International Journal of Nanoelectronics and Materials
Volume 16 (Special Issue) December 2023 [87-93]

Simulation and Analysis of Piezoresistive Microcantilever

Shazlina Johari[1,2,3,*], Catherine Lim Ee Chen[1], Bibi Nadia Taib[1,3], Mohd Hafiz Ismail[1]
and Siti Noorjannah Ibrahim[4,5]

[1]Faculty of Electronic Engineering and Technology, Universiti Malaysia Perlis (UniMAP),
Pauh Putra Campus, 02600 Arau, Perlis
[2]Institute of Nano Electronic Engineering, Universiti Malaysia Perlis (UniMAP),
01000, Kangar, Perlis, Malaysia
[3]Centre of Excellence for Micro System Technology (MiCTEC), Universiti Malaysia Perlis,
Arau, 02600, Perlis, Malaysia
[4]Department of Electrical Engineering, Kulliyyah of Engineering,
International Islamic University Malaysia, Kuala Lumpur, Malaysia
[5]Integrative Engineering Education and Ethics for Sustainability (INTEGRATES) Research Group,
International Islamic University Malaysia, Kuala Lumpur, Malaysia

ABSTRACT

Currently, most piezoresistive microcantilever sensors are configured with a dual-layer design that includes a piezoresistor integrated onto the upper surface of a microcantilever. The dual-layer design effectively enhances sensitivity and the piezoresistance effect. However, integrating the piezoresistor onto the microcantilever in the fabrication process necessitates additional steps, leading to extended manufacturing times and increased production costs. In this paper, the mechanical behavior of a single-layer piezoresistive microcantilever, namely displacement, stress, and strain, is investigated and analyzed using ANSYS Multiphysics. The contributing factors expected to affect the device's performance are its geometrical dimensions, and the materials used. Regarding the device dimensions, the length, thickness, and width of the cantilever were varied. It was found that the performance of the piezoresistive microcantilever can be improved by increasing the length and decreasing the thickness. The displacement of the microcantilevers increased by about 230%, from 75.76μm to 250.12μm, when the length was increased from 225μm to 350μm. The applied force ranged from 2uN to 12uN. Similarly, the stress and strain produced on the microcantilevers also increased by about 60.83% and 57.22%, respectively. From the material point of view, the microcantilever made with silicon always had the highest displacement value compared to silicon nitride, silicon dioxide, and polysilicon. This is due to the Young's modulus value, where materials with lower Young's modulus will have higher displacement and stress.

Keywords: Piezoresistive, microcantilever, ANSYS

1. INTRODUCTION

Microcantilevers are the most simplified MEMS based devices. Various applications of microcantilevers in the field of sensors have been explored and found due to the capability to sense the changes in the cantilever bending or vibrational frequency of various physical, chemical, and biological phenomena [1]. These properties make microcantilever requested by sensor technology as it is a perfect choice for sensing applications. MEMS microcantilever-based sensor integrated with piezoresistive read-out is normally used to measure the surface stress change induced from surrounding environment [2]. Piezoresistive microcantilever sensor has a very high sensitivity which is able to sense a few molecules or atoms and a very small change in mass will produce a superior displacement. The change in resistance is a function of the stress in the piezoresistor [3]. The resistivity change can be measured by using Wheatstone bridge.

---

[*] Corresponding authors: shazlinajohari@unimap.edu.my

Nowadays, the majority of the piezoresistive microcantilever sensors were designed in dual layers which embracing of the piezoresistor integrated on the top surface of a microcantilever [4-7]. The material for piezoresistor can be polysilicon or doped silicon meanwhile the microcantilever can be silicon nitride or silicon dioxide [8].

