Design optimization of silicon cantilever for strain based MEMS position sensor

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KEYWORDS

Silicon Cantilever,
Position Sensor,
Surface Roughness,
Strain.

ABSTRACT

Micro-cantilevers are often used in various fields of science and engineering, particularly in sensing and nanotechnology. These are integral components in MEMS (Micro-Electro-Mechanical Systems) devices such as position sensor, pressure sensor, Accelerometer etc. Silicon is a most preferred material for micro-cantilevers due to its mechanical strength and ease of fabrication. This study investigates the design and mechanical behavior of two different configuration i.e., without and with anchor silicon cantilever beam by comparing theoretical calculations with finite element simulation results. Theoretical deflection was calculated using Euler-Bernoulli beam theory, while simulations were conducted using a finite element analysis (FEA) software. This work involves experimental analysis and computational simulations to measure strain and deflection in both scenarios. The strain to deflection ratios is found out to be higher in case of configuration 2 which indicates that configuration 2 has better sensitivity than configuration 1.

1. Introduction

A silicon cantilever is a key component in various MEMS (Micro-Electro-Mechanical Systems) devices, including Accelerometer, Pressure sensor and position sensors (Xu et al., 2022). Silicon particularly single-crystal silicon is preferred over other materials due to its unique properties like Mechanical strength, stiffness, high sensitivity and easy to fabricate with Semiconductor processes. In strain based position sensor, cantilever serve as the probe element for measuring mechanical characteristics and surface topography at the micro scale to Nano scale. In many different industries, including semiconductor technology, automobile production and medical engineering, surface roughness is crucial (Wasisto et al., 2015). Typically, silicon cantilevers are rectangular or beam-shaped structures anchored at one end and the microprobe tip had an eight sided pyramidal shape, allowing them to deflect when a force is applied vertically on the tip (Teir et al., 2021; Xu et al., 2021). The tip Dimensions vary based on the application but typically range from a few micrometers to several millimeters in length. The beam deflection is indirectly measured by strain on cantilever. The strain can be measured using piezo-resistive element which can be directly fabricated on top of cantilevers using MEMS technology. In general the beam wide is less to make the beam more sensitive but if beam is not wide enough then it is difficult to accommodate piezo-resistors on cantilevers. In this paper, the design and mechanical behavior of two different configurations i.e., without and with anchor silicon cantilever beam is evaluated by comparing theoretical calculations with finite element simulation results. To evaluate the effects of varying beam dimensions on the mechanical behavior of cantilever beams, we systematically varied the length of the beam. This investigation aims to understand how these changes influence deflection, stiffness, and overall performance (Behle & Brand, 2020).

2. Design Configuration

Designing a silicon cantilever for a strain-based MEMS (Micro-Electro-Mechanical Systems) position sensor involves a multi-faceted approach that balances mechanical design and material properties. Here's a structured approach to optimizing such a cantilever in two configuration i.e., without anchored beam and with anchored beam to place piezo resistors on the anchor as shown in figure 1(a) and (b).

