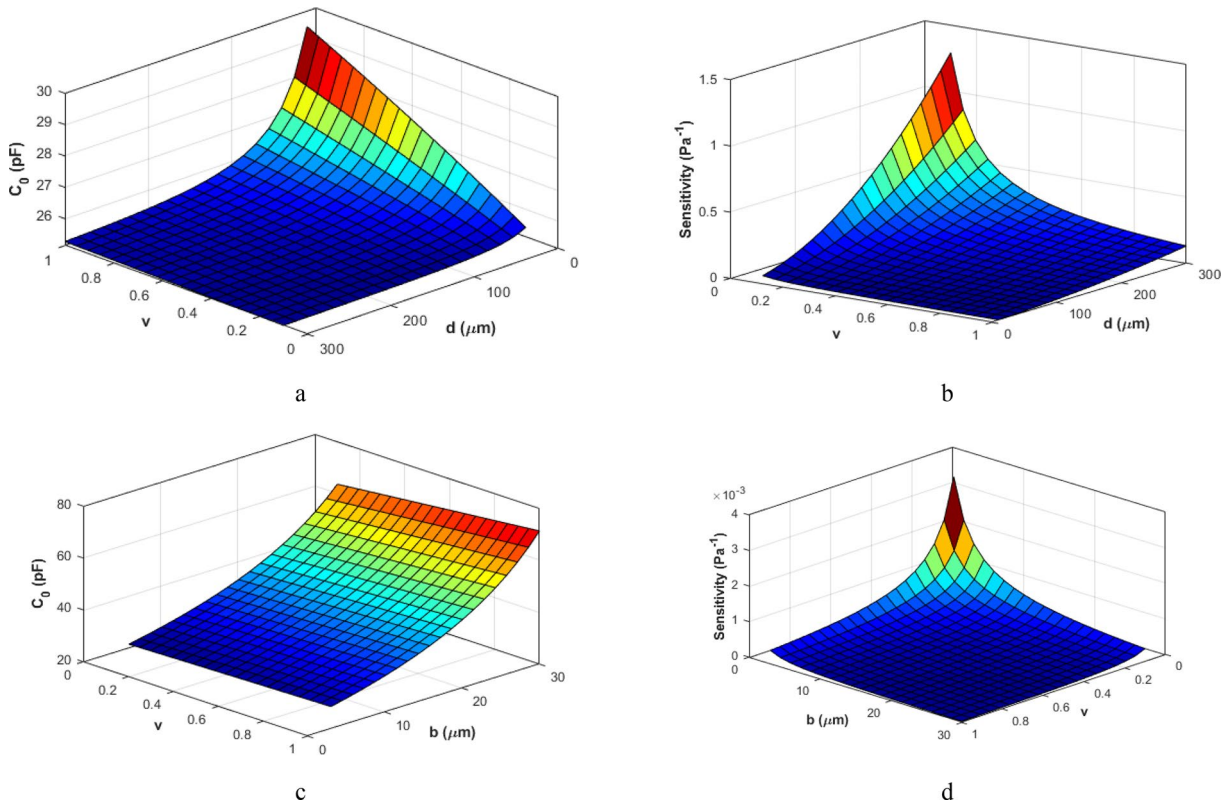

Fig. 6 A visual repetition of the initial capacitance and sensitivity of the pressure sensor with respect to characteristics of the dielectric layer, **a** influence of volume fraction and interstructural separation on initial capacitance, **b** influence of the volume fraction and interstructural separation on sensor sensitivity, **c** influence of porosity and pyramid tip width on initial capacitance, **d** influence of porosity and pyramid tip width on sensor sensitivity

the compressibility of the microstructure, which further improves sensor sensitivity. The sensor sensitivity exhibits a steeper slope as both the porosity and pyramid base length increase.

Figure 6a illustrates the changes in the initial capacitance of the sensor in terms of volume fraction and spacing between microstructures. When the micro pyramids fill the dielectric layer with a smaller spacing, the initial capacitance of the capacitor increases due to the decrease in the air-to-elastomer ratio. This behavior is a result of the increased dielectric constant corresponding to the densely packed arrangement of microstructures in the dielectric layer. The initial capacitance shows a more significant and rapid increase as a result of reducing porosity and decreasing the spacing between micro-pyramids.

Figure 6b shows how the sensitivity of the capacitive pressure sensor changes with respect to the distance between the micro pyramids and the volume fraction of the dielectric layer. A higher concentration of microstructures within the dielectric layer, achieved by reducing the spacing between them, results in a more compact arrangement of micro pyramids. This compact arrangement, however, decreases the flexibility of the dielectric layer. Given that the sensitivity of the sensor is inversely correlated with the modulus of elasticity, increasing the distance between micro pyramids enhances the sensitivity of the sensor. When the distance between the micro pyramids and the porosity of the dielectric layer is at its maximum, the capacitive pressure sensor exhibits the highest sensitivity to applied pressure. In lower volume fractions and higher distances between the micro pyramids, the sensitivity exhibits an abrupt increase.