The sensitivity and the piezoresistance effect can be enhanced effectively with the dual layers design [9-10]. And yet, the fabrication process of the piezoresistor integrated on the microcantilever required more steps and it will acquire longer manufacturing time and costly manufacturing expenses [8]. Therefore, this project introduced the design of single layer piezoresistive microcantilever that the piezoresistor and the microcantilever are integrated into one layer. The simulation will be conducted using ANSYS. For this design, the four materials that is going to act as both piezoresistor and microcantilever is p-doped silicon, polysilicon, silicon dioxide and silicon nitride with the same applied force and dimensions. The geometrical aspects microcantilever, such as length (l), thickness (t), width (w) and the width of the piezoresistors legs (w_leg) will be investigated in order to examine and characterize the performance of the microcantilever [8]. The displacement, strain and the von Mises stress will be obtained by varying by the force applied on the free surface, the materials used and the dimension of the microcantilever.

2. MATERIAL AND METHODS

The design of single layer piezoresistive microcantilever is based on a dual-leg microcantilevers [8][11]. The starting dimensions of microcantilevers is initially set to have the thickness of 0.5 μm, the width of 105 μm, the length of 275 μm and the distance between the piezoresistor legs of 45 μm as shown in Figure 1 [8]. The uniform load is set to be in the range from 2 μN to 12μN. The simulation results of the starting dimensions, such as displacement and von Mises stress value will serve as the references values for the geometrical variations. After that, the geometrical aspects are varied to characterize the performance of microcantilevers while, the uniform load is fixed to 2μN. The materials used are silicon, silicon dioxide, poly-silicon and silicon nitride.

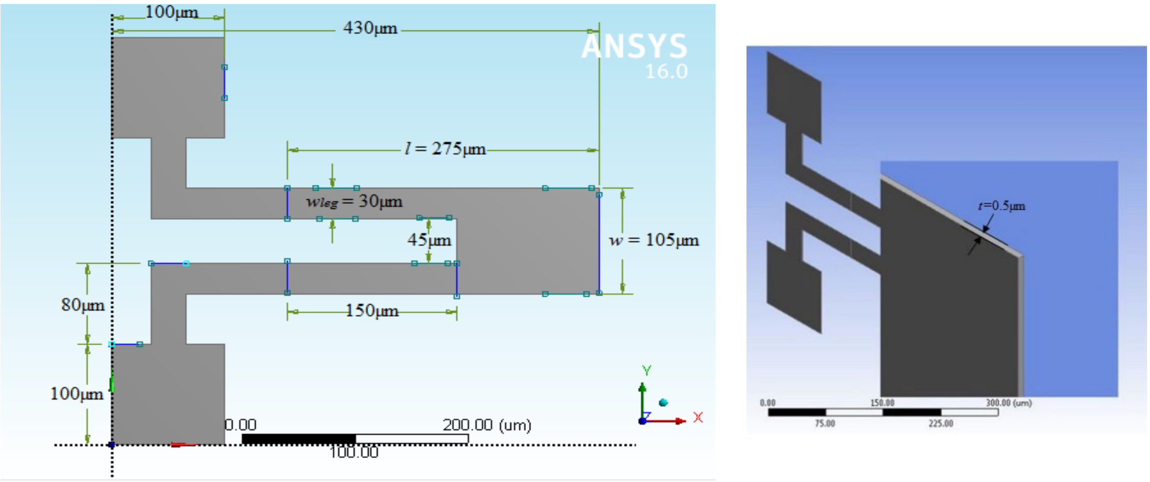

Figure 1. The design model of the single layer piezoresistive microcantilever with labeled dimensions (left) and thickness in X-Y Plane (right).

The simulation is carried out with the ANSYS multipurpose finite element simulator. The effect of the geometric aspects of the microcantilever on the displacement and von Mises is determined by manipulating the thickness (t), the width (w), the length (l) and the width of the piezoresistor legs (w_leg) [8]. Table 1 shows the range of each geometrical aspect.

