



Design and Fabrication of Indium Tin Oxide Based Thin Film Piezoresistive Pressure Sensor

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Abstract

The design and development of Indium Tin Oxide (ITO) thin film based piezoresistive pressure sensor is presented in this paper. ITO (90:10) nanoparticles were synthesized by green combustion method using indium and tin as precursors and carica papaya seed extract as fuel. ITO (90:10) thin film piezoresistors were deposited using synthesized nanoparticles on AlN coated circular steel (SS 304) diaphragm using E-beam evaporation technique. Diaphragm models of different thickness (0.75, 1 and 1.25 mm) were created using ANSYS finite element analysis in order to determine the maximum stress and deflection region for applied pressure of 1 to 10 bar. ANSYS results exhibited that maximum stress and deflection occurred at the center and circumference of diaphragm. ITO thin film piezoresistors were deposited at these regions using mechanical mask. TiW metal contact was established to these ITO thin film piezoresistors using DC sputtering method. ITO thin film piezoresistive pressure sensor with TiW contact connected in Wheatstone full bridge configuration was calibrated and tested for 50 pressure cycles by applying 2 V DC supply. Sensitivity (S) of the developed ITO thin film pressure sensor was obtained as 0.686, 0.566 and 0.495 mV/bar for diaphragm thickness of 0.75, 1, and 1.25 mm pressure sensors respectively. The non-linearity (NLI) in the output response of the pressure sensors was found to be 9.14, 9.82 and 11.27% for diaphragm thickness of 0.75, 1, and 1.25 mm respectively. Hysteresis errors were found to be 0.0344, 0.0525 and 0.054 for diaphragm thickness of 0.75, 1, and 1.25 mm respectively.

Keywords ITO thin film · Piezoresistors · TiW metal contact · Pressure sensor

Introduction

Measurement of various physical parameters such as pressure, force, flow and vibration under harsh environmental conditions (high radiation, high temperature, high shock, erosive flow/ impact and corrosive media) using sensors is very much essential for the efficient and safe operation of industrial processes [1–4]. The stability and selectivity of sensor depends on physical, electrical and mechanical properties of the sensing material used to fabricate them and processing techniques adopted to prepare sensing material [5]. These materials are processed either in the bulk form or thin

film depending on the applications. The thin film processing techniques such as physical vapour and chemical deposition methods are widely used to prepare the sensing materials [6–8]. Generally, metals, cermets, polymers and semiconductors are used as sensing materials to fabricate the sensors [9]. But each material has its own advantages and disadvantages or sometimes for a given application a single material cannot provide the desired properties; compound materials are used. The metals and alloys-based sensors are rigid and undergo plastic deformation. These are not suitable for elevated temperature applications because these materials possess high temperature coefficient of resistance (TCR) or more sensitive to changes in temperature and low sensitivity (gauge factor).

Sensors based on cermet are fabricated using either thick-film or thin film deposition techniques. Cermet based sensors have limited field of applications due to their variable time dependent electric and piezoresistive characteristics. Conducting polymers offer useful electrical and optical properties. Electrically conducting polymers undergo a geometric change because of their chemo-mechanical doping

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and de-doping characteristics. However, the response time is very slow because of chemo-mechanical doping and de-doping characteristics. Compared to metals, polymers have little rigidity and cannot withstand temperatures above 200 °C. Semiconductor material has the electrical conductivity between conductors and insulators. The properties (electrical and mechanical) of semiconductor can be varied based on doping. Hence, semiconductor materials find applications in the field of sensor and electronic devices. Depending on the applications electrical and mechanical properties are tuned. Widely used semiconductors are silicon, silicon carbide, gallium arsenide, gallium nitride etc. [10].

Among various physical parameters, pressure measurement is required in different fields of science and engineering [1, 11, 12]. The pressures can range from a few Pascal (Pa) to several Mega Pascal (MPa) depending on the application and the environment, which can range from being extremely sensitive in biomedical applications to being extremely harsh in industrial and automotive applications. As the requirements expand, new challenges arise. Therefore, they need to be robust and able to work consistently in temperatures much above 80 to 100 °C while still being biocompatible in some applications [13]. Over the last few decades, a variety of pressure sensors such as capacitive, piezoresistive, piezoelectric, resonating and fiber optic were developed [14]. In general, the piezoresistive sensors are semiconductor based and exhibit a very good linear resistance-pressure relationship [12, 15, 16]. Devices like pressure sensors [17–19], tactile sensors [20], strain gauges [21], flow sensors [22–24] convert physical quantity into electrical signal using piezoresistive effect. The piezoresistive pressure sensors consist of four sensing resistors and are placed on top of a silicon (Si) or metal diaphragm [25–27]. Silicon based sensors are preferred for low temperature applications due to their high sensitivity (gauge factor) [21, 28, 29]. For measurement of pressure at high temperatures, it is necessary to use materials with a wide band gap such as Gallium Arsenide (GaAs) or Diamond or Semiconductor metal oxides as sensing material [3, 25, 30, 31].

Wu et al. have fabricated pressure sensors with polycrystalline and single crystalline 3 C-SiC piezoresistors for high temperature. The gauge factor of the sensor was found to be -2.1 with a sensitivity of 20.9 mV V⁻¹ psi⁻¹ at room temperature [32]. Fraga et al. studied the effect of temperature on the performance of nitrogen doped amorphous SiC thin film piezoresistive pressure sensor. The piezoresistors connected in Wheatstone bridge configuration showed a linear output over a pressure range of 0 to 12 psi and sensitivity of 0.33 mV V⁻¹ psi⁻¹ at room temperature [33].

Semiconductor metal oxides such as ITO is one of the promising material because it is a wide band gap (3.2 to 4.0 eV) semiconductor material with low resistivity (~10⁻⁴ Ωcm), high carrier concentration (10²⁰ to 10²¹ cm⁻³), high transmittance (> 80%), good mobility (20–80 cm² (V.s)⁻¹)

and good thermal conductivity (0.102 W·(cm K)⁻¹) [34–36]. ITO nanoparticles can be synthesized using techniques such as sol-gel route, combustion, or solvothermal method [37, 38]. In our work, ITO nanoparticles were green synthesized using tin and indium as precursors and Carica papaya seed extract as fuel. ITO thin films were deposited using synthesised nanoparticles by e-beam evaporation technique. The structure of sensor and type of electrical circuit in addition to the materials employed are crucial for the sensitivity and in particular the integration of the sensor with the other microelectronics. In the present work ITO thin film based piezoresistor pressure sensor is fabricated and tested at room and temperature at 150 °C. The geometry of the sensors was designed via FEA simulation using ANSYS before fabrication. The detailed aspects of fabrication and calibration of designed and developed ITO piezoresistive pressure sensor is discussed in this paper.

