Design and Analysis of Various Microcantilever Shapes for MEMS Based Sensing

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Abstract. One the major requirements for sensing devices is its sensitivity. This paper presents the design, analysis and simulation of various types of MEMS based microcantilevers shapes and their influence on sensing sensitivity. A commercial finite element analysis software ANSYS is used to analyze the designs. Six different analytical model of the microcantilever were investigated for its Equivalent (von-Mises) stress, maximum deflection and fundamental resonant frequency. Finally, the best sensitive structure is then identified. It is found that the trapezoidal design microcantilever would have significant sensing advantages compared to other remaining microcantilever shape.

1. Introduction

In the mid-1990s, the interest of cantilever-based sensing has initiated due to the advent of atomic force microscopy (AFM) application [1]. However, recently it has taken wide surge interest since it is now made commercially available. Apart from that, microcantilever is the most MEMS versatile structure as it can be used as physical, chemical or biological sensor by detecting the changes in cantilever bending or vibration frequency. A general structure of microcantilever is shown in Figure 1 where a cantilever is actually a beam rigidly supported at one end, or in the middle, but not at both ends, which has forces applied along the free arm or at the free end [2]. Compared to conventional sensor, microcantilever based sensing has very high sensitivity, short response time and low power operation due its miniature in size.

Figure 1. General structure of a microcantilever
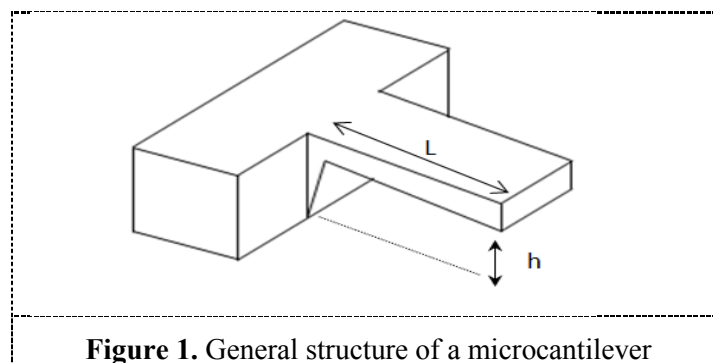
One of the sensing methods done was to coat the microcantilever with a piezo material thin film which in this case is zinc oxide, to achieve the resistive deflection readout [3]. In the case of chemical-sensing applications, due to chemical reactions, such as the platinum-assisted catalytic conversion of hydrogen and oxygen into water, the deflection of the cantilever happened at very high sensitivity [4].

One of microcantilever most current research is as a platform for gas sensing application. Microcantilevers that are used to sense the presence of a certain particle or analyte are coated with a chemically sensitive material. This material will provide a high degree of specificity in detecting certain particles or analytes within a sample.This deflection of micro cantilever occurs when a specific mass of an analyte is specifically adsorbed on its surface. As a result, it would produce a deflection at the free end when a force is applied.

Figure 2. General structure of a microcantilever for gas sensing application
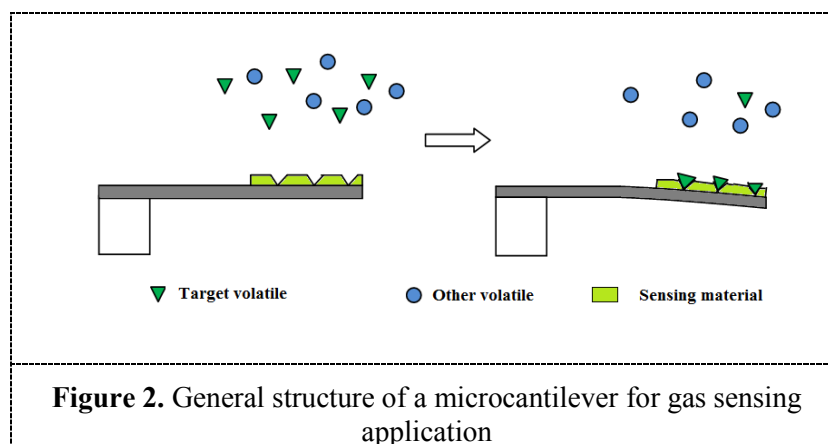
For sensing, microcantilever relies on their flexibility or elasticity to create some type of measurable change when exposed. The reaction of the cantilever is referred as mechanical stress and would result in a change either the cantilever mechanical or electrical properties. The most common properties used to measure this change the microcantilever's natural resonant frequency, angular deflection or resistivity. This technique can be used to directly measure surface stress changes and as a sensing mechanism by functionalizing one surface of the cantilever with a specific detector layer [5].

