Original Article

Simulation of Circular Shaped SiC Diaphragm based Pressure Sensor and Comparing Its Deflection Characteristics with Square Shaped Diaphragm for Improved Sensor Performance.

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Abstract

Aim: Simulation of circular and square-shaped Silicon Carbide (SiC) diaphragm based pressure sensor and to study its deflection characteristics over a uniform pressure range of 0 to 200 kPa. **Materials and Methods:** COMSOL Multiphysics 5.6 is used for the simulation. Samples are divided into 2 groups, group 1 SiC circular diaphragm-based pressure sensor, and group 2 SiC square diaphragm-based pressure sensor with a pretest power of 80 %. **Results:** Square-shaped and circular-shaped SiC diaphragm based pressure sensors exhibited displacement of 2.278 µm and 0.19874 µm respectively. On performing an independent sample t-test, the circular and square-shaped SiC-diaphragms exhibited the mean displacement values of 1.1390 μm 0.1057 μm respectively with a significance value of 0.000 ($p<0.05$). **Conclusion:** Silicon carbide (SiC) based piezoresistive pressure sensor with circular diaphragm exhibited good deflection characteristics compared to square geometry.

Keywords: Novel Pressure Sensor, Diaphragm, Deflection, Silicon Carbide (SiC), Stress, Pressure, Displacement, Micro Electro Mechanical System.

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INTRODUCTION

The effect of geometric aspects of the SiC-based diaphragm for better pressure sensing application is described in this work. Micro Electromechanical Systems (MEMS) based piezoresistive Micro Electro Mechanical System based novel pressure sensors have gained much research interest in various fields including material science (Song et al. 2020), engineering (Zhang et al. 2021), automobile (Marek et al. 2006), biotechnology (Bao 2000), and optoelectronics (Subramani, Siddaramaiah, and Lee 2021) due to its distinct properties such as versatility, simple working principle, linear response, stability, etc. Among the various materials available silicon carbide (SiC) is widely used as Micro Electromechanical Systems (MEMS) based piezoresistive Micro Electro Mechanical System based novel pressure sensor material due to its high hardness (Jiang and Cheung 2009), chemical inertness (Ledoux et al. 1988), wear resistivity (Teng et al. 2007), good thermal stability (Shen et al. 2013), high thermal conductivity (Judy 2001), mechanical robustness and high critical electric field (Luo, Zhou, and Yu 2014). The main objective of this work is to study the deflection characteristics of silicon carbide (SiC) based diaphragms with different geometries.

In the last 5 years, several research papers have been published on Micro Electro Mechanical System based novel pressure sensors. Google Scholar has publications of around 16800 and IEEE Xplore has publications of around 800. Micro Electro Mechanical System based novel pressure sensors are vital in our daily life. Selection of the most suitable material is one of the complex tasks associated with current pressure sensors. For optimum performance, maximum deflection of a Micro Electro Mechanical System based novel pressure sensor diaphragm is one of the key requirements (Mehmood, Haneef, and Udrea 2020). Most widely used materials for pressure sensing applications are silicon (Madou 2011), germanium (Gonzalez et al. 2012), and silicon carbide (Tian, Shang, Zhao, Wang, et al. 2021).

Our institution is passionate about high quality evidence based research and has excelled in various fields (Parakh et al. 2020; Pham et al. 2021; Perumal, Antony, and Muthuramalingam 2021; Sathiyamoorthi et al. 2021; Devarajan et al. 2021; Dhanraj and Rajeshkumar 2021; Uganya, Radhika, and Vijayaraj 2021; Tesfaye Jule et al. 2021; Nandhini, Ezhilarasan, and Rajeshkumar 2020; Kamath et al. 2020). For optimum performance, maximum deflection of a Micro Electro Mechanical System based pressure sensor diaphragm is one of the key requirements. This can be improved by proper selection of geometry and dimensions of diaphragms. This work aims on the geometrical aspects of the SiC diaphragm for improved pressure sensing applications.