Experimentation

Selection of Diaphragm Material

Material that can be selected for the fabrication of diaphragm depends on the application and range of pressure measurement. Some of the ideal characteristics of the material required for the fabrication of diaphragm are high mechanical strength, high fatigue life, low creep property, resistance to chemicals, acids, propellants, oxidizers and environmental corrosion, better linearity, low hysteresis, good repeatability, easy to get better surface finish during machining and moderate cost. In the present work, stainless steel (SS 304) material is selected for diaphragm fabrication, since it satisfies most of the above characteristics. The SS 304 alloy is an austenitic stainless steel. Due to high strength and better corrosion resistance, it finds applications in aerospace, medical industries, petroleum and chemical industries, metallurgical machinery, and automobile industries.

Design of Diaphragm

Diaphragm acts as a mechanical component for sensors and actuators. Diaphragms may be either circular, square or rectangular in shape. The geometry and dimension of diaphragm must be properly selected for the optimal performance of a sensor. Due to high deflection and sensitivity, circular diaphragms are advantageous than other diaphragms. In the present work diaphragm is designed using small deflection theory [39].

From small deflection theory center deflection of metal diaphragm is given by

$$Y_c = \frac{3PR_0^4(1 - \nu^2)}{16t^3E} \quad (1)$$

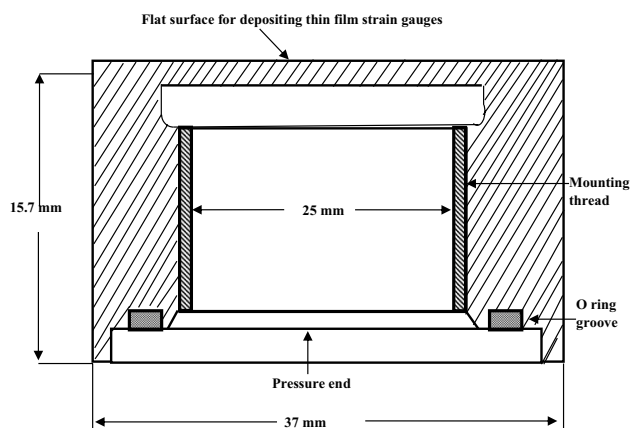


Fig. 1 Schematic of the circular diaphragm

Where, P is applied pressure in bar, R_0 is Diaphragm radius in mm, t is Diaphragm thickness in mm, ν is Poisson's ratio of diaphragm material (0.3), E is Modulus of elasticity (190 GPa).

In order to achieve high sensitivity for a pressure sensor, diaphragm thickness should be small to enhance the load deflection responses. The integrated diaphragm of 0.75, 1 and 1.25 mm thickness and diameter 37.0 mm is designed for pressure sensor and the schematic is shown in Fig. 1.

Simulation Tool

In the present work, the software ANSYS 2021 R2 is used for simulation of diaphragm based pressure sensor. Simulation is carried out to know the position of mechanical stress created on the diaphragm when pressure is applied. This information is required for depositing the ITO thin film piezoresistors on circular diaphragm. The initial step is to build the geometry of circular diaphragm. A circular diaphragm of thickness 0.75, 1 and 1.25 mm and diameter of 37 mm is designed from solid works (2020 student). The 3D view of circular diaphragm of 1 mm thickness and 37 mm diameter is shown in Fig. 2, and is imported into ANSYS software. Before simulation, the physical properties such as Young's modulus (190Gpa), density (8000 kg/m³) and poisson's ratio (0.3) of diaphragm material (SS 304) should defined, and mesh is generated.

The deformation, stress and strain distribution of the circular diaphragm under applied pressure are determined using the finite element method after the overall volume is decomposed into smaller components.

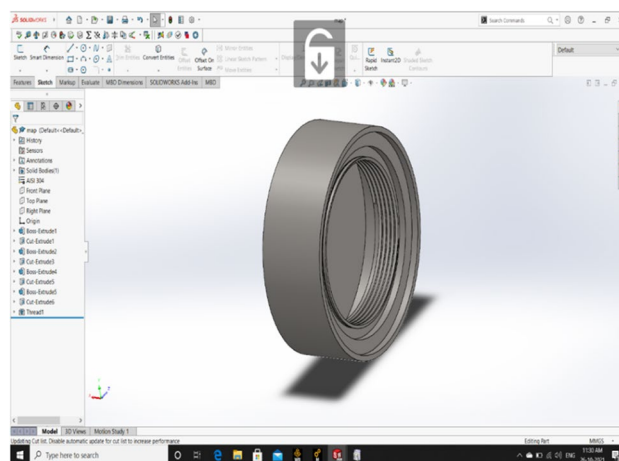


Fig. 2 3D View of circular diaphragm designed using solid works

Deposition of ITO and TiW Thin Films

ITO nanoparticles are synthesized using green combustion method and ITO thin films are deposited from synthesized ITO nanoparticles using E-beam evaporation technique. The structural and electrical properties studies of ITO thin films deposited from synthesized ITO nanoparticles were conducted and reported elsewhere [40, 41]. From the results, ITO piezoresistive thin films annealed at 500°C exhibits good structural and electrical properties and these ITO piezoresistors has to be deposited on electrically isolated diaphragm pressure sensor (SS 304). Titanium Tungsten (TiW) thin films were deposited using DC sputtering (M/s Hind High Vacuum Co. (P) Ltd., Model 12'' MSPT) at room temperature for 20 min and the deposition pressure was maintained as 6×10^{-3} mbar at 100 watts. The deposition procedure, structural and electrical properties of TiW thin films are reported elsewhere [42].

Fabrication of Pressure Sensor

Three pressure sensors were fabricated with diaphragm thickness of 0.75, 1 and 1.25 mm and diameter of 37 mm using SS 304. The photographs of the diaphragm which is designed and fabricated is shown in Fig. 3(a) and (b). Buffing is performed on the surface of diaphragm in order to achieve flatness and smoothness. Figure 3(b) shows the internal threading to connect the diaphragm with the help of adaptor to the pressure port of the pressure calibrator. The photograph of the adaptor specially designed for the interconnection of pressure sensor to the pressure port with a suitable O-ring is shown in Fig. 4. The adaptor is made of stainless-steel material with a small hole in it to apply pressure. The dimensions of threads of the diaphragm are chosen in such a way that when the diaphragm is threaded there is

Fig. 3 Photograph of the fabricated diaphragm (a) Top surface of the diaphragm (b) Internal threading of the diaphragm

