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# DEVELOPMENT OF A CAPACITIVE PRESSURE SENSOR BASED ON NANOPOROUS ANODIC ALUMINIUM OXIDE

**Trishna Moni Das[a], Devabrata Sarmah[b], Sankar Moni Borah[a], Sunandan Baruah[b]**
*[a]Department of Applied Sciences, Gauhati University, Jalukbari, Guwahati-781014, India*
*[b]Centre of Excellence in Nanotechnology, Assam down town University, Guwahati -781026, India*
*[*]Corresponding Author e-mail: trishnamani.das@gmail.com*
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Capacitive pressure sensors make pressure sensing technology more accessible to a wider range of applications and industries, including consumer electronics, automotive, healthcare etc. However, developing a capacitive pressure sensor with brilliant performance using a low-cost technique remains a difficulty. In this work, the development of a capacitive pressure sensor based on nanoporous Anodic Aluminium Oxide (AAO) fabricated by a two-step anodization approach which offers a promising solution for precise pressure measurement is fabricated by a two-step anodization approach. A parallel plate capacitive sensor was fabricated by placing two AAO deposited sheets are placed face to face, with the non-anodized aluminum component at the base functioning as the top and bottom electrodes. A variation in the capacitance value of the as fabricated sensor was observed over an applied pressure range (100 Pa-100 kPa). This change in capacitance can be attributed to the decrease in the distance between the two plates and the non-homogenous distribution of contact stress and strain due to the presence of nanoporous AAO structure. In this pressure range the sensor showed high sensitivity, short response time and excellent repeatability which indicates a promising future of the fabricated sensor in consumer electronics, intelligent robotics etc.
**Keywords:** *Capacitive pressure sensor; Anodic Aluminium Oxide (AAO); Anodization; Sensitivity; Response time; Repeatability*
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## 1. INTRODUCTION

In recent years, the field of sensor technology has witnessed a significant breakthrough with the emergence of Anodic Aluminium Oxide (AAO) based sensors. These sensors have demonstrated exceptional potential in various applications, including pressure sensing, biomedical monitoring, and environmental detection. The unique properties of AAO, including its highly ordered porous structure, high dielectric constant, and mechanical robustness, make it an ideal material for developing electrical and optical sensors that can operate accurately and reliably in harsh environments. As the demand for advanced sensors continues to grow, AAO based sensors are poised to play a critical role in revolutionizing various industries. One of the most significant advantages of AAO-based sensors is their ability to accurately measure capacitance and resistance variations. By depositing a thin metal coating on the surface of AAO, these sensors can detect even the slightest changes in pressure, making them ideal for a wide range of applications. The highly ordered porous structure of AAO allows for a high surface area-to-volume ratio, which enables the sensors to detect pressure changes with high sensitivity and accuracy. Moreover, AAO's high dielectric constant and mechanical robustness ensure that these sensors can operate accurately and reliably in harsh environments, making them ideal for industrial and aerospace applications.

Pressure sensors are classified into five types based on their sensing techniques, which include piezoelectricity, piezoresistivity, capacitance, triboelectricity, and transistors [1-17]. The capacitive pressure sensor is one type that has received much attention because of its stable structure, low pressure need, rapid dynamic reaction, and minimal temperature drift [18]. As the dielectric layer in a capacitive pressure sensor plays a vital role, therefore, incorporation of a porous dielectric material into a capacitive pressure sensor in place of a normal dielectric material would be more advantageous as it will provide increased sensitivity, low hysteresis, reduced stiffness, improved response time, lightweight, customizable properties and wide range applications. Developing a simple cost effective, controllable method to create a capacitive pressure sensor with excellent sensitivity, quick response and wide detection extent continues to be a formidable obstacle [18-28].

In this paper, we have reported the development of a pliable capacitive type sensor formed on nanoporous AAO. The conventional two-step anodization method is adopted to fabricate AAO layer over a commercially available aluminium sheet. As the thickness of the dielectric material has an inverse relationship with the capacitance of a parallel plate capacitor, we have prioritized the development of a thicker AAO layer in a short period of time. The hard anodization method is used for this purpose because it has proven to be a fast fabrication method. Two pieces of AAO on Al substrate are joined together where the AAO layers get stuck face to face to form a parallel plate capacitor. The pressure sensing response of aforesaid capacitor is studied here as a function of the capacitance.