To obtain an application specific optimum design parameter and predict the cantilever performance, ANSYS workbench V12.0 software was used. The microcantilever size leads to significant advantages in the absolute device sensitivity. Precise measurement of the deflection at the end of the cantilever was achieved through this arrangement.

II. Design Parameter of Cantilever

A cantilever is a beam fixed firmly at only one end and left freely at other end. The beam carries the load to the support where it is resisted by moment and stress.

The structure is made up of silicon single crystal where the fracture strength of silicon is 7000 MPa [6] while other properties as shown in the table 1.

Table 1 Material Properties used

	Value	*Conditions*
Density	2330 kg/m^3 [7]	Solid Density
Poisson's ratio	0.22[8]	Silicon Substrate, isotropic & linear thermo elastic
Young's modulus	165GPa[8]	Silicon Substrate, isotropic & linear thermo elastic

Resonant frequency is the frequency of a system at which it oscillates at maximum amplitude. With little damping, this frequency is usually equal to the system's natural frequency. When a system reaches this resonant frequency, this state is resonance. As the mass of the system changes, so does the resonant frequency.

$$(\omega^o) = \sqrt{\frac{k}{m}} \qquad (1)$$

Natural frequency

$$(k) = \frac{Et^3w}{4t^3}) \qquad (2)$$

Spring constant

The natural frequency (ω^o) of a cantilever is related to its spring constant (k) and mass (m). This is also applies for both macro and microcantilever. For a rectangular cantilever beam, the spring constant (k) is a function of

E = Young's modulus of Elasticity (a property of the material)
w = Width of the beam
l = length of the beam
t = thickness of the beam

Young's modulus of Elasticity (E) is the measure of the stiffness or elasticity of a given material. The stiffer or less elastic a material is, the higher the E value. Young's modulus allow the behaviour of a material to be evaluated under load or stress.

The fundamental frequency of vibration is

$$f = \frac{1}{2\Pi} \bullet \sqrt{\frac{k}{m}}) \qquad (3)$$

For a rectangular profile microcantilever, the differential surface stress ($\Delta\square$) and deflection (Δz) are related to Stony equation given as [3] :

$$\Delta z = \frac{4(1-v)\,\Delta\sigma}{E}\left(\frac{l}{t}\right)^{2})$$

(4)

where l and t are the length and the thickness of the cantilever, and E and v are the elastic modulus and Poisson ratio of the cantilever material.

The fundamental resonant frequency (f_o) for rectangular profile cantilever of mass density (m) is given as

$$f_o = \sqrt{\frac{E}{m}} \bullet \frac{1}{t^2})$$

(5)

For a microcantilever of trapezoidal profile, $t(x) = t_l + (t_o - t_l)\,x/l$, the Stoney equation(4) can be given as

$$\Delta z = \frac{3(l-v)\Delta\sigma l^2}{E(t_o - t_1)^2}\left[\ln\left(\frac{t_o}{t_1}\right) + \frac{t_1}{t_o} - 1\right]$$

(6)

The geometric structure of the cantilever beam and also the properties of the material used to construct the shapes of cantilever determine the stiffness of the cantilever. Thus the sensitivity of the cantilever beam changes with the change is shape of the cantilever.