MATERIALS AND METHODS

This work is done at Nanoelectronics Lab, Department of Electronics and Communication Engineering at Saveetha School of Engineering, Chennai. This work involves two groups, group-1 SiC circular diaphragm (SiC-C) based Micro Electro Mechanical System novel pressure sensor, and group-2 SiC square diaphragm (SiC-SQ) based Micro Electro Mechanical System novel pressure sensor. Total sample size is taken as 34 with group-1 (17 samples) and group-2 (17 samples) having 80 % G-power (Campbell et al. 2004). Pretest power is determined with Alpha and Beta value of 0.05 and 0.2 respectively. The deflection characteristics of the SiC diaphragm with circular and square geometries were studied.

Two preparation methods are adopted for two groups. In group 1, the design of SiC based circular shaped diaphragm was carried out using COMSOL Multiphysics 5.6 software (Zimmerman 2006) with 50 μm radius.

Similar to group 1, preparation for group 2 is also done. In group 2, the design of SiC based square-shaped diaphragm was carried out using COMSOL Multiphysics 5.6 software with 88 μm radius.

The entire work is done in Windows 10 Pro, Intel Core i7, 8th Gen. COMSOL Multiphysics 5.6 software was used for simulation. 3D space dimension was selected. To add physics to the model, a structural mechanics module was used. The structural analysis was carried out using solid mechanics interface. The study type is chosen as stationary. The geometry and the material are selected as per the requirement. SiC is selected as the material and the studies were carried out for both square and circular geometries. The deflections at the surface of the diaphragm were measured with respect to the applied pressure.

Statistical Analysis

Statistical analysis was carried out using SPSS version 21 Software tool (Johnson 2001). SPSS is used to calculate the mean and significant difference of the results obtained through simulation. Mean, standard deviation, and standard mean error are calculated for circular and square geometries of SiC diaphragms. In this research work, the diaphragm thickness and applied pressure are the independent variables and displacement is the dependent variable because it depends on the inputs and varies for every change in the input. The analysis of the research work is done using the independent sample t-test, which is used to compare the displacement characteristics of SiC-C and SiC-SQ.

RESULTS

A uniform pressure ranging from (0-200 kPa) is subjected to the centre of the diaphragms. COMSOL Multiphysics software is used for the simulation. Maximum displacement is observed at the centre of the diaphragm in both circular and square-shaped diaphragms (SiC-C and SiC-SQ). Circular shaped diaphragm has a larger reflection compared to the square-shaped diaphragm. A maximum deflection of 2.278 μm was obtained for SiC circular-shaped diaphragm for the thickness of 20 μm whereas SiC square diaphragm exhibited a significant deflection of 0.19874 μm.

Figure 1 shows Von Mises stress distribution of circular SiC diaphragm under a uniform pressure range of 0-200 kPa. Maximum stress distribution observed at the centre of the diaphragm. As the applied pressure increases the corresponding stress also increases. Fig. 2. shows the surface displacement plot of the circular SiC diaphragm under a uniform pressure range of 0-200 kPa. Maximum displacement occurs at the centre of the diaphragm. Fig. 3. Von Mises stress distribution of square-shaped SiC diaphragm under a uniform pressure range of 0-200 kPa. It is observed that maximum stress distribution occurs at the centre of the diaphragm. Fig. 4. shows the surface displacement plot of the square-shaped SiC diaphragm under a uniform pressure range of 0-200 kPa. Maximum displacement occurs at the centre of the diaphragm. Fig. 5 and Fig. 6 depict the deflection plot of the SiC-C diaphragm and SiC-SQ diaphragm with respect to applied pressure (0-200 kPa). Bar charts comparing the mean (±1SD) of the statistical analysis of Si-C and Si-SQ diaphragms are depicted in Fig. 7. Compared to the SiC-SQ diaphragm, the SiC-C diaphragm exhibited large displacement values. There is a significant difference between the two groups are 0.000 ($p<0.05$) (Independent Sample T-Test) where x-axis: groups based on the shape of the diaphragm and y-axis: mean of the displacement with applied uniform pressure ±1SD.