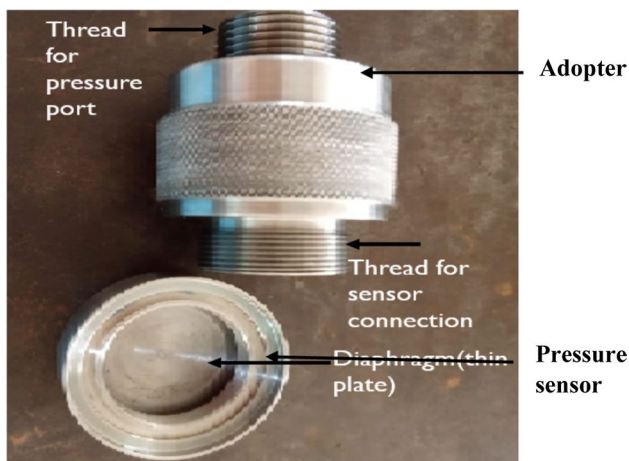
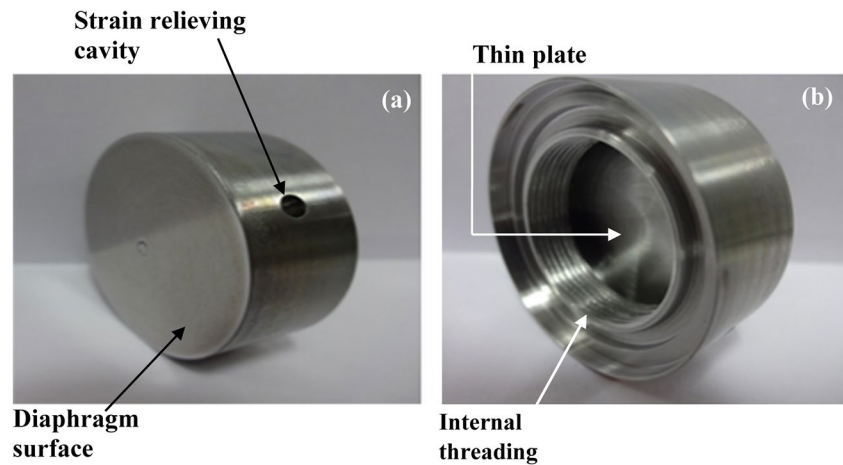


Fig. 4 Photograph of the adapter for pressure sensor

a sufficient gap between the thin plate of the diaphragm and adapter. This avoids the damage that may happen to thin plate (diaphragm) and provides free space for the deflection of the diaphragm. The O-ring provides leak proof fitting

of the diaphragm with adapter on the pressure port of the pressure calibrator.

Deposition of AlN Thin Films

In order to electrically isolate the ITO piezoresistors (sensing films) from the metal diaphragm, AlN thin films are deposited on SS 304 using RF reactive sputtering before depositing the ITO thin film piezoresistors. The aluminium target used for the deposition is of 2" (99.9% purity) dia with a thickness of 0.25". The surface of SS 304 pressure sensor is cleaned using isopropyl alcohol and dried by blowing N_2 gas, and placed below the target at a distance of 56 mm in vacuum chamber. Before the deposition, the chamber is evacuated to a vacuum pressure of 1×10^{-5} mbar. Argon gas (Ar) is purged into deposition chamber and is maintained at 1×10^{-3} mbar during the deposition and RF power is maintained at 250 watts. Nitrogen gas is purged into the deposition chamber and is maintained at $(5-7) \times 10^{-3}$ mbar. Before the deposition, the target is pre-sputtered for 10 min by closing the shutter. This is done in order to remove the contamination present on the target. Before the deposition

Fig. 5 Photograph of diaphragm coated with AlN thin films (a) front view (b) side view

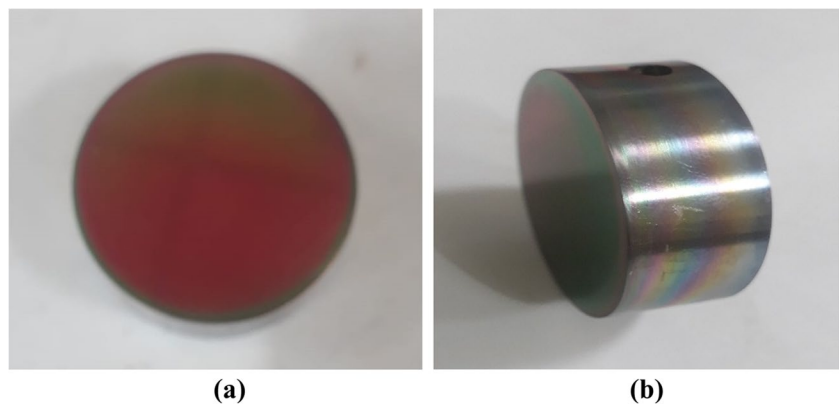
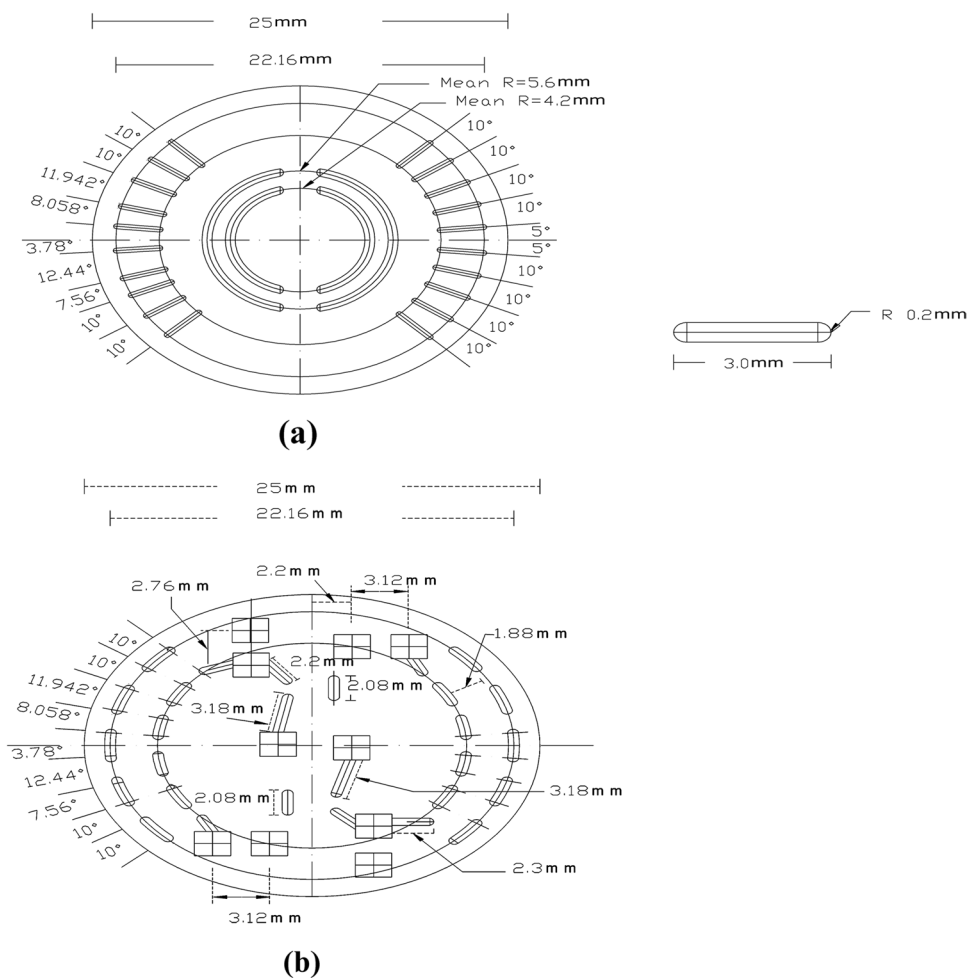