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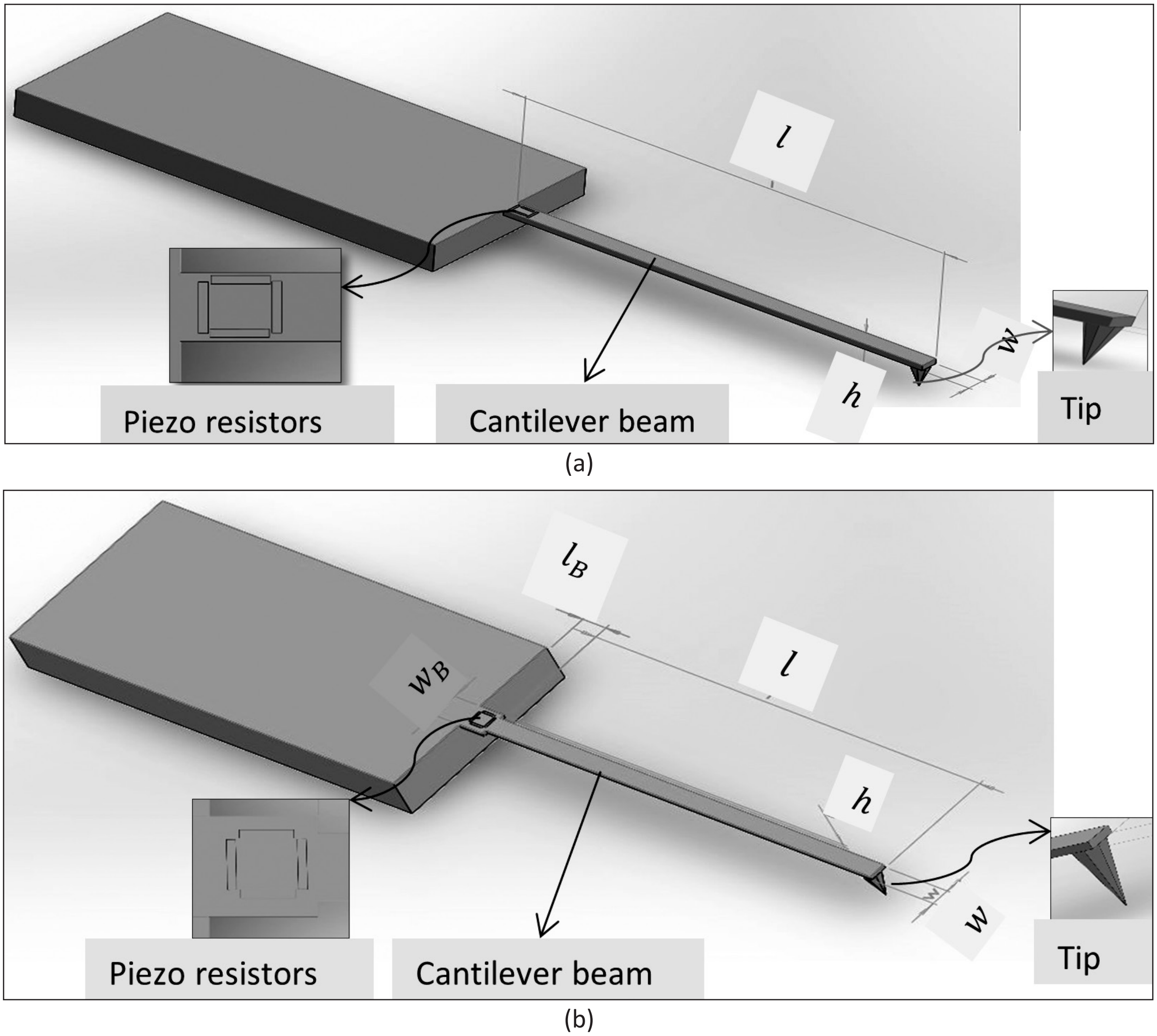
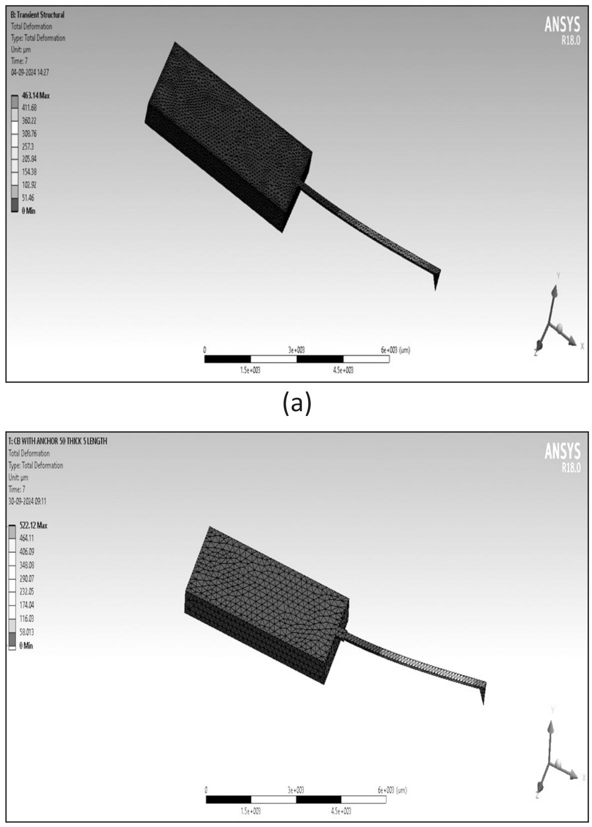


Fig. 1. Cantilever beam (a) without anchored (b) with anchor.