Material properties associated with the SiC diaphragm are depicted in Table 1. Deflection values corresponding to the Silicon Carbide (SiC) circular-shaped diaphragm under a uniform pressure range of 0-200 kPa are presented in Table 2. The pressure increases and the deflection also increases. Table 3 exhibited the deflection values corresponding to the Silicon Carbide (SiC) square-shaped diaphragm under a uniform pressure range of 0-200 kPa. Table 4 represents the group statistics for both sample groups providing mean, standard deviation, and standard error mean values for SiC-C and SiC-SQ diaphragm. Table 5 represents a statistical analysis of independent sample tests for both sample groups. Significance value 0.000 ($p<0.05$) is considered to be statistically significant and a 95 % confidence value is calculated. On performing an independent sample t-test, the circular and square-shaped SiC-diaphragms exhibited the mean displacement values of 1.1390 µm and 0.1057 µm respectively.

DISCUSSION

According to the simulation result, at a consistent pressure range of 0-200 kPa, the circular-shaped Si diaphragm displayed the most deflection compared to the square-shaped Si diaphragm. The material's thickness is maintained at 20 μm. The circular and square-shaped SiC-diaphragms had mean displacement values of 1.1390 μm and 0.1057 μm, respectively, after performing an independent sample t-test with a significant value of 0.000 ($p<0.05$). Since the diaphragm is fixed at all four edges, maximum shear stress was obtained at the midpoint of the diaphragm.

The main objective of this work is to study the role of the geometric features of the diaphragm for better pressure sensing applications. PDMS-based diaphragms with different geometries were studied in the article (Sushmita et al. 2019), that supports this work. The main finding of the study was the circular diaphragm exhibited good deflection compared to other geometries like square and rectangular which is in line with the present work. They have obtained deflection values of 107.77 μm and 93.3 μm respectively at a pressure of 20 kPa for circular and square diaphragms of width 100 μm. Similar to our work, (Verma, Punetha, and Pandey 2020) in this article they have obtained a deflection value of 0.5 μm for square shaped SiC diaphragm. (Huang and Zhang 2020) have obtained almost less than 5 µm deflection for square shaped SiC diaphragm. Similarly (Tian, Shang, Zhao, and Wang 2021) have obtained deflection of 2.4 µm for SiC membrane diaphragm. Compared to many of the existing works the proposed work is having better deflection at low pressure range.

The main limitation of novel pressure sensors is the high-temperature applications. due to p-n junction failure and current leakage sensor fails at high temperatures. So in future work, SiC diaphragms with different geometries and high temperature ranges can be studied.

CONCLUSION

SiC based piezoresistive pressure sensor with circular diaphragm exhibited good deflection compared to square geometry. Also, this study predicts that the theoretical analysis has an excellent linear variation of deflection over the working range of pressure.

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DECLARATION

Conflict of Interest

No conflict of interest in this manuscript.

Author's Contribution

Author NV was involved in designing, simulation, and manuscript writing. Author AD was involved in the conceptualization, validation, and critical view of the manuscript.

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TABLES AND FIGURES

Table 1. SiC diaphragm membrane material and parameters such as Young’s Modulus (140 GPa), Poisson’s ratio (0.265), density (2329 Kg/m^3) and relative Permittivity (11.7).

Material	Young’s Modulus (GPa)	Poisson’s Ratio	Density (Kg/m^3)	Relative Permittivity

SiC	137	0.37	4.36	1

Table 2. Simulated displacement values of SiC based circular diaphragm with respect to applied pressure range of 0-200 kPa. Maximum displacement of 2.278 µm was obtained for a pressure of 200 kPa.