Fig. 6 Drawings of (a) Mask for depositing ITO piezoresistors (b) Mask for depositing TiW contact pad and interconnecting pad films



various trial depositions are carried out on SS 304 substrate for different RF power and deposition time to optimize the deposition parameters of AlN thin films. The deposition is carried out for 150 min and thickness of AlN films obtained is 800 nm. A photograph of diaphragm coated with AlN thin films is shown in Fig. 5.

Suitable precision mechanical sensing and contact film masks are designed and fabricated by non-magnetic stainless-steel material of thickness 0.2 mm using a computer numerically controlled (CNC) spark erosion machine. Figure 6(a) and (b) show the detailed drawings of the masks for depositing ITO piezoresistors and TiW contact respectively. The photograph of the fabricated metal masks for ITO thin film piezoresistors and TiW metal contact is shown in Fig. 7.

The metal mask (Fig. 7) used for the deposition of the ITO piezoresistors is cleaned using isopropyl alcohol and dried with N₂ gas is tightly fixed on the surface of the AlN

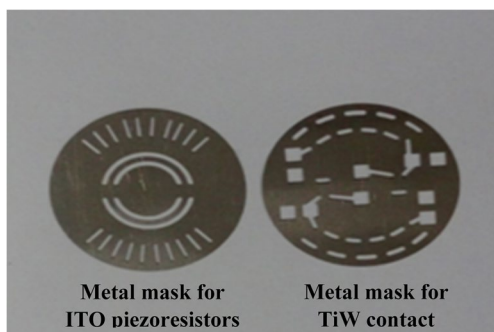


Fig. 7 Photograph of the fabricated metal masks for ITO piezoresistors and TiW contact

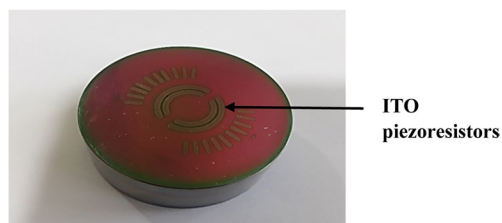


Fig. 8 Photograph of ITO piezoresistors deposited on AlN coated diaphragm

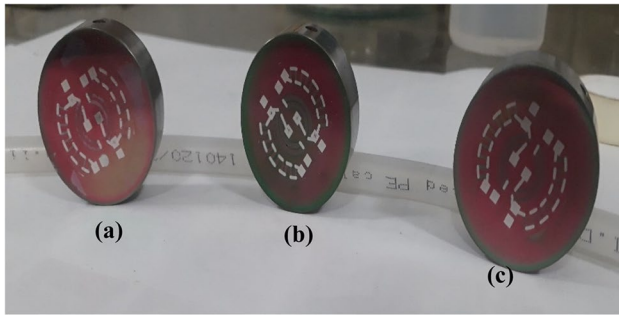


Fig. 9 Photograph of ITO piezoresistors with TiW contact connected as Wheatstone bridge pattern for diaphragm thickness of (a) 0.75 (b) 1.00 (c) 1.25 mm

coated diaphragm with the help of kapton tape. ITO piezoresistors are deposited on the masked diaphragm by maintaining the optimized sputtering parameters [39]. A photograph of the ITO piezoresistors deposited on the AlN coated diaphragm is shown in Fig. 8.

In order to measure the pressure sensor output, contact has to be established to the ITO piezoresistors. Therefore, to establish contact to the ITO piezoresistors (Fig. 9) on the surface of diaphragm, the contact and interconnecting pads are deposited using TiW by DC magnetron sputtering technique. The proper alignment of contact mask to ITO piezoresistors is made by looking through magnification lens and tightly fixing the contact mask with kapton tape. ITO thin film piezoresistors with TiW contact films are connected in Wheatstone full bridge configuration, which is shown in Fig. 10.

ITO thin film piezoresistors with TiW metal contacts are deposited for all the three pressure sensors and are annealed at 600 °C as shown in Fig. 9 and electrical leads (copper wire) are soldered on the TiW contact pads for electrical measurement is shown in Fig. 11.

When pressure is applied on diaphragm, the centre two ITO piezoresistors experiences tensile strain and outer two strain gauges experience compressive strain. The calibration and testing of developed pressure sensor is carried out using

Fig. 10 Photograph of ITO piezoresistors with TiW contact configured as Wheatstone bridge pattern (a) front view (b) side view

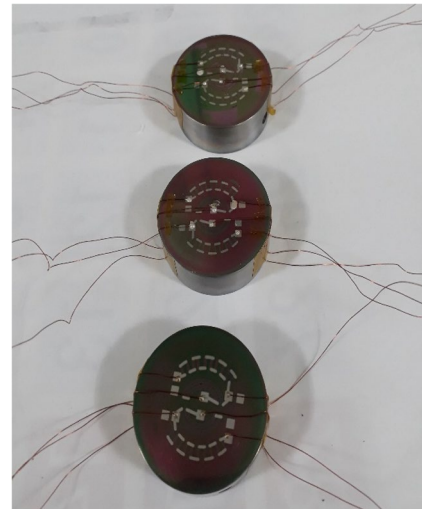
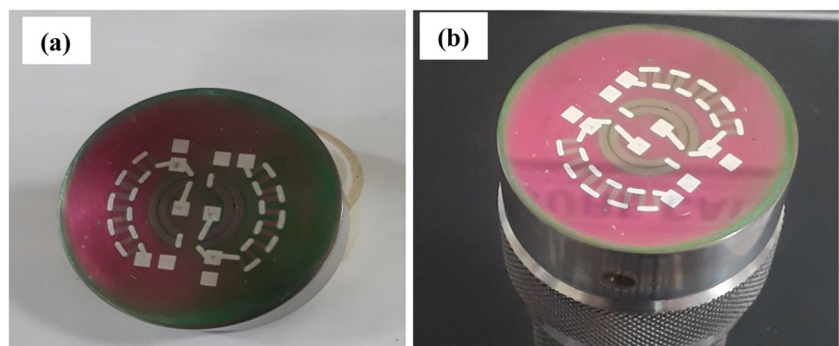