Table 1
Design parameters.

Sl No	Parameter	Dimension	
		Configuration 1: (Beam without Anchor)	**Configuration 2: (Beam with Anchor)**
1	Beam Length (l)	3mm and 5mm	3mm and 5mm
2	Beam Width (w)	200 µm	200 µm
3	Beam Thickness (h)	50 µm	50 µm
4	Force (F)	0.75MN – 4mN	0.75MN – 4mN
5	Anchor Width (w_B)	200 µm	300 µm
6	Anchor Length (l_B)	0	300 µm



(a) (b) (c) (d)

Fig. 2. Simulation results at F=4000 µN (a) Beam deflection in configuration 1 (b) Strain in configuration 1 (c) Beam deflection in configuration 2 (d) Strain in configuration 2.

3. Theoretical Analysis

This section details about the theoretical modeling of cantilever to calculate strain and cantilever. This provides insight into the design, implementation, and execution of the simulations. Two different designs are considered whose geometrical parameters are given in Table 1.

A force F vertically acting on the tip results in a deflection (δ) is given in below equation 1 (Behle & Brand, 2020).

$$\delta = \frac{4l^3(1-\upsilon^2)}{Ewh^3} C_B F \quad \text{.........................(1)}$$

With the young's modulus E=170 Gpa and poisons ratio (υ) is 0.3 and in accordance with the widening of the cantilever beam at its clamped end by the factor C_B is given by below equation 2 (Behle & Brand, 2020).

$$C_B = 1 - \frac{3l_B(l-l_B)}{l^2}\left(1 - \frac{w}{w_B}\right) \quad \text{.........................(2)}$$

When the force is applied on the tip, the cantilever beam gets deflected and strain (ε) is generated at the fixed end is given by below equation 3 (Behle & Brand, 2020)

$$\varepsilon = \frac{3h}{2l^2}\frac{w}{w_B C_B}\,\delta \quad \text{.........................(3)}$$

From equation 2 while considering the parameter from Table 1, C_B =1 and 0.88 for configuration 2.

4. Finite Element Modeling (FEM) and Simulation

In contemporary research and development, simulations have become an invaluable tool for investigating complex systems and processes that are difficult to analyze through traditional experimental methods. The primary aim of the simulation in this study is to model the behavior of a cantilever beam under different varying conditions, predict the impact of changes on cantilever beam. Deflection and strain values are calculated for the given cantilever geometries

Table 2
Calculated and simulated deflection and strain values.

Design	Force (μN)	Calculated Value						Simulated Value					
		Length						Length					
		3mm			5mm			3mm			5mm		
		δ(μm)	ε	ε/ δ (/μm)	δ (μm)	ε	ε/ δ (/μm)	δ(μm)	ε	ε/ δ (/μm)	δ(μm)	ε	ε/ δ (/μm)
Configuration 1 (without anchor)	750	19.05	158.75	8.33	88.23	264.69	3	18.18	162.7	8.94	86.08	277	3.21
	850	21.6	180	8.33	100	300	3	20.65	184.6	8.93	97.58	314	3.21
	950	24.14	201.1	8.33	111.7	335.28	3	23.08	206.4	8.94	109.1	351	3.21
	1000	25.41	211.7	8.33	117.6	352.92	3	24.3	217.2	8.93	114.8	369.5	3.21
	2000	50.82	423.5	8.33	235.2	705.87	3	48.68	434.9	8.93	230.6	740.7	3.21
	3000	76.23	635.2	8.33	359.9	1079.8	3	73.26	653.7	8.92	346.7	1112.7	3.20
	4000	101.6	847	8.33	470.5	1411.7	3	97.94	873.1	8.91	463.1	1484.7	3.20
Configuration 2 (with anchor)	750	17.34	105.77	6.09	82.94	176.41	2.12	22.28	151.0	6.78	97.13	256.2	2.63
	850	19.65	119.86	6.09	94	199.93	2.12	25.24	171.4	6.79	110	290.4	2.64
	950	21.96	133.95	6.09	105.05	223.44	2.12	28.22	191.7	6.79	123.1	324.7	2.63
	1000	23.12	141.03	6.09	110.58	235.2	2.12	29.71	201.8	6.79	129.6	341.8	2.63
	2000	46.24	282.06	6.09	221.17	470.42	2.12	59.52	404.2	6.79	260.2	685.4	2.63
	3000	69.37	423.15	6.09	331.76	705.65	2.12	89.59	608	6.78	391.2	1030.3	2.63
	4000	92.49	564.18	6.09	442.35	940.87	2.12	119.7	812.5	6.78	522.1	1375.1	2.63