The design and dimension of the microcantilever used in the research is summarized in figure 3. Different microcantilever design based on trapezoid and rectangular structure with double and single legged structure were designed and simulated.
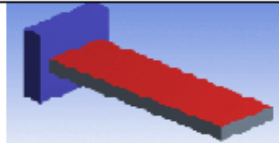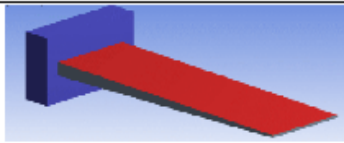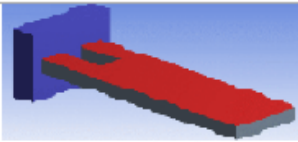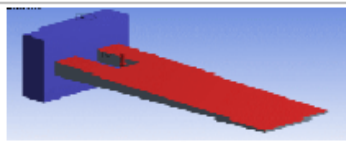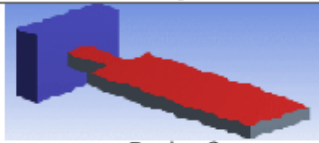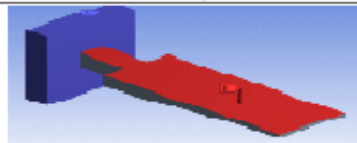

Microcantilever Dimension x= 110 μm , y =50 μm, z= 40 μm		Microcantilever Design
Design 1	Design 4	Rectangular/ Trapezoid
Design 2	Design 5	Double-legged Rectangular/ Trapezoid
Design 3	Design 6	One-legged Rectangular/ Trapezoid

Figure 3. Schematic Design of Microcantilever

III. Simulation results

Using static structural analysis in Mechanical (ANSYS Multiphysic) which uses the ANSYS solver, static structural analysis were performed. Structural analysis determines the Equivalent Elastic Strain, Equivalent Stress and total deformation in structure or components caused by loads that did not induce significant. In this static structural analysis, all the designs in figure 4 were applied with 50uN on the surface in the downward direction. It is assume that there were steady loading and response conditions for area.

For Equivalent (von-Mises) stress analysis, equation (7) are used for finding the strain value.

$$\sigma_e = \left[\frac{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2}{2} \right]) \qquad (7)$$

For Equivalent (von-Mises) stress comparison (figure 4), maximum strain for all six microcantilever design was simulated and compared. It was found that the trapezoidal design microcantilever would have a slight higher strain compared to rectangular design microcantilever.
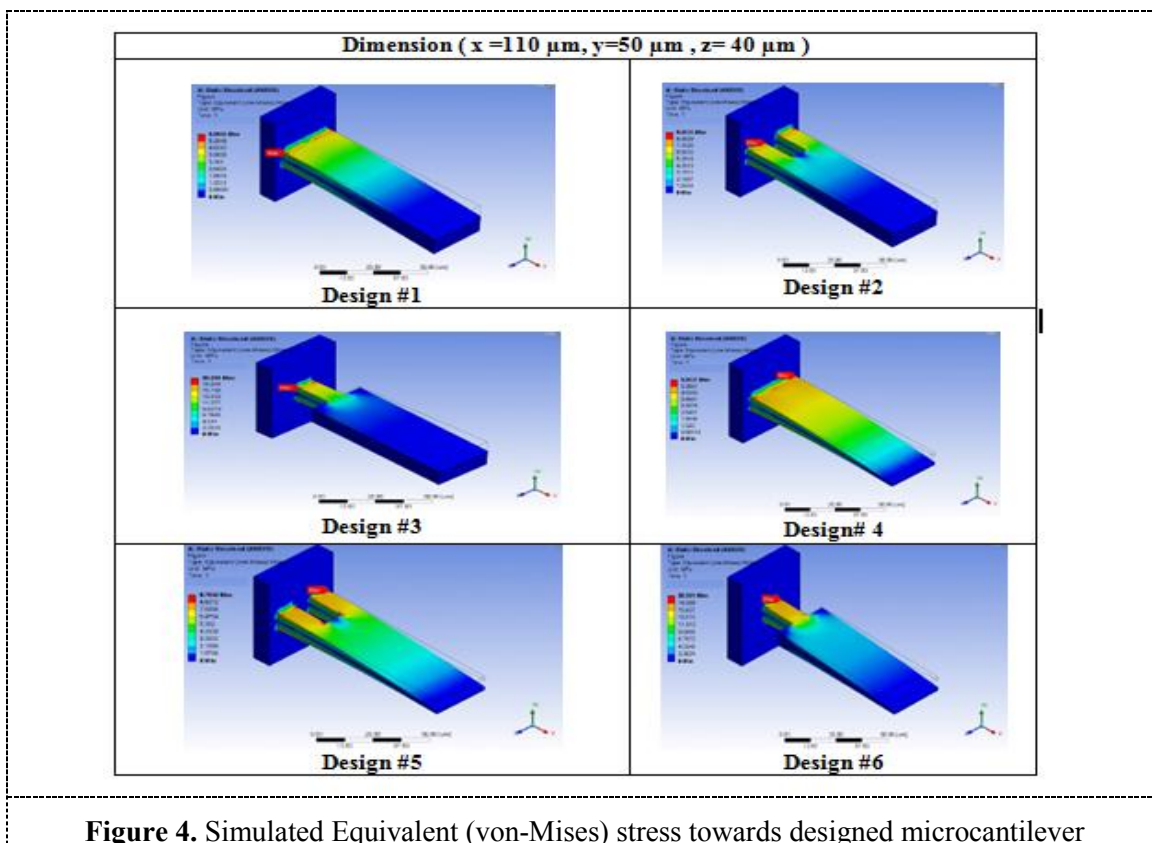