## 2. MATERIALS AND METHODS

The studies were carried out using commercially available Al sheets. The 0.5 mm thick Al sheet was cut into the appropriate sizes for anodization. Al sheets were cleaned with acetone and deionized water for 10 minutes, then

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annealed at 250˚C for 4 hours. To dissolve the naturally occurring oxide layer, the aluminium sheets were electropolished in a solution of $H_3PO_4$, $H_2SO_4$ and deionized water at a weight ratio of 2:2:1. The Al sheets were then cleaned with deionized water numerous times before being dried and used as anodes in the as developed AAO fabrication setup. The nanoporous AAO structures were created using a simple two-step hard anodization procedure with a Pb sheet serving as the cathode. The anodization process was performed at a voltage of 140 V and a temperature of ~5˚C. Here, 0.3M $H_2C_2O_4$ was used as the electrolyte.The morphology of nanoporous AAO has been proven to be affected by different parameters for instance the anodization time, anodization voltage, type and concentration of the electrolyte, and the temperature of the electrolytic bath. In this work a sample H1 was synthesized by keeping the anodization time 1 minute. The morphology of the as-prepared AAO structures was examined using a ZEISS Sigma 300 field emission scanning electron microscope (FESEM).

The pressure sensing ability of the nanoporous AAO structure was investigated by fabricating a flexible parallel plate capacitor, where, two nanoporous AAO deposited sheets of same size (Length=1 cm, Breadth= 1 cm, Height= 0.5 mm) are placed face to face, with the non-anodized aluminium component at the base functioning as the top and bottom electrodes. In this parallel plate capacitor arrangement, AAO layer serves as the dielectric layer. The capacitance variations of the as fabricated sensor were observed under a pressure range (100Pa-100 kPa) applied over the sensor. Responses were recorded by connecting the AAO sensor to a LCR meter. Figure 1 shows a schematic of the experimental sequence.

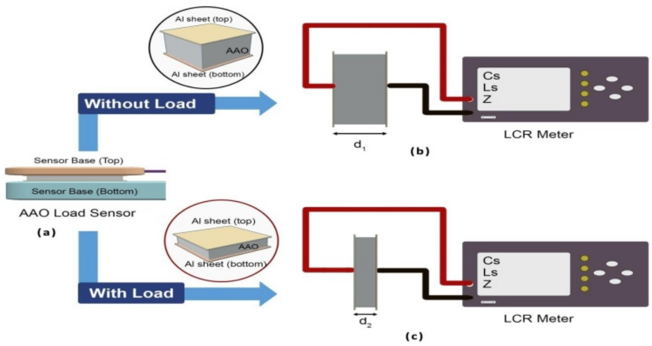
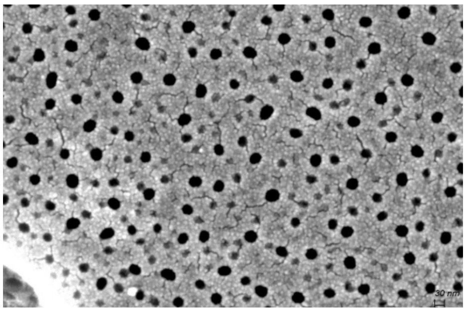


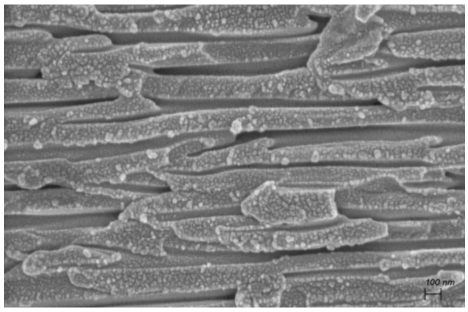

**Figure 1**. Schematic representation of the(a) as prepared AAO based capacitive sensor (b) Sensor without applying any load (c) Sensor with load where the distance between the two Al plates are decreasing

## 3. RESULTS AND DISCUSSION

The Scanning Electron Microscopy (SEM) photographs of the sample H1 are depicted in Figure 2(a) and (b). Figure 2(a) depicts the top view of the sample, while Figure 2(b) represents cross sectional view of the sample.