Table 1 Range of each geometric aspects of microcantilever dimensions

Geometrical Aspects	**Range (μm)**
Thickness, t	0.5-3.5
Width, w	95-120
Length, l	250-400
Width of legs, $wwllllll$	22.5-35

3. RESULTS AND DISCUSSION

The effects of geometrical aspects on piezoresistive microcantilever, such as length (l), thickness (t), and width (w) were investigated. The simulation is repeated with different materials such as Silicon, Silicon Dioxide, Poly-Si and Silicon Nitride. The length of the microcantilever ranged from 225μm to 350μm. From the simulation, the highest displacement obtained is 250.12μm when the SiO2 microcantilever is at a length of 350μm with an applied force of 2μN. The value of the applied force is chosen because surface stress and deformation changes at this level have been typically observed in many microcantilevers that act as chemical and biosensors [12]. The displacement is observed to be at the edge of the microcantilever. Figure 2 shows the deformation and stress for different dimensions of the microcantilever parameters. The least displacement is 75.75μm when the length is 225μm. Therefore, the displacement increases 3.30 times from 75.75μm to 250.12μm as the length increases from 225μm to 350μm. The thickness of the piezoresistive microcantilever ranges from 0.5μm to 3.0μm. The force of 2μN is applied during the entire simulation to observe the effect of thickness on the piezoresistive microcantilever. Through the simulation, it is observed that the displacement, stress, and strain of the microcantilever decrease as the thickness of the microcantilever is increased.

The results also indicate that a silicon microcantilever has the highest displacement of 131.81μm when the thickness is 0.5μm. However, as the thickness is increased to 1.0μm, the displacement drastically reduces to 8.68μm, which means that the deflection decreases by about 93.4%. As the thickness is increased from 0.5μm to 3.0μm, the displacement decreases until it becomes 0.34 μm, resulting in a percentage decrement in the displacement of about 99.50%. This observation agrees with Stoney's equation [13] as shown in Equation (1), where the displacement is inversely proportional to the thickness.

$$\delta = \frac{3\sigma(1-\gamma)l^2}{Et^2} \tag{1}$$

From the equation above, δ is the displacement, σ is the stress, γ is the Poisson's ratio, E is the Young's Modulus and l is the length. The stress of silicon microcantilever also falls rapidly as the thickness rise.