Pn (Pa)	**Displacement Magnitude (µm)**
0	0
12500	0.14238
25000	0.28475
37500	0.42713
50000	0.5695
62500	0.71188
75000	0.85426
87500	0.99663
100000	1.139
112500	1.2814
125000	1.4238
137500	1.5661
150000	1.7085
162500	1.8509
175000	1.9933
187500	2.1356
200000	2.278

Table 3. Simulated displacement values of SiC square shaped diaphragm with respect to applied pressure range of 0-200 kPa. Maximum displacement of 0.19874 µm was obtained for a pressure of 200 kPa.

Pn (Pa)	**Displacement Magnitude (µm)**
0	0
12500	0.023676

25000	0.035513
37500	0.047351
50000	0.059189
62500	0.071027
75000	0.082865
87500	0.094702
100000	0.10654
112500	0.11838
125000	0.13022
137500	0.14205
150000	0.15389
162500	0.16573
175000	0.17757
187500	0.1894
200000	0.19874

Table 4. Represents group statistics for both sample groups providing mean (1.1390 and 0.1057), standard deviation (0.71896 and 0.06076), and standard error mean (0.17437 and 0.01474) values for SiC-C and SiC-SQ diaphragm.

	Groups	No of samples	Mean	Std Deviation	Std.Error Mean
Displacement	SiC-C	17	1.1390	0.71896	0.17437
	SiC-SQ	17	0.1057	0.06076	0.01474

Table 5. Represents statistical analysis of independent sample tests for both sample groups. Significance value 0.000 ($p<0.05$) considered to be statistically significant and 95% confidence value is calculated.

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
SAMPLE	Equal variances assumed	39.423	.000	5.905	32	.000	1.03331	0.17500	0.67686	1.8976
	Equal variances not assumed			5.905	16.229	.000	1.03331	0.17500	0.66276	1.4086

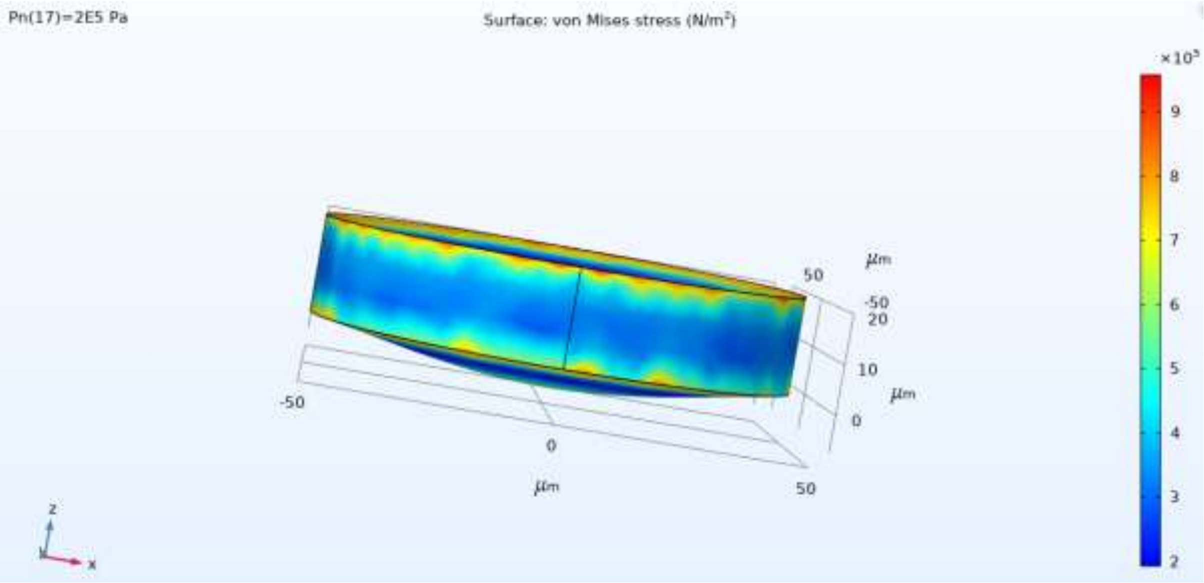

Fig. 1. Von Mises stress distribution of circular SiC diaphragm under uniform pressure of 200 kPa. The displacement is observed to be highest at the centre and decreased towards the edge.