**(a)**

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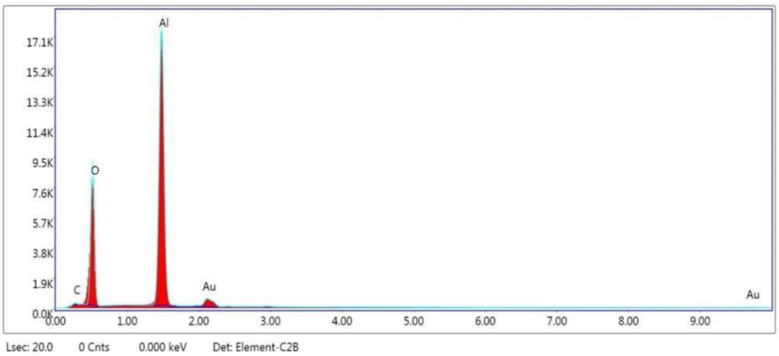


**(c)**

| Element | Weight % | Atomic % |
|---|---|---|
| CK | 1.69 | 3.10 |
| OK | 37.16 | 51.35 |
| AlK | 54.71 | 44.83 |
| AuM | 6.44 | 0.72 |

**(d)**

**Figure 2**. (a-b) SEM micrograph (Top view and Cross-sectional view) of the sample H1. (c) EDS pattern of the sample H1 (d) Atomic percentages of the different elements from the EDS.

The SEM micrograph (Top view) of sample H1 (Figure 2(a)) shows the extended-range ordering, homogeneity, shape, and size of the pores. This micrograph can reveal a variety of structural morphological details for instance pore diameter, inter-pore distance, porosity, and so on. Values were averaged over 20 measurements. The diameter of the pores is determined by the electrolyte type, anodization time, and anodization voltage. The porosity P of the hexagonal cell nanoporous AAO with a pore within each hexagon can be expressed as follows (with each pore assumed to be a perfect circle) [29]

$$P = \frac{pore\ area}{hexagon\ area} = \frac{\pi}{2\sqrt{3}}\left(\frac{D_p}{D_i}\right)^2, \tag{1}$$

where, $D_p$ and $D_i$ are the diameter of the pores and the interpore distance of the nanoporous AAO respectively, as shown in Figure 2 (a). The pore density, n of the porous AAO with a hexagonal distribution of pores can be described as the overall quantity of pores present in the 1 $cm^2$ surface area of the porous AAO, and expressed as follows [29]:

$$n = \frac{10^{14}}{A_{hex}} = \frac{2x10^{14}}{\sqrt{3}D_i^2}. \tag{2}$$

Where $A_{hex}$ represents the surface area of a single hexagonal cell (measured in $nm^2$). These structural parameters for the as prepared sample are analyzed through ImageJ software from the SEM micrographs and calculated using equations (1) and (2). The average diameter of pores ($D_p$), interpore distance ($D_i$) , porosity (P) and the density of the pores (n) of the sample H1 are found to be 38 nm, 83nm, 18.95% and $1.7\times10^{28}$ pore/$cm^2$ respectively. The Energy dispersive X-ray spectroscopy (EDS) micrograph of sample H1, as depicted in figure 2 (c), confirms the presence of Al and O in the sample. Figure 2(d) represents the atomic percentages of the different elements present in the sample H1 from EDS. External loads were applied to the as-fabricated sensor in increasing order, generating pressures ranging from 100 Pa to 100 kPa, and the corresponding change in capacitance was observed. To evaluate the effectiveness of a pressure sensor, the pressure sensitivity (*S*) plays an important role and is represented by [30].

$$s = \frac{\delta(\Delta C/C_0)}{\delta P} \tag{3}$$

Here, $C_0$ denotes the initial capacitance without external pressure, ΔC denotes the relative change in capacitance *(C - $C_0$)*, and P denotes the applied external pressure. The equation demonstrates how the slope of the tangent to the graph of pressure-capacitance can be used to calculate the sensor's sensitivity. Figure 3(a) shows the variation in relative capacitance of a sensor formed on nanopoous AAO over a wide pressure range. For example, when the pressure is around 40 kPa, the sensitivity of the as-fabricated sensor can reach 0.02 $kPa^{-1}$.