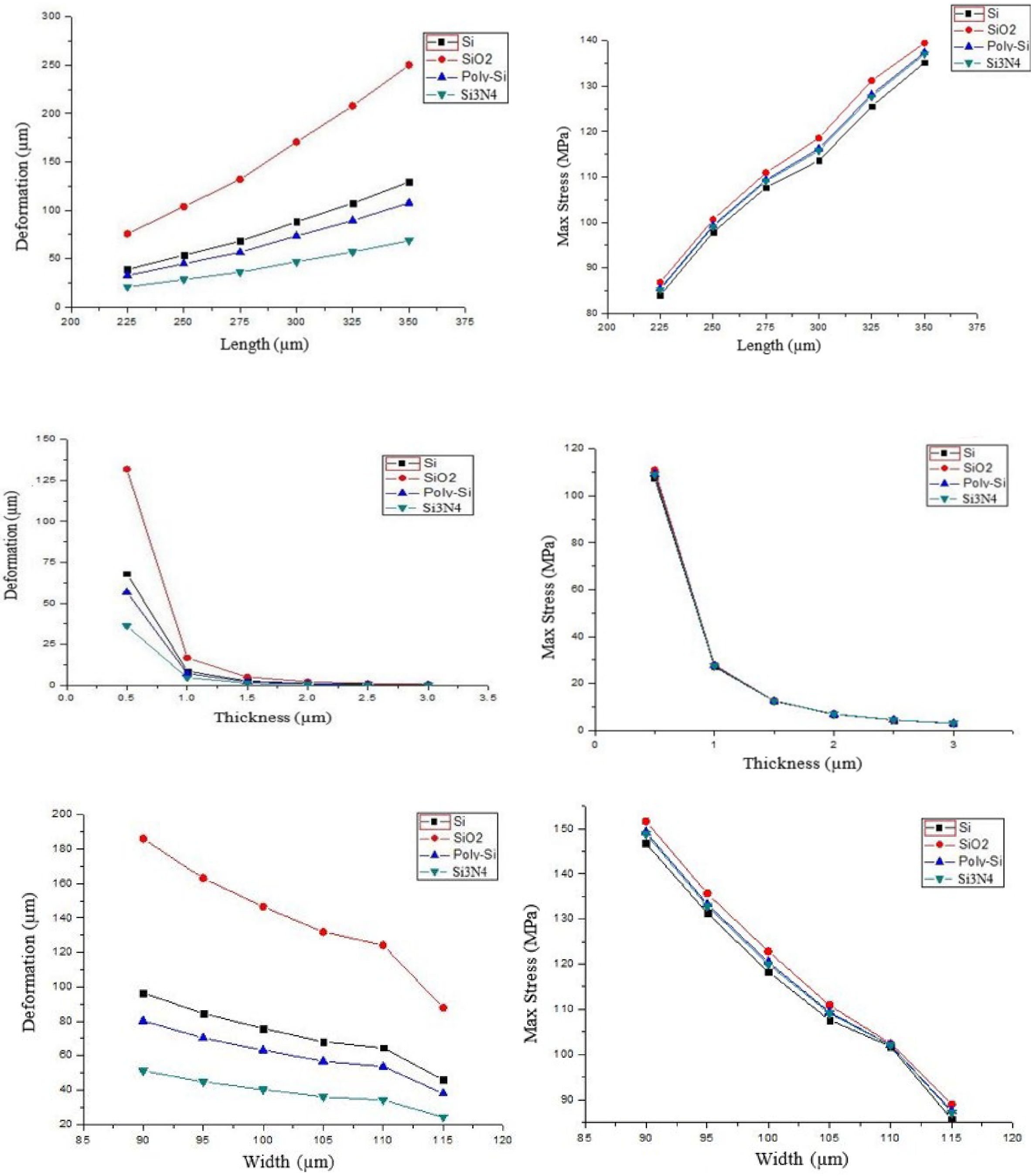

Figure 2. The graph of deformation and stress with respect to different length, thickness and width.

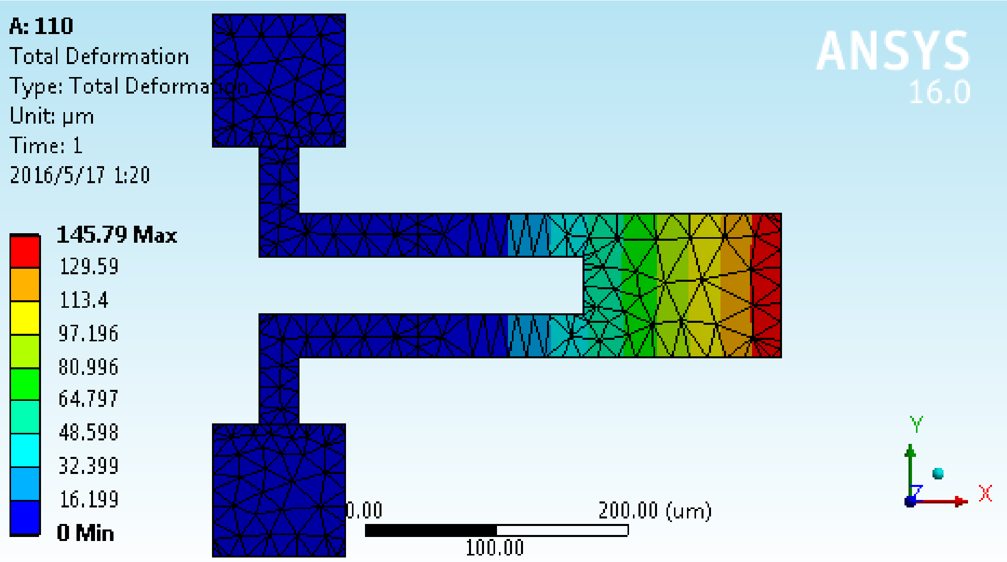

Figure 3. Simulation output of microcantilever indicating maximum displacement occurred at the end of the tip (red area).

Figure 3 shows one of the simulation outputs obtained, indicating that the maximum deformation occurs at the tip (red area). The results in Figure 2 indicates that the silicon microcantilever have maximum stress of 107.64 MPa when the thickness is equal to 0.5µm, and the stress fall drastically to 3.07MPa when thickness is equal to 1.0µm. The stress of the silicon microcantilever reduces about 97.96% from the thickness of 0.5µm to 3.0µm. The thickness of microcantilever is 3.0µm when the stress is equal to 3.07MPa. This can be explained by equation (1), the stress is inversely proportional to the thickness.