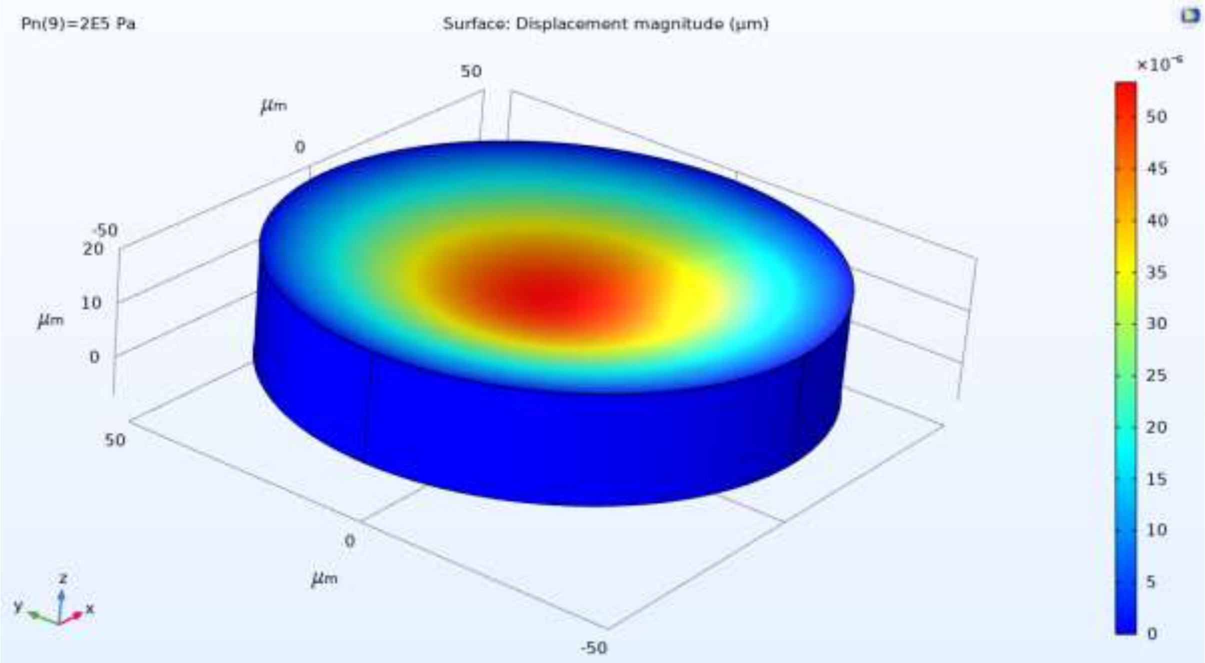

Fig. 2. Surface displacement plot of circular SiC diaphragm under uniform pressure of 200 kPa. Maximum displacement observed at the centre and decreased towards the edge.