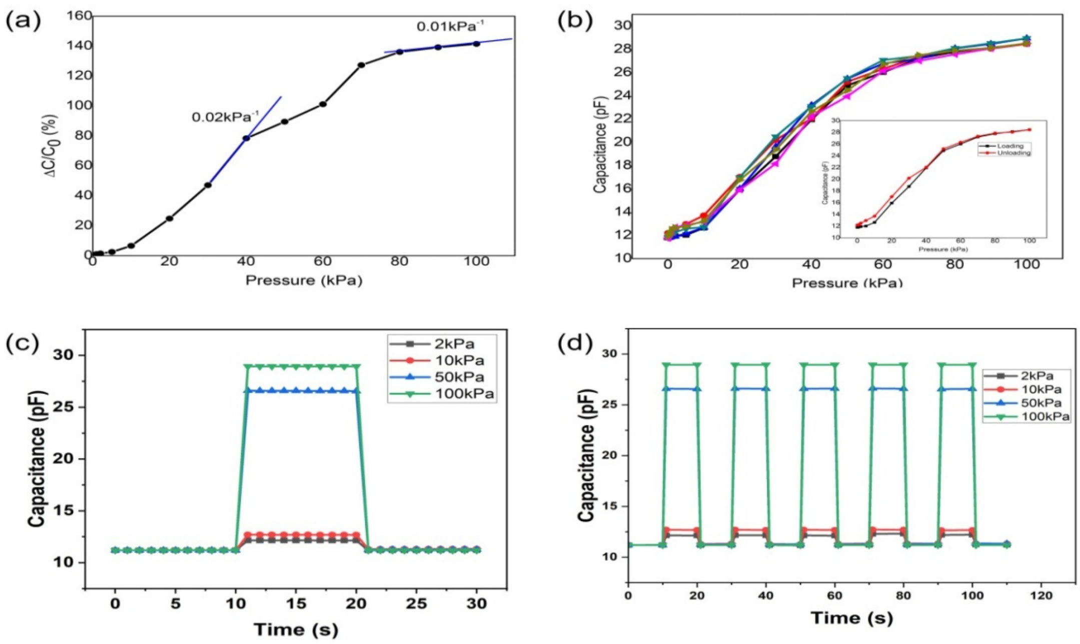


**Figure 3.** (a) The variation in the relative capacitance of the as fabricated sensor formed on nanoporous AAO. (b) Capacitance response by the as fabricated sensor with respect to pressure change for three loading/unloading cycles (inset is the single loading/unloading cycle). (c) The response of the sensor and the time of recovery when subjected to a pressure of 2, 10, 50 and 100kPa. (d) The sensor's capacitance response to repeated mechanical loads at pressures of 2, 10, 50 and 100kPa.

The sensitivity decreases to 0.01 $kPa^{-1}$ when the pressure is increased above 80 kPa. Figure 3(b) clearly shows an apparent variation in capacitance response with regard to pressure change of the as-fabricated sensor during the loading/unloading process. When it comes to the application of flexible pressure sensors in various fields, short response as well as recovery time, in addition to high sensitivity, plays a vital role. The aforementioned features were also assessed by loading and unloading pressure on the as-fabricated pressure sensor. As demonstrated in Figure 3(c), putting on a pressure of 50 kPa causes the capacitance of the sensor to rapidly grow from its initial value to a steady value within 1 second. By releasing the loading force, the capacitance returns to its original value in around 1s. The repeatability of the sensor under 3 loading/unloading cycles is illustrated in Figure 3(d). Figure 3(b) shows that the capacitance response throughout the operation is quite uniform, with very little hysteresis, showing the sensor's stability. The capacitance of a parallel plate capacitive pressure sensor can be expressed as

$$c \,\alpha\, \varepsilon A/d \tag{4}$$

Where $\varepsilon$ signifies the dielectric layer's dielectric constant, $A$ represents the overlapping area of the two plates, and $d$ represents the distance between the two plates [30]. Again, $\varepsilon$ can be expressed as

$$\varepsilon = \varepsilon_0\, \varepsilon_r \tag{5}$$

where $\varepsilon_0$ stands for dielectric constant of free space and $\varepsilon_r$ stands for relative dielectric constant [30].