According to [2], the sensitivity of the microcantilever increases when the thickness decreases. This shows that the sensitivity is inversely proportional to the thickness of the microcantilever. That means the smaller the thickness of the microcantilever, the greater the sensitivity. Although thinner microcantilevers have higher sensitivity, there are several faults associated with them. Compared to thicker microcantilevers, thinner microcantilevers are more easily prone to breaking, and the probability of surface cracks increases during the fabrication process [14].

Stoney's equation (1) states that the displacement in the microcantilever is directly proportional to the length. Therefore, a longer microcantilever will improve the deflection. On the other hand, a thinner width of legs will decrease the spring constant of the microcantilever. As a result, the microcantilever will be stiffer and exhibit higher stress. This is followed by the strain, which is proportional to the stress. Thus, the highest strain is observed in the geometrical aspect of the width of the legs.

The width of the microcantilever is set to range from 90µm to 115µm. As the width of the microcantilever is increased, the distance between the legs remains 45µm, while the width of the legs increases from 22.5µm to 35µm. The force applied is fixed at 2µN for the entire simulation. The results show that the displacement and stress of the microcantilever decrease simultaneously as the width is increased. This can be explained by equation (2), which relates the width to the displacement and stress.

$$k = \frac{F}{\delta} = \frac{EWt^3}{4l^3} \tag{2}$$

where k is the spring constant, F is the applied force, $\delta\delta$ is the displacement, E is the Young's Modulus, and W, t and l is the width, thickness and length respectively. Increasing the width will cause the legs of the microcantilever to become thicker, resulting in a reduced spring constant. From equation (2) [1], the spring constant is inversely proportional to the displacement of the microcantilever. As the width increases, the spring constant also increases because they are directly proportional. The increased width leads to thicker legs of the microcantilever, while maintaining a distance of 45µm between the legs. For instance, when the width is 90µm, the width of each leg is 22.5µm, and when the width is 115µm, the width of each leg is 35µm. The highest displacement is 185.93µm when the width of the SiO_2 microcantilever is 90µm. On the other hand, when the width of the microcantilever is 115µm, it shows the least displacement of 87.72µm. The displacement of the microcantilever decreases by 52.8% from a width of 90µm to 115µm. At the same time, the stress of the microcantilever decreases by 41.37% as the width is increased. Similarly, the strain of the microcantilever reduces by 41.47% due to the decrease in stress.

By referring to the graph for the entire simulation, it can be noticed that silicon dioxide always have the highest output i.e displacement, stress and strain, while the silicon nitride always have the lowest output among the materials. According to [15], it is obvious that the Young's Modulus is inversely proportional to the displacement and stress. Therefore, the lower Young's modulus will produce the higher displacement and stress. From Table 2, the silicon dioxide has the lowest Young's Modulus of 70GPa and silicon nitride has the highest value of 250GPa. From the simulation, the displacement of silicon dioxide always shows the value of 72.50% higher than silicon nitride. Therefore, the silicon nitride always shows the least output and silicon dioxide have the highest output from the simulation. Even though, the SiO_2 have the maximum mechanical displacement, but it is not suitable for the single layer design because of its insulation properties. Therefore, the materials of Si, Poly-Si and Si_3N_4 are more suitable for the design [16].

Table 2 The Young's Modulus of the Materials

Material Properties	**Material**			
	Si	**SiO_2**	**Poly-Si**	**Si_3N_4**
Young's modulus (GPa)	130	70	160	250
Density(kg/m3)	2330	2200	2320	3100
Poisson's ratio	0.278	0.17	0.22	0.23