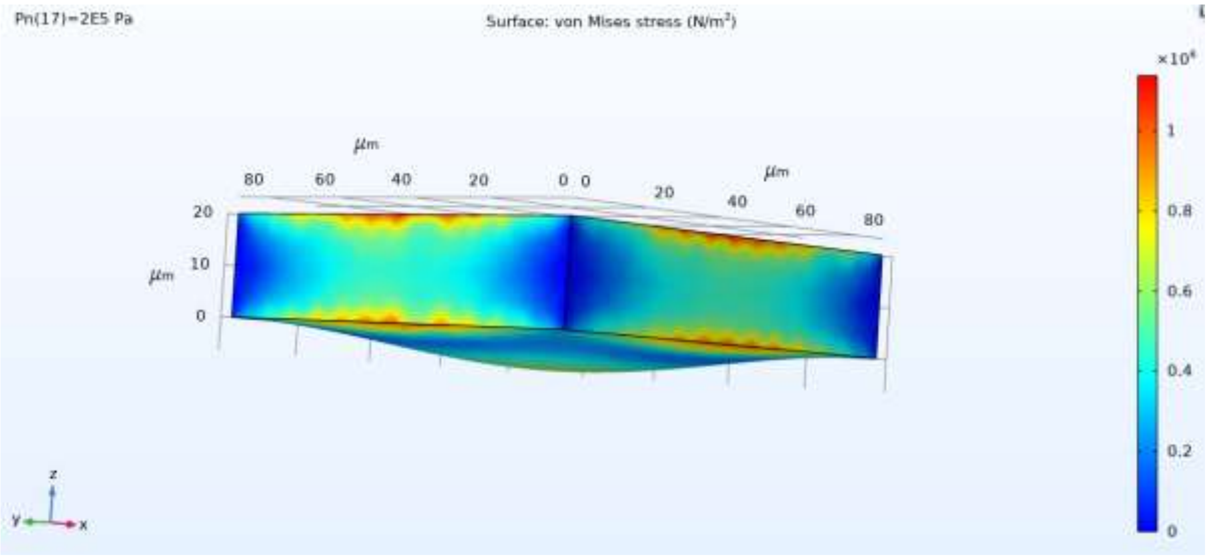

Fig. 3. Von Mises stress distribution of square shaped SiC diaphragm under uniform pressure of 200 kPa. The displacement is observed to be highest at the centre and decreased towards the edge.

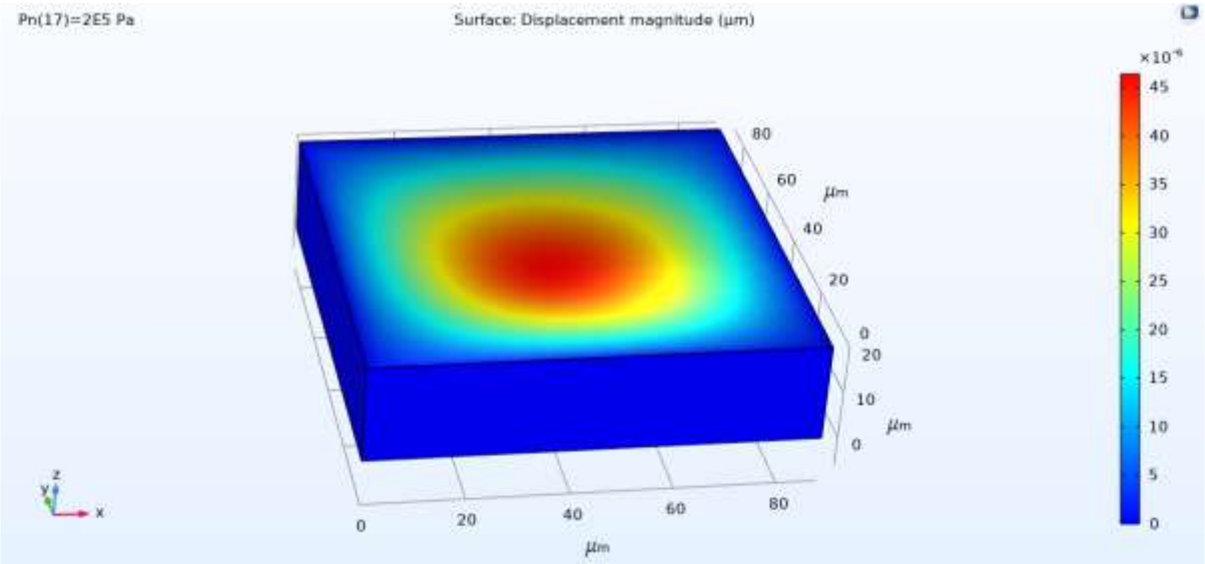

Fig. 4. Surface displacement plot of square shaped SiC diaphragm under uniform pressure of 200 kPa. Maximum displacement observed at the centre and decreased towards the edge.