Figure 4. Simulated Equivalent (von-Mises) stress towards designed microcantilever

For example, in figure 5, there was 0.13% strain difference between rectangular microcantilever and trapezoid microcantilever. When double-legged design was simulated, strain difference between rectangular microcantilever and trapezoid microcantilever was found to increase by 59%. The highest Equivalent (von-Mises) stress was simulated on the one-legged trapezoid microcantilever where the maximum strain increased significantly to 20.361Mpa compared to the double-legged trapezoid microcantilever.
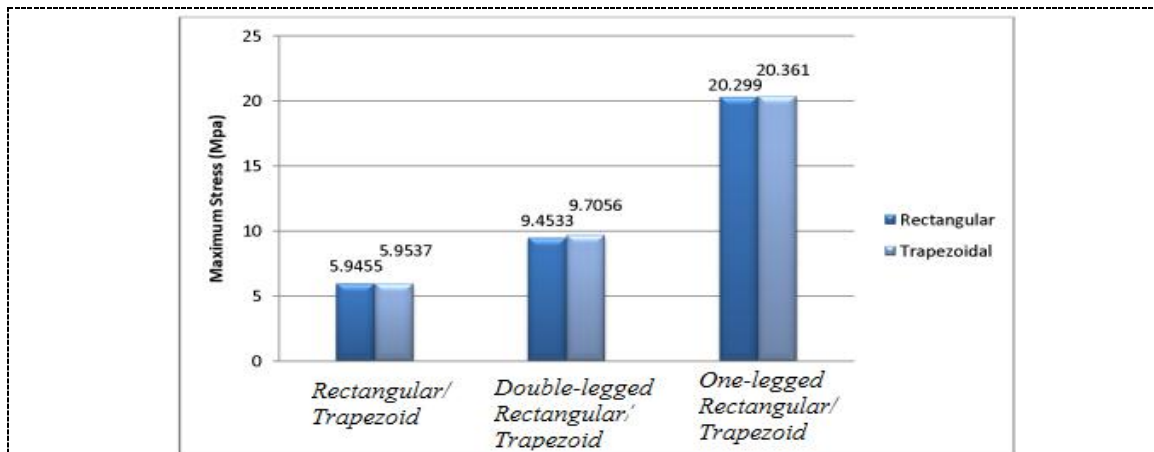
Figure 5. Comparison of Equivalent (von-Mises) stress result of the microcantilever design