The effects of the volume fraction of the dielectric layer and pyramidal microstructure's tip width on the initial capacitance and sensitivity of the pressure sensor are shown in Fig. 6c, d. The investigation of the impact of pyramid tip width on the performance of the sensor in this study stems from the inherent challenges associated with fabricating sharp apexes and enhancing the microstructure-electrode contact. These limitations necessitate

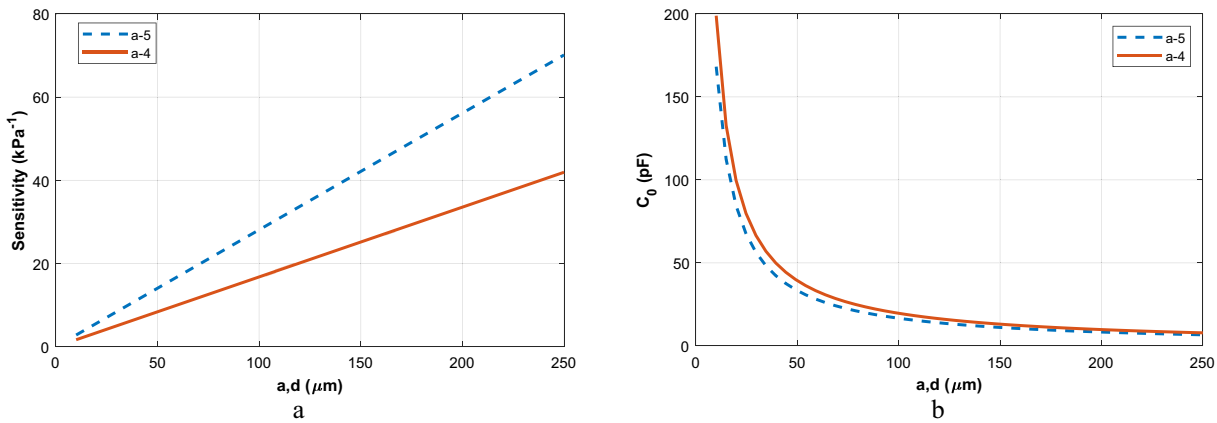

Fig. 7 A comparison of 5-element vs. 4-element arrays of microstructured dielectric layer for **a** the sensor sensitivity and **b** initial capacitance

a thorough examination of the tip width as a crucial parameter affecting the sensor's overall functionality and accuracy. When the tip width of the micro-pyramid increases while maintaining other geometric parameters constant, the volume of PDMS incorporated within the dielectric layer experiences a corresponding increase. This augmentation in the amount of PDMS results in a higher dielectric constant, subsequently boosting the initial capacitance of the sensor.

Figure 6d provides a visual representation of the relationship between the sensitivity of the sensor and two influential factors, namely the tip width of the micro pyramid and the volume fraction of the dielectric layer. The results depicted in the graph indicate that reducing the tip width and increasing the porosity both contribute to enhanced sensitivity. The sensitivity of the sensor can be improved by reducing the tip width of the micro-pyramid, which in turn reduces the cross-sectional area of the pyramid's tip. This reduction in area results in higher pressure being exerted on the smaller contact surface, leading to increased stress. The increased stress induces a greater deformation in the dielectric layer, ultimately enhancing the sensor's sensitivity. The sensitivity of the sensor experiences a steeper slope as both the volume fraction and pyramid tip width decrease.

Figure 7 illustrates how the sensitivity and initial capacitance within the dielectric layer are affected by the base length (a) and spacing of the micro pyramids (d). This analysis specifically focuses on the diagonal and lateral arrangements, where the spacing between the micro pyramids equals the base length. In the diagonal arrangement, according to Fig. 1, each unit of the dielectric layer comprises five micro pyramids (a-5), whereas the lateral arrangement consists of four micro pyramids per unit (a-4). In the lateral configuration, the spacing between two adjacent micro pyramids is equal to d. As depicted in Fig. 7a, when a and d are equal, and the pyramid's height is determined using Eq. (6), the sensor sensitivity exhibits a linear change with a relatively constant slope in both arrangement types. When utilizing a 5-element micro pyramid array in the dielectric layer, the sensor sensitivity increases by 1.65 times with respect to the lateral configuration, while the initial capacitance remains relatively unchanged. At lower base lengths, the sensitivity of the sensor is relatively low, and there is not much difference between a-5 and a-4 configuration. However, even under these circumstances, the sensor's sensitivity with the diagonal configuration remains higher compared to the lateral configuration, maintaining the same ratio.