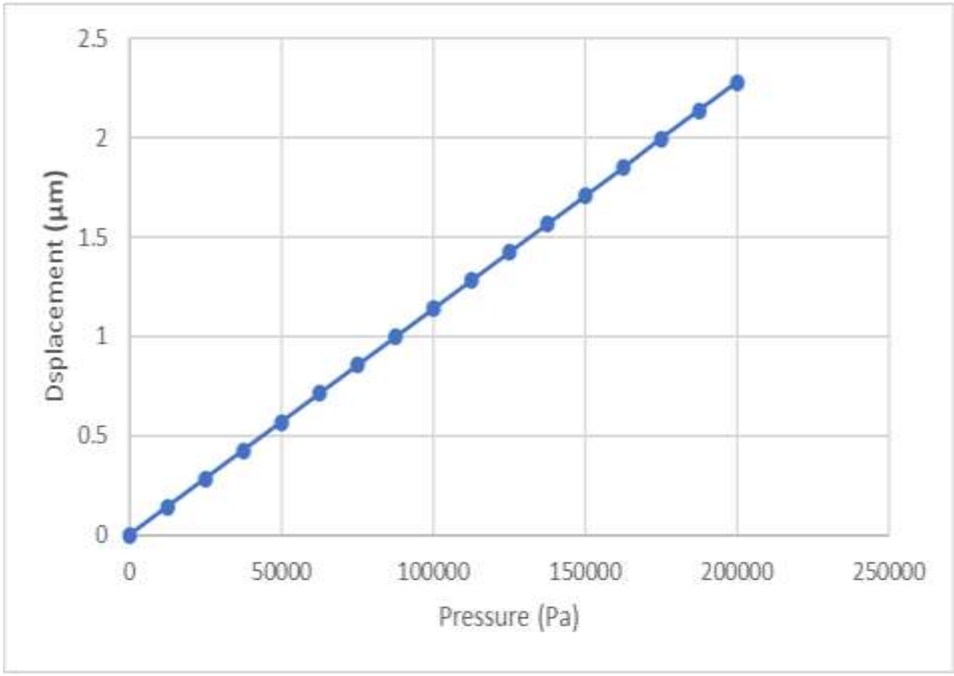

Fig. 5. Deflection plot of SiC-C diaphragm with respect to applied pressure range of 0-200 kPa (X-axis: pressure and Y-axis: displacement).