For displacement comparison (figure 6), maximum displacement for all six microcantilever design was simulated and compared. For the displacement comparison, there is a significant displacement difference between the rectangular microcantilever and trapezoid microcantilever design.
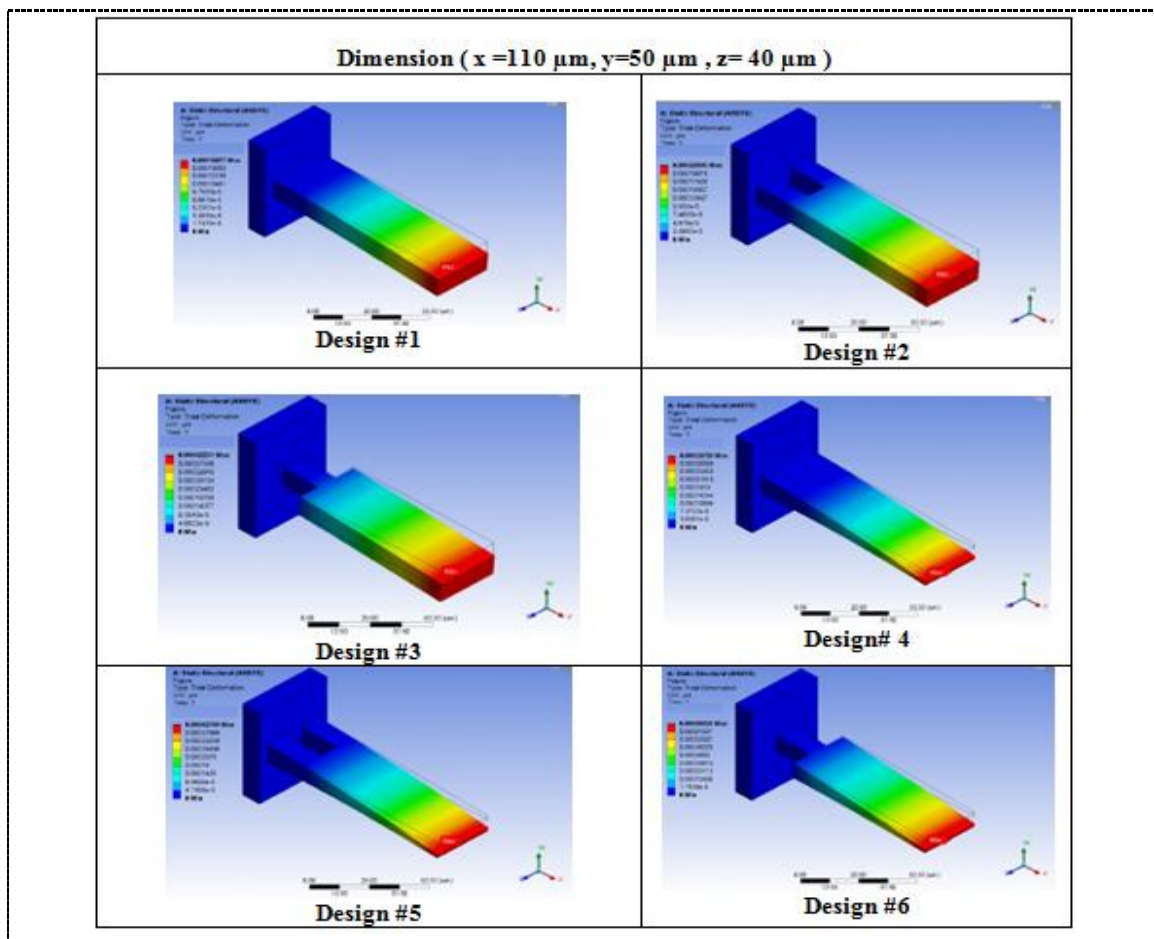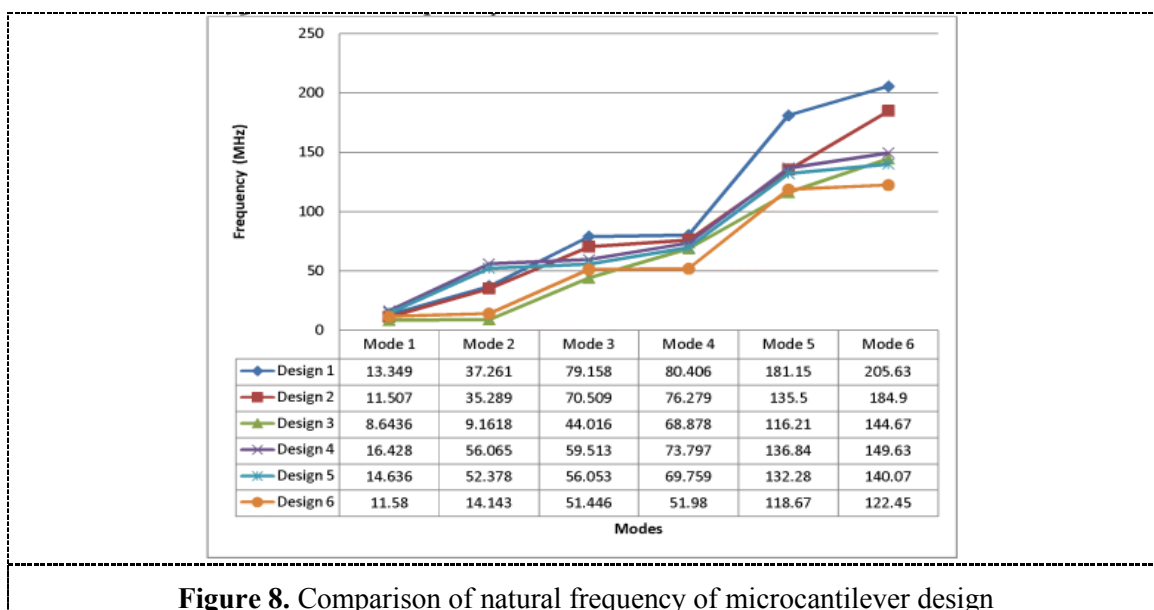