This study aimed to assess the performance of the capacitive pressure sensor by focusing on the initial capacitance and sensitivity as key evaluation criteria. The significance of enhancing the initial capacitance lies in its potential to reduce costs and simplify the manufacturing process. Furthermore, achieving higher sensitivity enables the measurement of subtle pressure variations. Therefore, in the design of the capacitive pressure sensor, enhancing sensitivity and initial capacitance were considered the ultimate goals by implementing the most optimal modifications. To this end, we investigated the influence of dielectric material properties, as well as the arrangement and geometric parameters of micro-pyramids, on both the initial capacitance and sensitivity of the sensor. One of the considerations when analyzing these factors is the impact of geometric parameters, which necessitates the creation of individual molds specific to

each design. However, this approach proves to be economically inefficient as it requires accommodating geometric modifications for every design. Porosity offers the ability to tune the sensor according to the desired application while affecting the physical and electrical properties of the dielectric material. Nevertheless, the precise regulation of porosity poses a challenge.

The objective of this article was to propose a predictive model for assessing the initial capacitance and sensitivity of the pressure sensor with a diagonal microstructure arrangement. The development of the model involved employing COMSOL Multiphysics software, which utilized a finite element approach to generate the necessary dataset. To evaluate the accuracy of the numerical solution, a comparative analysis was conducted, comparing the simulation outcomes with experimental measurements. The optimal amount of data was determined using the design of the experiment method, specifically the response surface model. With this approach, it is possible to determine the influence of input variables on output parameters using an optimal number of data points efficiently. In this model, pyramid tip width, height, base length, dielectric layer porosity, intermicrostructural spacing, dielectric constant, and modulus of elasticity were considered as input variables, while sensitivity and initial capacity were defined as responses. Upon completion of the data collection process, the acquired results are obtained through numerical simulations. The analysis involves not only visually representing the influence of two input variables on each corresponding output response but also establishing equations to estimate the initial capacitance and sensor sensitivity. These equations are derived using curve fitting techniques applied to the simulation outcomes, aligning with the recommended design of the experimental approach. It is crucial to take into account that the equations utilized in this context are developed based on low-pressure conditions. Hence, the outcomes derived from these equations are valid and applicable when the pressure exerted on the sensor remains relatively low.

$$\frac{b}{a+d} < 0.18 : C_0 = \frac{A}{t}\left(1-\frac{b}{a}\right)\epsilon_0\epsilon_{air} \left[0.7032 + 3.304\left(\frac{b}{a}\right) + \left(5.473\left(\frac{b}{a}\right)^2 - 1.7757\left(\frac{b}{a}\right) + 0.44\right)\left(\frac{\nu}{2}\left(\frac{\frac{\epsilon}{\epsilon_{air}}-1}{\left(1+\frac{d}{a}\right)^2}\right)\right)^{\left(2.353\left(\frac{b}{a}\right)+0.5487\right)}\right] \tag{7}$$

$$\frac{b}{a+d} > 0.18 : C_0 = \frac{A}{t}\left(1-\frac{b}{a}\right)\epsilon_0\epsilon_{air} \left[\left(\frac{12028.5\left(\frac{b}{a}\right) - 149.85}{\left(\frac{b}{a}\right)^2 - 25,840\left(\frac{b}{a}\right) + 25,860}\right)\left(\nu\left(\frac{\frac{\epsilon}{\epsilon_{air}}-1}{\left(1+\frac{d}{a}\right)^2}\right)\right) + \frac{0.6733}{\left(\frac{b}{a}\right)^3 - 2.525\left(\frac{b}{a}\right)^2 + 1.399\left(\frac{b}{a}\right) + 0.1311}\right] \tag{8}$$

$$\frac{b}{a+d} < 0.18 : S = \frac{\left(1+\frac{d}{a}\right)^2}{\nu E\left(\frac{b}{a}\right)} \left[\left(114.88\left(\frac{b}{a}\right)^2 - 20.572\left(\frac{b}{a}\right) - 4.76\right) exp\left((-0.9865\left(\frac{b}{a}\right)^2 + 0.08535\left(\frac{b}{a}\right) - 0.035)(\nu)\frac{\frac{\epsilon}{\epsilon_{air}}-1}{(1+\frac{d}{a})^2}\right) + \left(-118.24\left(\frac{b}{a}\right)^2 + 20.8\left(\frac{b}{a}\right) + 7.132\right) exp\left((-0.10075\left(\frac{b}{a}\right)^2 - 0.01\left(\frac{b}{a}\right) + 0.00579)(\nu)\frac{\frac{\epsilon}{\epsilon_{air}}-1}{(1+\frac{d}{a})^2}\right)\right] \tag{9}$$

$$\frac{b}{a+d} > 0.18 : S = \frac{\left(1+\frac{d}{a}\right)^2}{\nu E\left(\frac{b}{a}\right)} \left[\left(-8.652\left(\frac{b}{a}\right)^2 + 15.312\left(\frac{b}{a}\right) - 7.06\right) exp\left(\left(-0.253\left(\frac{b}{a}\right) - 0.002605\right)(\nu)\frac{\frac{\epsilon}{\epsilon_{air}}-1}{\left(1+\frac{d}{a}\right)^2}\right) + \left(8.612\left(\frac{b}{a}\right)^2 - 15.56\left(\frac{b}{a}\right) + 9.448\right)\right] \tag{10}$$