Fig. 11 Photograph of electrical leads soldered on the TiW contact pads for electrical measurement

a pressure calibrator (Fluke 2271 A) at ambient temperature is shown in Fig. 12. The resolution of the calibrator is 0.1 mbar with an accuracy of 0.025%, maximum pressure that can be applied is 20 bar. High purity nitrogen gas is used to achieve required pressure for the calibration. The developed pressure sensor is fixed with a suitable adpoter to the pressure port of the pressure calibrator. The required input pressure is applied using nitrogen gas through supply valve and is adjusted using pressure regulator and vent valve. The measurement are carried at ambient temperature.

Results and Discussions

Deposition of ITO Thin Films

The deposition of ITO thin films and deposition procedures were discussed and reported [41]. The as-deposited ITO thin films were annealed at 200, 400 and 500 °C. The average TCRs of the ITO films annealed at 400 and 500 °C are -336 ppm/°C and

Fig. 12 Photograph of (a) Pressure calibrator set up (b) Developed pressure sensor connected to pressure port

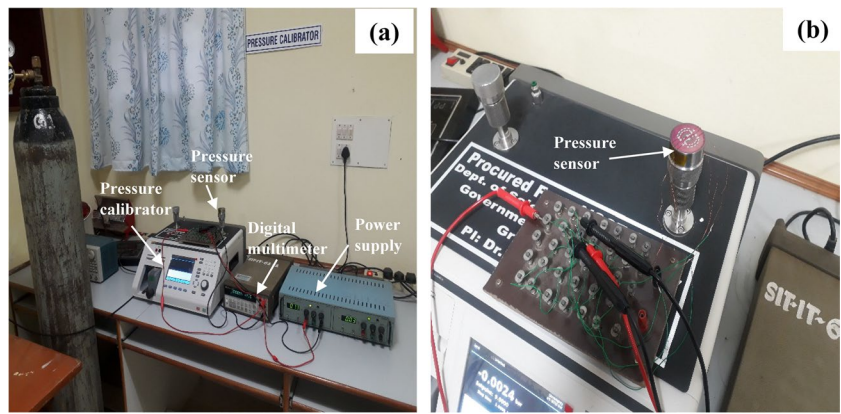


Table 1 Number of nodes and elements of circular diaphragm

Thickness(mm)	Number of nodes	Number of elements
0.75	76,271	42,005
1.00	80,983	45,658
1.25	82,393	46,682

−414 ppm/°C, respectively. The films annealed at 500 °C exhibited good structural and electrical properties. The gauge factor was found to be 7.25, 8.20 and 8.37 for the films annealed at 200, 400 and 500 °C, respectively [41]. The piezoresistive coefficient of the ITO films resistor was obtained from Eq. (2)

$$\frac{\Delta R}{R} = \pi(1 - \nu)\sigma \tag{2}$$

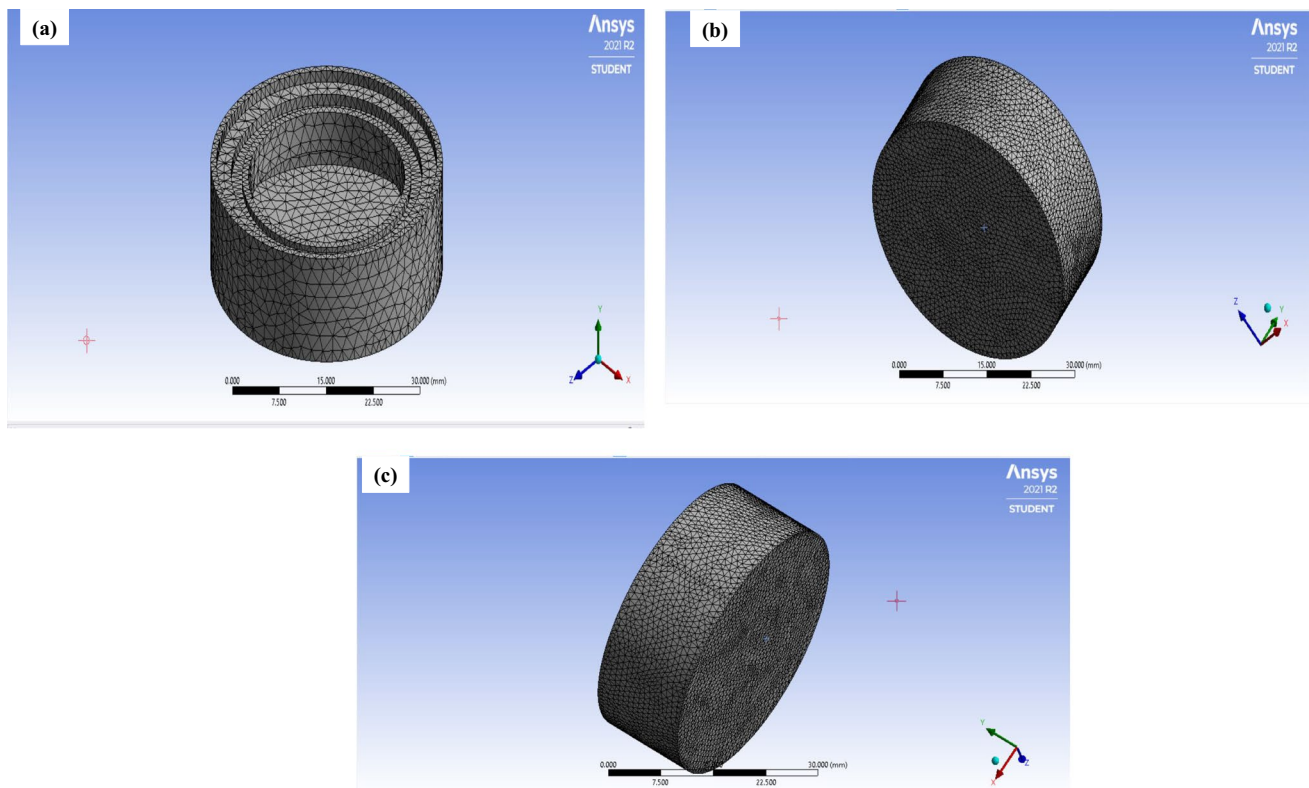


Fig. 13 Mesh structure of circular diaphragm for thickness (a) 0.75 mm (b) 1.00 mm (c) 1.25 mm