Figure 6. Simulated displacement result of designed microcantilever

As in figure 7, shows the comparison between rectangular and trapezoidal shape. The 50 µN load is given to the microcantilever surface. For rectangular microcantilever shape, it showed an increased of displacement from between design 1 to design 3. However, the displacement value for the trapezoidal microcantilever shape increased to about 2 times more for the rectangular microcantilever shape.

Figure 7. Comparison of displacement result of the microcantilever design
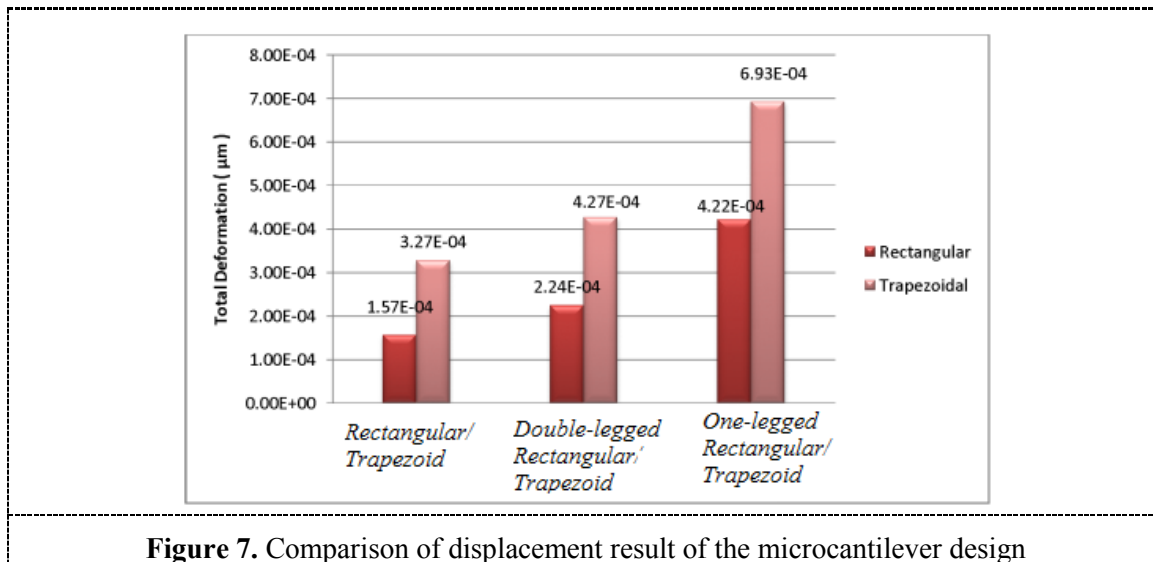
Next, using ANSYS solver, natural frequency for each mode using was compared as in figure 8. Natural frequencies and mode shapes are important parameters in the design of a structure for dynamic loading conditions. In this analysis, we determine 6 modes of natural frequency and mode shape for each design to determine the level of flexibility of each design.