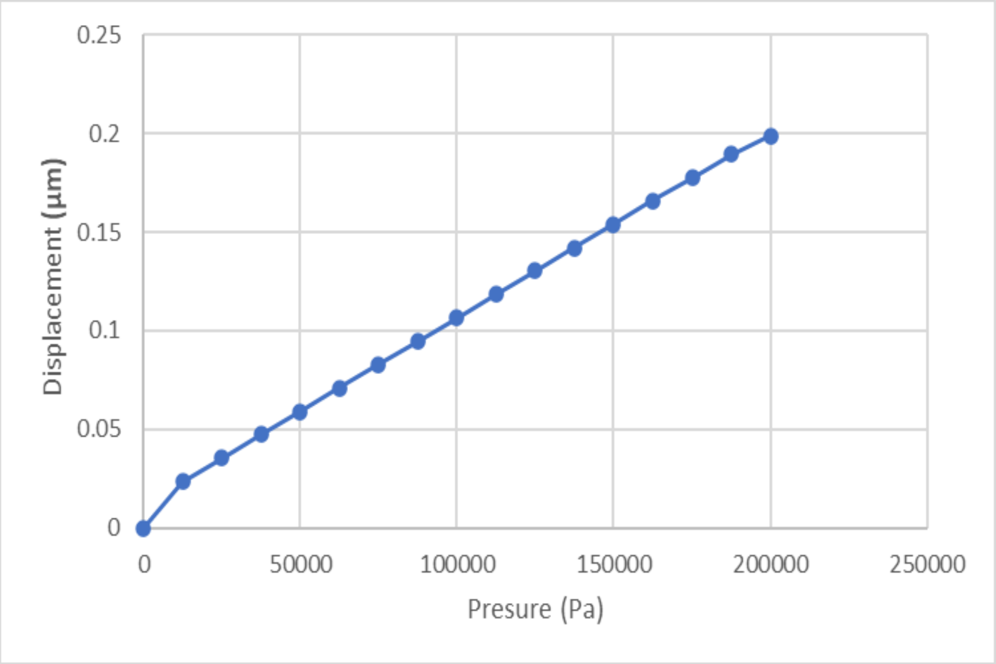

Fig. 6. Deflection plot of SiC-SQ diaphragm with respect to the applied pressure range of 0-200 kPa (X-axis: pressure and Y-axis: displacement).

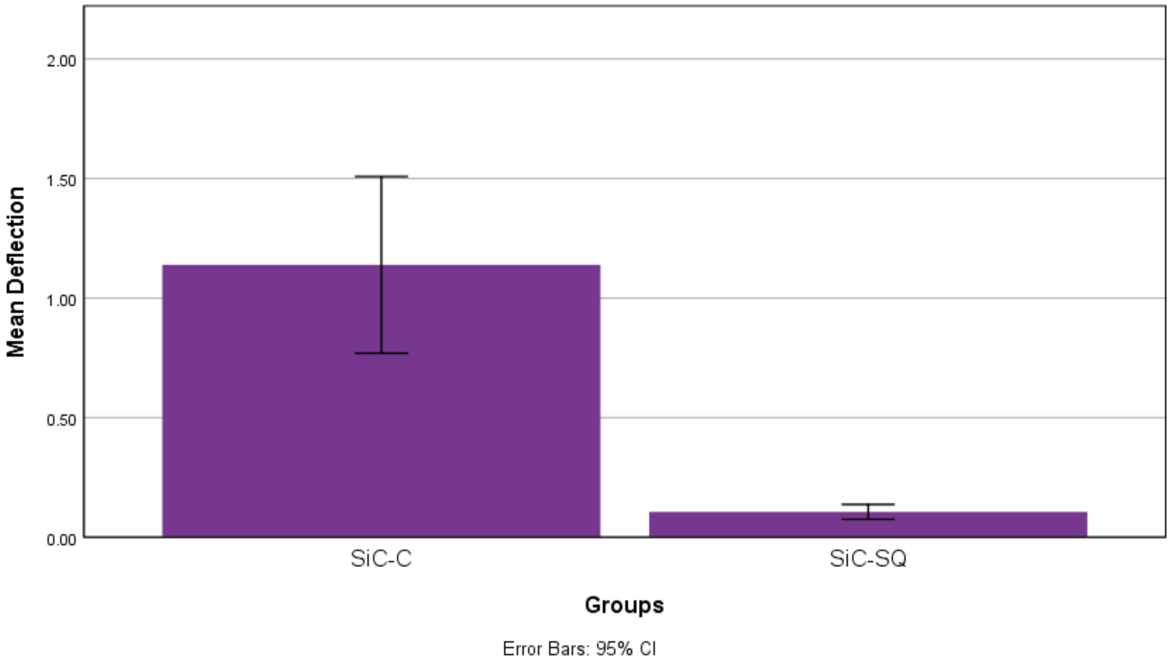

Fig. 7. Bar chart comparing the mean (± 1SD) of the statistical analysis of SiC-C and SiC-SQ diaphragm. There is a significant difference between the two groups p<0.05 (Independent Sample T-Test) Where x-axis: groups based on the shape of the diaphragm and y-axis: mean of the displacement with applied uniform pressure ± 1SD.