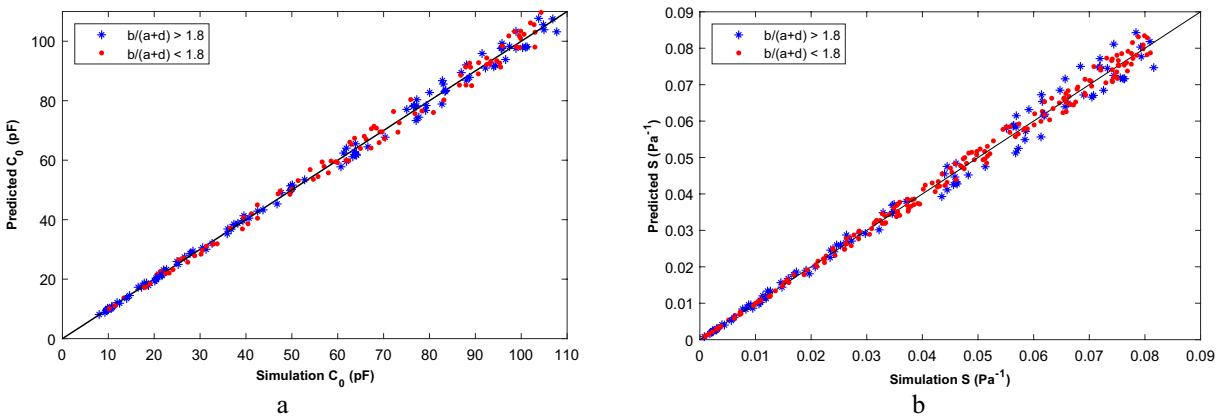

Fig. 8 A comparison of predicted data vs. simulation data for **a** initial capacitance values, and **b** sensor sensitivity

To assess the predictive capability of the proposed model in determining the initial capacitance and sensitivity of the pressure sensor, a comparative analysis was conducted between the numerical outcomes and the values suggested by the equations depicted in Fig. 8. The graphs illustrate the sensitivity and initial capacitance values for two distinct geometric states. It is evident that a smaller disparity between these two values signifies a more desirable performance of the proposed mathematical model. The comparison between the results obtained from numerical computations and the proposed model reveals a good agreement with the provided model. This close correspondence underscores the reliability and precision of the proposed approach in capturing the desired outcomes.

Conclusion

The present research focuses on designing a capacitive pressure sensor by incorporating a dielectric layer with a porous micro-pyramidal structure, where the pyramids are arranged diagonally. Through the utilization of the three-dimensional finite element method, we have analyzed the impact of various geometric characteristics (such as base length, tip width, height, and interstructural spacing) and material properties (including dielectric constant and porosity) on the sensor's performance. The sensor's performance was evaluated based on two key criteria: initial capacitance and sensor sensitivity. The results indicate that improving the sensor's sensitivity can be achieved by increasing the dielectric constant, the base length of the pyramids, and the spacing between them. Additionally, reducing the volume fraction and the tip width of the pyramids also contributes to the enhanced sensitivity of the sensor. The initial capacitance of the sensor rises as the base length and tip width of the pyramid increase, along with the reduction in porosity and the distance between the pyramids. These changes can be attributed to the higher volumetric percentage of elastomer in the dielectric layer, resulting in an increased dielectric constant. By investigating the arrangement of micro pyramids in both diagonal and lateral directions within the dielectric layer, it was found that diagonal configuration can increase the sensor's sensitivity by approximately 1.6 times without significantly affecting its initial capacitance. Our research objectives included developing a model to estimate the initial capacitance and sensitivity of the sensor. The required dataset was obtained by simulating various conditions. These conditions were determined using a statistical method known as response surface methodology. These predictive models provided results for the sensitivity and initial capacitance of the sensor for analysis in two distinct geometric states.

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Author contributions
RJ: conceptualization, analysis, methodology, writing—original draft, visualization—MMZ: supervision, writing—review and editing, methodology, validation, project administration, software—SAM: methodology, writing—original draft, software, validation.

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Declarations

Ethics approval and consent to participate
The authors declare that they have no competing interests.

Consent for publication
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