	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5	Mode 6
Design 1	13.349	37.261	79.158	80.406	181.15	205.63
Design 2	11.507	35.289	70.509	76.279	135.5	184.9
Design 3	8.6436	9.1618	44.016	68.878	116.21	144.67
Design 4	16.428	56.065	59.513	73.797	136.84	149.63
Design 5	14.636	52.378	56.053	69.759	132.28	140.07
Design 6	11.58	14.143	51.446	51.98	118.67	122.45

Figure 8. Comparison of natural frequency of microcantilever design

In figure 8, we can see that microcantilever trapezoid design has a higher natural frequency than rectangular microcantilever design.
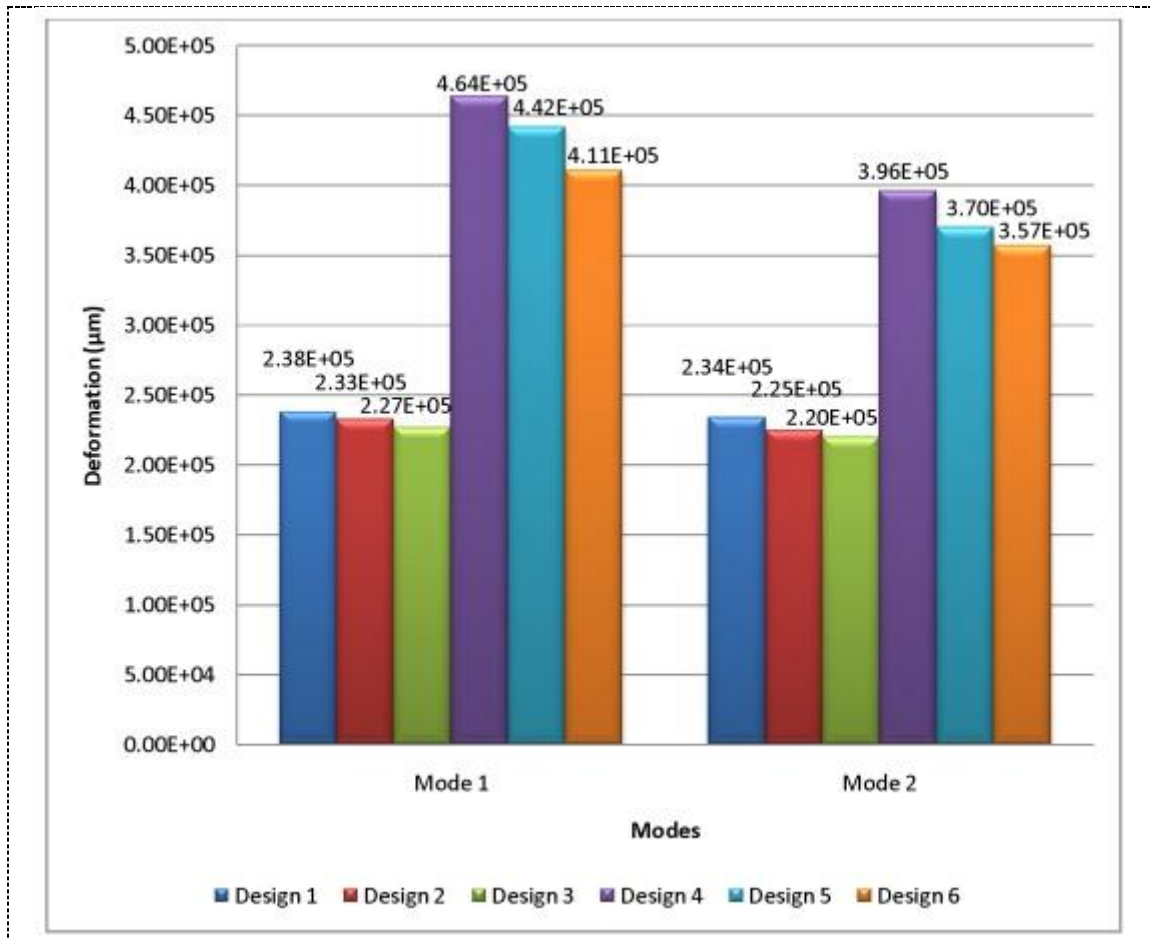