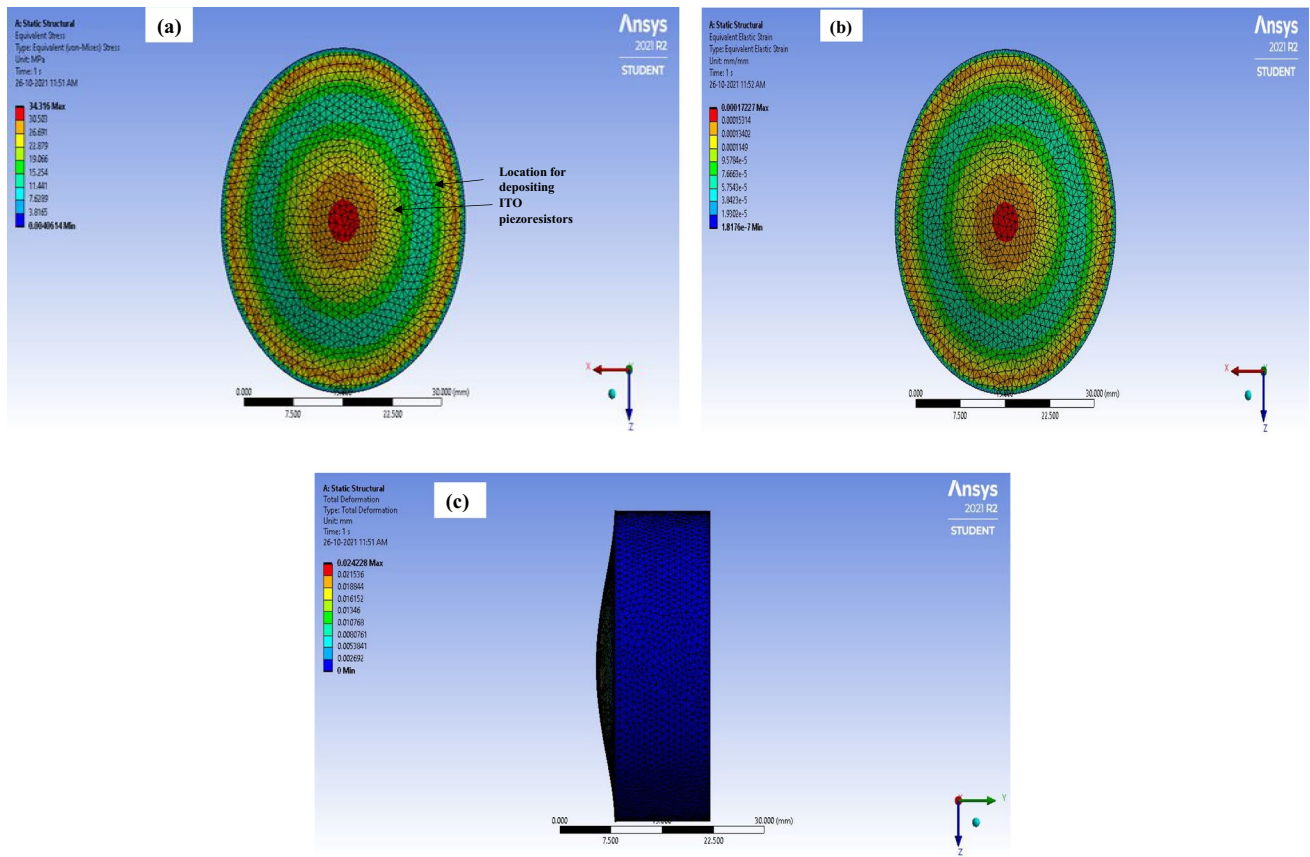


Fig. 14 Circular diaphragm of thickness 0.75 mm for applied pressure 1 bar (a) stress distribution (b) strain distribution (c) Deformation

Where π is the piezoresistive coefficient, $\Delta R/R$ is the fractional change in electrical resistance of the piezoresistor, ν is Poisson ratio and σ is longitudinal mechanical stress.

The GF or mechanical sensitivity was calculated by using Eq. (3)

$$GF = \frac{\Delta R/R}{\epsilon} \quad (3)$$

Where ϵ is the strain calculated by using Eq. (4)

$$\epsilon = \frac{\sigma}{E} \quad (4)$$

Where E is the young's modulus.

To obtain the piezoresistive coefficients (π), we assumed that the ITO films have Poisson coefficient (ν) of 0.25 and Young modulus (E) of 49 GPa [43]. From the experimentally obtained gauge factors piezoresistive coefficients were obtained between $(1.97\text{--}2.23) \times 10^{-10} \text{ m}^2/\text{N}$.

Deposition of TiW Thin Films

The deposition of TiW thin films and deposition procedures were discussed and reported [42]. The as-deposited films were annealed at 200, 400 and 600 °C under vacuum environment. The effect of annealing temperature on microstructure and electrical properties were analyzed. The TiW contact annealed at 400 and 600 °C shows improved ohmic property compared to as-deposited ITO thin films. The TiW thin film annealed at 600 °C exhibits improved microstructural properties and improved ohmic contact till 2 V [42]. Therefore, TiW thin film annealed at 600 °C was used as metal contact for development of ITO piezoresistive pressure sensor.

ANSYS Simulation

The number of elements and nodes created for circular diaphragm is listed in Table 1 and the mesh structure of circular diaphragm for different thickness is shown in Fig. 13. The