4. CONCLUSION

The effects of geometrical aspects on the performance of the piezoresistive microcantilever were characterized by varying its length (l), thickness (t), and width (w). Through simulation, it was observed that the displacement, stress, and strain increased with the length of the piezoresistive microcantilever. On the other hand, as the thickness, width of the legs, and the width of the piezoresistive microcantilever increased, the displacement, von-Mises stress, and strain decreased. Additionally, the sensitivity of the piezoresistive microcantilever increased with the increment of the stress. These results were discussed theoretically using several equations. To improve the displacement of the microcantilever, increasing the length and/or decreasing the thickness is recommended. However, increasing the length of the microcantilever cannot be done randomly, as it would make the device larger, opposing device miniaturization. Furthermore, the thickness cannot be decreased beyond 0.5µm, as it would cause the microcantilever to become too thin, affecting its structural integrity and increasing fabrication costs [13]. Another factor to consider is the effect of materials on the piezoresistive microcantilever. As discussed earlier, silicon dioxide always produces higher output values compared to other materials. This is because silicon dioxide has the lowest Young's modulus among all the materials. However, the insulation properties of SiO2 are not suitable in the single- layer design.

ACKNOWLEDGEMENTS

The author would like to acknowledge the financial support in the form of publication incentive grant from Universiti Malaysia Perlis (UniMAP).

REFERENCES

[1] Jain, V. & Verma, S. "Design and characteristics comparison of MicroCantilever for integrated sensing applications," in 2013 International Conference on Advances in Technology and Engineering (ICATE), Mumbai, India, (2013) pp. 1-4.

[2] Rahim, R. A., Bais, B. & Majlis, B. Y. “Design and analysis of MEMS piezoresistive SiO2 cantilever-based sensor with stress concentration region for biosensing applications,” in IEEE Int. Conf. Semicond. Electron. Proceedings, ICSE, (2008) pp. 211–215.

[3] Barlian, A. A., Park, W. T., Mallon, J. R., Rastegar, A. J. & Pruitt, B. L. Proc. IEEE, vol. 97, no. 3 (2009) pp. 513–552.

[4] de Oliveira, F. A. C., Monteiro, D. W., Colombo, D. M. Sensors and Actuators A: Physical, vol. 326 (2021) pp. 112709.

[5] Ghaderi, R,. Dehkordi, B. M. & Fard. A. R. Physica Scripta vol. 96 no. 11 (2021) pp. 115205.

[6] Jing, H.-X., He, X.-T., Du, D. W., Peng, D.-D., Sun, J.-Y. Appl. Sci. vol. 10, (2010) pp. 5557.

[7] Wang, L., Tong, X., Yang, H., Wei, Y. & Miao, Y. Int. J. Pavement Res. Technol. vol. 12, (2019) pp. 259–268.

[8] Zakaria, M. H., Bais, B., Rahim, R. A. & Majlis, B. Y. “Geometrical characterization of single layer silicon based piezoresistive microcantilever using ANSYS,” in 2012 10th IEEE International Conference on Semiconductor Electronics, ICSE (2012) pp. 336–339.

[9] Chivukula, V., Wang, M., Ji, H., Khaliq, A., Fang, J. & Varahramyan, K. Sensors and Actuators A, vol. 125 (2006) pp. 526–533.

[10] Y. Tang, J. Fang, X. Yan, & H. Ji, “Sensors and Actuators B: Chemical, vol. 7, no. 1, (2004), 109-113.

[11] Doll., J. C. & Pruitt., B. L. “Piezoresistor Design and Applications” Springer, (2013)

[12] Butt, È., Skla, P., Raiteri, R. & Grattarola, M. Sensors and Actuators B: Chemical, vol. 79, Issues 2–3, (2001) pp. 115-126.

[13] Bao, M. “Chapter 2 - Mechanics of Beam and Diaphragm Structures,” in Analysis and Design Principles of MEMS Devices, M. Bao, Elsevier Science, (2005) pp. 33-114.Ansari, M. Z. and Cho, C. Sensors, vol. 8(11) (2008) pp. 7530-7544.

[14] Jones, D. R. H. & Ashby, M. F. “Engineering Materials 1 An Introduction to Properties, Applications and Design,” 5th Edition, London, Elsevier (2019) R. A. Rahim, B. Bais, B. Y. Majlis & S. Fareed, "Design optimization of MEMS dual-leg shaped piezoresistive microcantilever," RSM 2013 IEEE Regional Symposium on Micro and Nanoelectronics, Daerah Langkawi, Malaysia, (2013) pp. 379-382.