Figure 9. Simulated displacement result of designed microcantilever using mode 1 and mode 2

Next, using the mode 1 and mode 2 value, comparison of the displacement of the microcantilever design were analyzed. In figure 9, the sensitivity of the microcantilever were calculated by determing the value ΔZ* Freq.

ΔZ is the deformation value and freq is the frequency of mode 1. From the table 2, design 4 shows highest value of ΔZ* Freq followed by design 5 and design 4. This shows that the design 4 would be the most suitable design for dynamic mode operation.

Table 2 Sensitivity values of microcantilever design shape

	Deformation, ΔZ	*Frequency, MHZ*	*ΔZ* Freq*
Design 1	2.38×10^5 µm	13.349	3.18
Design 2	2.33×10^5 µm	11.507	2.68
Design 3	2.27×10^5 µm	8.6436	1.96
Design 4	4.64×10^5 µm	16.428	7.62

| Design 5 | 4.42 x 10^5 μm | 14.636 | 6.47 |
| Design 6 | 4.11x 10^5 μm | 11.58 | 4.76 |

IV. Conclusion

One of the most MEMS versatile structures available is microcantilever where it is used in many type sensing application. However, typical microcantilever shape available is in the form of uniform rectangular beam. In this research, microcantilevers of various shapes have been designed and their displacement, stresses, natural frequency and mode shape were analyzed when the same amount of force is applied. The highest Equivalent (von-Mises) stress was simulated from the one-legged trapezoid microcantilever shape where the maximum strain increased significantly to 20.361Mpa compared to the other microcantilever. However, since the fracture stress value for the material is much higher, this indicates that the cantilever is reliable enough for detection and will break under normal conditions. Another observation is on the microcantilever displacement analysis. The trapezoidal design microcantilever would have significant displacement compared to rectangular design microcantilever where the value for the trapezoidal microcantilever shape increased to about 2 times more than the rectangular microcantilever shape. This is important as with the same amount force applied, the trapezoidal design microcantilever was able to deflect more thus contributing to higher resistive value contribute by the piezoresistive material and ultimately, increasing the microcantilever sensing sensitivity. Design 4 showed the highest value of ΔZ* Freq than the other microcantilever design. For dynamic mode operating modes where the microcantilever is used especially to extract and sensing mass changes, design 4 would be the most suitable design due its sensitivity. Finally, based on the result of this investigation, we can conclude that the trapezoidal microcantilever shape has better overall sensitivity than the rectangular microcantilever shape due its better deflection and resonant frequency characteristics.

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