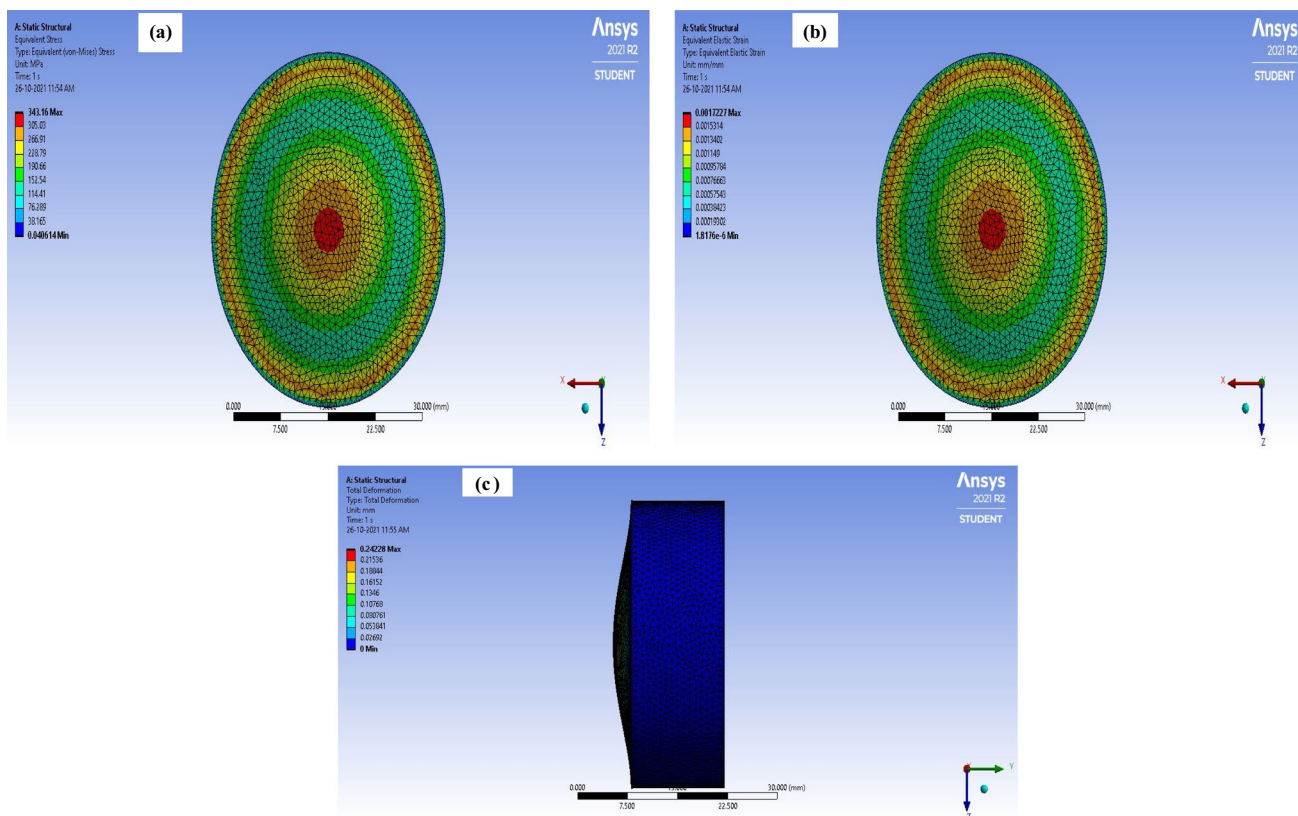


Fig. 15 Circular diaphragm of thickness 0.75 mm for applied pressure 10 bar (a) stress distribution (b) strain distribution (c) Deformation

Table 2 Comparison of analytical results with ANSYS Simulation results for applied pressure 1 bar

Thickness (mm)	Stress (MPa) Simulation	Strain (µm/mm)		Deformation (mm)	
		Analytical	Simulation	Analytical	Simulation
0.75	34.31	117.7	172	0.028	0.024
1.00	21.00	66.24	91.8	0.011	0.010
1.25	15.79	42.39	57.85	0.006	0.007

next step of simulation is to apply pressure (1 bar and 10 bar) and capture the simulation results.

The simulated parameters such as stress distribution (Von Mises), strain and deformation of circular diaphragm for applied pressure of 1 bar and 10 bar for 0.75 mm thickness diaphragm is shown in Figs. 14 and 15.

Similarly the diaphragm for thickness of 1 and 1.25 mm are simulated using ANSYS. The strain and deformation values calculated from small deflection theory [37] are compared with simulation results and are tabulated in Tables 2 and 3 for applied pressure of 1 bar and 10 bar respectively.

Table 3 Comparison of analytical results with ANSYS Simulation results for applied pressure 10 bar

Thickness (mm)	Stress (MPa) Simulation	Strain (µm/mm)		Deformation (mm)	
		Analytical	Simulation	Analytical	Simulation
0.75	343.16	1177	1722	0.28	0.24
1.00	210	662.4	1180	0.11	0.106
1.25	158	424	578.5	0.06	0.074

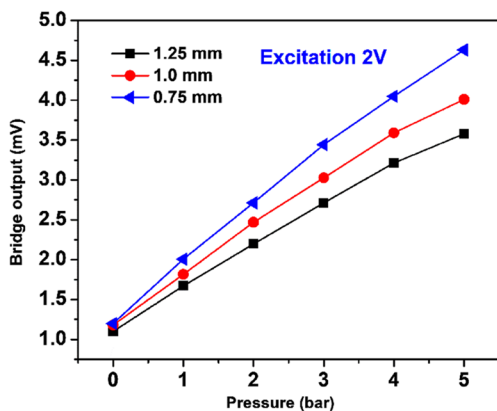


Fig. 16 Output response of developed ITO piezoresistor based pressure sensor

Results show that maximum deformation occurs for the diaphragm having less thickness.

From the ANSYS simulation results, stress, strain and deformation is maximum at the center. Therefore, ITO piezoresistors in the form of thin films has to be deposited at maximum stress and maximum deformation region in order to achieve high sensitivity for pressure sensor.

Pressure Sensor Calibration and Testing

ITO piezoresistors with TiW contact are connected in Wheatstone full bridge configuration is calibrated and tested for 50 pressure cycles by applying 2 V DC excitation. The variation of bridge output voltage for three

different thickness of diaphragm with applied pressure in the range of 0 to 5 bar at ambient temperature is shown in Fig. 16. A linear variation in ITO pressure sensor output is observed. Sensitivity (*S*) of the designed and developed ITO pressure sensor is calculated using Eq. (5) [13] and are obtained as 0.686, 0.566 and 0.495 mV/bar at 2 V excitation for diaphragm thickness of 0.75, 1, and 1.25 mm pressure sensors respectively.

$$S = \frac{\Delta V_o}{\Delta P} \tag{5}$$

The non-linearity (*NL_i*) in the output response of the developed ITO pressure sensors is calculated using Eq. (6) [13] and are found to be 9.14, 9.82 and 11.27% for diaphragm thickness of 0.75, 1, and 1.25 mm respectively (Fig. 17).

$$NL_i = \frac{V_{oi} - V_{oL}}{V_{oL} - V_{off}} \tag{6}$$

Where *V_{oi}* is the sensor output voltage at pressure *P_i*, and *V_{oL}* is the value of *V_o* that would have occurred if the output characteristics coincided with the end point straight line and *V_{off}* is the offset voltage.

The hysteresis plot for diaphragm thickness of 0.75, 1, and 1.25 mm pressure sensors is shown in Fig. 18. Hysteresis error is calculated using Eq. (7) and is found to be 0.0344, 0.0525 and 0.054 for diaphragm thickness of 0.75, 1, and 1.25 mm respectively. Hysteresis in the fabricated pressure sensor may be due to the sensing material composition (ITO), shape, thickness, and material used for the diaphragm (SS 304).