using equation (1) – (3) are shown in Table 2 in comparison with data obtained by ANSYS 18.1. By employing simulation techniques, we can explore scenarios that how, the deflection and strain are change by varying different parameters like force, thickness and length. The insights gained from these simulations are intended to observe the where more deflection and strain is happening and enhance understanding of the system as shown in Figure 2.

5. Results and Discussion

Initially, the cantilever beam of two configurations was designed with a length of 3mm to 5mm and a thickness of 50μm. Table 2 summarizes and compares the calculated values of deflection and strain with simulated values for both beam configuration with 3mm and 5 mm beam length.

5.1. Variation of length

The length of the beam was adjusted from 3mm to 5mm. As the length increased, the deflection of the beam under a varying load became more distinct in both the configurations. This is due to the cubic relationship between length and deflection in the beam theory equation. The stiffness of the beam, inversely related to length, decreased, making the beam more flexible.

5.2. Strain to deflection ratio

The strain to deflection ratio is a measure used to describe the relationship between strain in the beam and the resulting deflection of a cantilever beam which indirectly defines the sensitivity of the cantilever beam. This ratio helps to understand how cantilever beam will behave under loads.

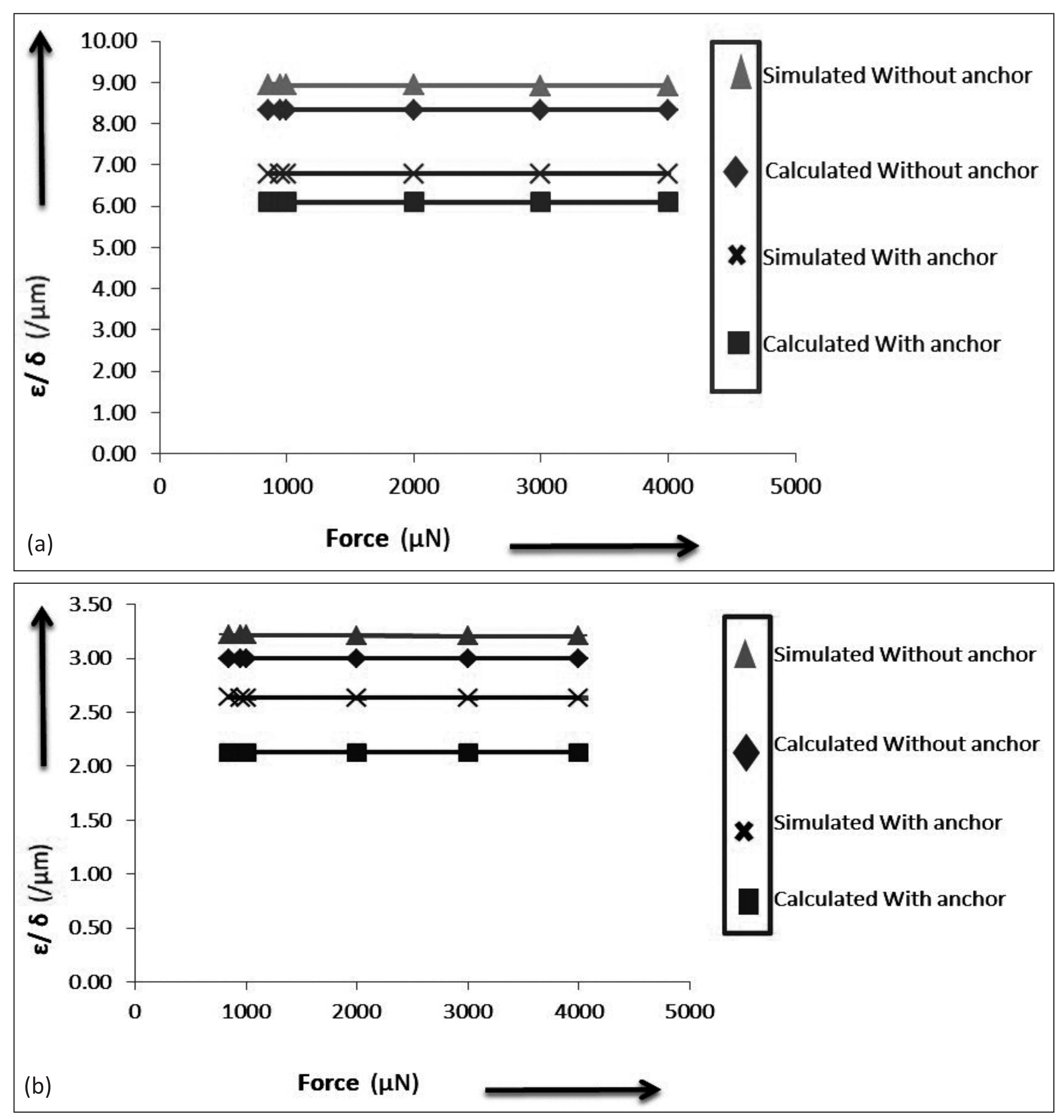


Fig. 3. Strain to deflection ratio vs. force graph for beam length (*l*) of (a) 3mm (b) 5mm.

Here, strain to deflection ratio is essential to compare the amount of strain experienced by the beam to the amount of deflection that occurs in a cantilever beam due to that strain as indicated in Figure 3. Here, higher ratio indicates that a beam experiences less deflection for a given amount of strain, suggesting greater stiffness and stability. Conversely, a lower ratio can indicate excessive bending or deformation. It is also observed short beam will provide better Strain to Deflection ratio and improve the sensitivity.

6. Conclusion