Here, under vertical stress, the overlapping area remains practically constant; therefore, the value of the capacitance of the fabricated flexible capacitor is dependent on the dielectric constant and distance between the two plates. Since the two plates of AAO grown on Al are placed face to face to form the parallel plate capacitor, therefore, the value of dielectric constant will not affect the capacitance. Hence, capacitance will be primarily influenced by the separation distance. With the increase of external pressure, the gap between the two plates of the parallel plate capacitor decreases, and an enhanced capacitance response was observed for the as fabricated flexible capacitive pressure sensor formed on AAO. Also, the capacitance value of the as fabricated capacitive pressure sensor may be affected by the porous structure of the AAO. In a study, it was demonstrated that under the same applied pressure, a structured dielectric layer (nanopillars based on AAO) provided much higher strain concentration and contact stress in its territory, where the highest value was recorded at the deformation area when compared to a structure less dielectric layer, where stress and strain are distributed uniformly at the conjoined point of the electrode and the film [1].

## 4. CONCLUSION

This work describes the successful build out of a capacitive type pliable pressure sensor based on nanoporous AAO which was fabricated using a simple two step anodization method. The novelty of the as fabricated capacitive type pressure sensor lies in its construction, where two plates of AAO grown on Al are simply placed face to face. The Al on either side of these two AAO plates serves as the metal electrodes for the as fabricated parallel plate capacitor.The sensor shows excellent repeatability, high sensitivity, better stability and a very less hysteresis loss over the applied pressure range (100 Pa – 100 kPa). The mechanism behind the increase in capacitance with an increase in pressure for the as fabricated sensor is the decrease in the gap between the two AAO based plates and also the nanoporous structure of AAO, which offers enormous contact stress and strain. We hope that this strategic effort will pave way for the advancement of pliable pressure sensors, as well as be of great interest to many pressure sensing device applications.

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**ORCID**

**Trishna Moni Das**, https://orcid.org/0000-0001-5754-5608; **Sankar Moni Borah**, https://orcid.org/0000-0002-7891-270X
**Sunandan Baruah**, https://orcid.org/0000-0003-2963-6128

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# РОЗРОБКА ЄМНІСНОГО ДАТЧИКА ТИСКУ НА ОСНОВІ НАНОПОРИСТОГО АНОДНОГО ОКСИДУ АЛЮМІНІЮ

**Трішна Моні Дас[a], Девабрата Сармах[b], Санкар Моні Борах[a], Сунандан Баруах[b]**
[a]*Департамент прикладних наук, Університет Гаухаті, Джалукбарі, Гувахаті-781014, Індія*
[b]*Центр передового досвіду в області нанотехнологій, Університет міста Асам, Гувахаті -781026, Індія*

Ємнісні датчики тиску роблять технологію вимірювання тиску більш доступною для ширшого спектру застосувань і галузей промисловості, включаючи побутову електроніку, автомобілебудування, охорону здоров'я тощо. Однак розробка ємнісного датчика тиску з блискучою продуктивністю за допомогою недорогої техніки залишається складною. У цій роботі розробка ємнісного датчика тиску на основі нанопористого анодного оксиду алюмінію (AAO), виготовленого за допомогою двоетапного підходу анодування, який пропонує перспективне рішення для точного вимірювання тиску, виготовлено за допомогою двоетапного підходу анодування. Паралельний пластинчастий ємнісний датчик був виготовлений шляхом розміщення двох нанесених AAO листів лицем один до одного, причому неанодований алюмінієвий компонент у основі функціонував як верхній і нижній електроди. Спостерігалася зміна значення ємності готового датчика в діапазоні прикладеного тиску (100–100 кПа). Цю зміну ємності можна пояснити зменшенням відстані між двома пластинами та неоднорідним розподілом контактної напруги та деформації через наявність нанопористої структури AAO. У цьому діапазоні тиску датчик показав високу чутливість, короткий час відгуку та чудову повторюваність, що вказує на багатообіцяюче майбутнє виготовлених датчиків у побутовій електроніці, інтелектуальній робототехніці тощо.

**Ключові слова:** *ємнісний датчик тиску; анодний оксид алюмінію (AAO); анодування; чутливість; час відгуку; повторюваність*