Fig. 17 Output response of ITO piezoresistor based pressure sensor exhibiting nonlinearity for diaphragm thickness of (a) 0.75, (b) 1.00 (c) 1.25 mm

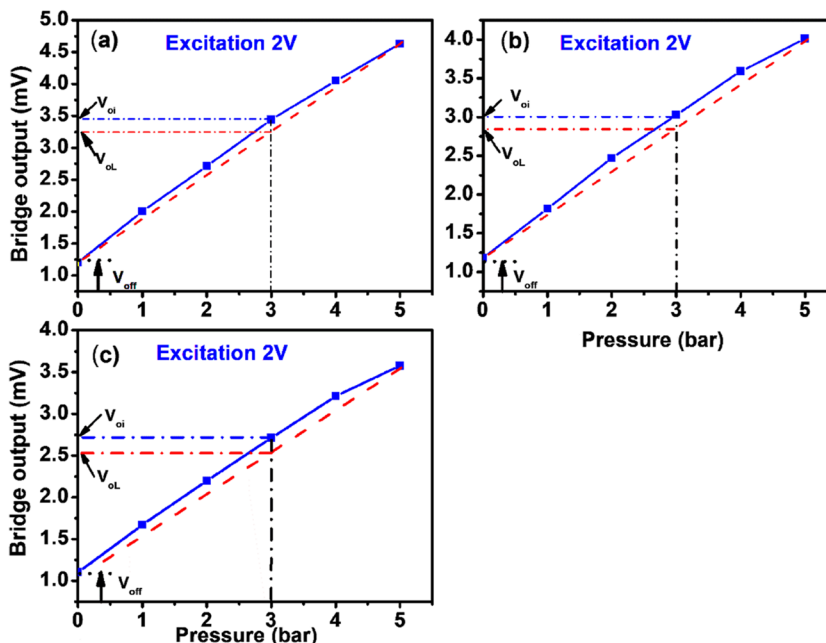
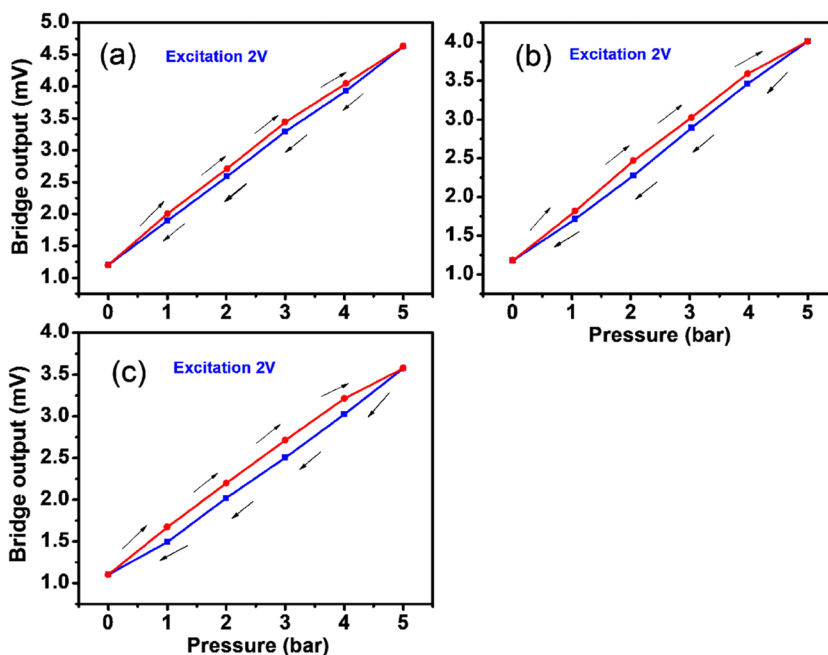


Fig. 18 Hysteresis plots of ITO piezoresistor based pressure sensor for diaphragm thickness of (a) 0.75 (b) 1.00 (c) 1.25 mm



$$\text{Hysteresis error} = \frac{A - B}{\text{FSO}} \tag{7}$$

Where A-B is the maximum difference in sensor output at a pressure, when that pressure is first approached with pressure increasing and then approached with pressure decreasing. FSO is the full scale output.

The ITO pressure sensor with diaphragm thickness 0.75 mm exhibits better sensitivity low values of non-linearity and hysteresis error. Therefore ITO pressure sensor (diaphragm thickness of 0.75 mm) is tested by varying the temperature from room temperature to 150 °C and the bridge output is measured by applying pressure of 5 bar and excitation voltage of 2 V. Due to the limitation of the test equipment and method, the test was conducted

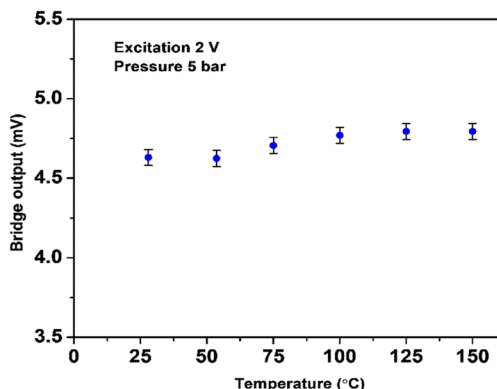


Fig. 19 Output response of pressure sensor (diaphragm thickness of 0.75 mm) with variation in temperature

only within the 150 °C. Calibration of the pressure sensor at controlled temperatures 0, 25, 50, 75, 100, 125 and 150 °C is carried out using a hot and cold chamber. The selected temperature is allowed to stabilize for 1 h. At each temperature the values of output voltage were measured. Response of pressure sensor is shown in Fig. 19. It was observed that, the effect of temperature on response of ITO pressure sensor above 100 °C is negligibly small. Hence, developed ITO pressure sensor can be used for pressure measurement upto 5 bar above 100 °C.

Conclusion

Three ITO piezoresistor based pressure sensors were designed and fabricated with circular diaphragm of 37 mm diameter and different thickness (0.75, 1, 1.25 mm) using SS 304. From the simulation results it was observed that stress and strain was maximum at the centre and circumference of diaphragm. Therefore, ITO piezoresistors were deposited at the centre and circumference on electrically isolated diaphragm. The pressure sensor with diaphragm thickness 0.75 mm exhibits better sensitivity (0.686 mV/bar), low values of non-linearity (9.14) and hysteresis error (0.0344), and can be used for pressure measurement from 0 to 5 bar at 150 °C in gas turbine engines and aerospace applications.

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Declarations

Research Involving Human Participants and/or Animals This article does not contain any studies with human participants or animals performed by any of the authors.

Consent for Publication Not applicable.

Competing Interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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