This study indicates that anchored cantilever beams demonstrate significantly reduced deflection compared to their unanchored counterparts, highlighting enhanced stability and load distribution. This reduced deflection is crucial for maintaining the integrity and functionality of the structure, especially under substantial loads. The strain experienced by anchored beams is also lower, suggesting improved material efficiency and safety. This study underscores the importance of anchoring in cantilever beam design, providing valuable insights for ensuring the reliability and performance of the cantilever beam. The comparison of strain to deflection ratios for cantilever beams with and without anchors clearly demonstrates that incorporating anchors significantly enhances structural performance and stiffness.

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References

Behle, H., & Brand, U. (2020). Mode analysis for long, undamped cantilevers with added diamond tips of varying length for fast roughness measurements. *SMSI 2020 Conference – Sensor and Measurement Science International.* 10.5162/SMSI2020/P2.7.

Peiner, E., Balke, M., Doering, L., & Brand, U. (2008). Tactile probes for dimensional metrology with microcomponents at nanometre resolution. *Measurement Science and Technology, 19*(6), 064001. 10.1088/0957-0233/19/6/064001

Teir, L., Lindstedt, T., Widmaier, T., Hemming, B., Brand, U., Fahrbach, M., Peiner, E., & Lassila, A. (2021). In-Line Measurement of the Surface Texture of Rolls Using Long Slender Piezoresistive Microprobes. *Sensors, 21*(17), 5955. https://doi.org/10.3390/s21175955

Wasisto, H. S., Yu, F., Doering, L., Völlmeke, S., Brand, U., Bakin, A., Waag, A., & Peiner, E. (2015). Fabrication of wear-resistant silicon microprobe tips for high-speed surface roughness scanning devices. *Smart Sensors, Actuators, and MEMS VII; and Cyber Physical Systems, 9517*. https://doi.org/10.1117/12.2179866

Xu, M., Li, Z., Fahrbach, M., Peiner, E., & Brand, U. (2021). Investigating the Trackability of Silicon Microprobes in High-Speed Surface Measurements. *Sensors, 21*(5), 1557. https://doi.org/10.3390/s21051557

Xu, M., Zhou, Z., Ahbe, T., Peiner, E., & Brand, U. (2022). Using a Tip Characterizer to Investigate Microprobe Silicon Tip Geometry Variation in Roughness Measurements. *Sensors, 22*(3), 1298. https://doi.org/10.3390/s22031298

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