Enhancement of the Sensitivity of a Piezoresistive Sensor using SCR's Orientation

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SEP, 2014

Declaration

I certify that this research work titled "*Enhancment of the Sensitivity of a Piezoresistive Sensor using SCR's Orientation"* is my own work. The work has not been presented elsewhere for assessment. The material that has been used from other sources it has been properly acknowledged / referred.

Signature of Student

Tayyab Shahid

2011-NUST-MSPhD-Mts-33

Language Correctness Certificate

This thesis has been read by an English expert and is free of typing, syntax, semantic, grammatical and spelling mistakes. Thesis is also according to the format given by the university.

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Tayyab Shahid

2011-NUST-MS PhD-Mts-33

Signature of Supervisor

Copyright Statement

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Dedicated to my exceptional parents and adored siblings whose tremendous support and cooperation led me to this wonderful accomplishment

Abstract

The sensitivity of a piezoresistive sensor holds great importance in case of bio-medical applications. In this paper, we will discuss how to enhance the sensitivity of a cantilever based piezoresistive sensor. The methodology behind this enhancement is, creating Stress Concentration Region (SCR) on the beam. These SCRs are created by introducing defects on the beam. When these Stress Concentration Regions are introduced in the cantilever beam through any means of fabrication process; they distribute the surface stresses present on the cantilever beam under load. This distribution increases the surface stresses around the defect. As the defect is near to the piezoresistive layer; diffused or deposited on the cantilever beam; the surface stress will tend to increase the strain and longitudinal deflection around the piezoresistive surface. This increase in the strain will ultimately lead to increase in change in resistivity.

After plotting the change in resistance against the applied load, the slope of the curve will give us the sensitivity of the piezoresistive sensor. This paper will discuss the methods to enhance the sensitivity to optimal level without critically damaging the peizoresistive sensor. With the introduction of an optimal defect (Star design), selecting the optimal geometrical aspects or parameters of the defect and in comparison with the previous defects, this paper will lead to an enhanced sensitive piezoresistive sensor.

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CHAPTER-1: INTRODUCTION

1.1 Background and scope:

Micro-Electromechanical System (MEMS) device has created a milestone in these emerging Silicon technologies of the 21st century. The reason behind this hall mark technology is the tendency to sense, compute and control; all by a single chip. MEMS cantilever piezoresistive sensors on the other hand, are growing popular in bio-chemical and bio-molecular devices. The reason behind this popularity is the simple and inexpensive setup. Another reason is that it requires no additional supportive devices as compared to optical detection (which is an expensive setup and cannot be used in point of care applications). In any electronic device, the key factor that proves its worth is its sensitivity. A device capable of detecting the smallest changes in the input and give a substantial output. This relationship among the force and electric output is being exploited in bio-chemical and bio-molecular technology. Normally one cannot compare a piezoresistive resistor with a metal strain gauge, although both show the same output. The basic difference between piezoresistive resistor and metal strain gauge is the material and its physical properties. In piezoresistor, silicon crystal is doped or deposit on the semi conductor; unlike strain gauges which have metal deposit on the semi conductor devices. The difference in gauge factor between strain gauge and piezoresistor is also comparable. Metal strain gauges have gauge factor to 10-25 whereas, piezoresistor can have up to 120. So in short, a piezoresistive resistor is a more sensitive device as compared to a metal strain gauge due to large gauge factor.

A cantilever based system depends upon the mechanical properties of the sensor [1]. So if we alter the mechanical properties of the sensor, the capability to detect the smallest change in the displacement and produce its equivalent output will definitely increase. There are many methods to optimize the sensor's sensitivity. For example, changing the design of the beam leads to change in properties; doping levels embedded supportive devices that optimize the sensitivity etc. C. Pramanik et al. discussed the enhancement of sensitivity of a piezoresistive pressure sensor by creating pressure bossed diaphragms structures on the embedded on porous silicon oxide. Shushen Huang et al. designed a high performance beam by creating pure axial stressed tiny beams embedded on the piezoresistive cantilever beam. The designer fabricated the beams in such a way that when deformed, the beam is axially stressed which increases the surface stress of the cantilever beam. This increase depends upon the distance between the tiny axial stressed beams and central supportive cantilever beam. Another approach used to maximize the sensitivity is to increase the doping level during fabrication. Xinxin Li proposed a method that will optimize the sensitivity of a piezoresistive sensor, if it is doped heavily with boron atoms. Doping the beam with boron atoms will lead to enhanced structural properties of the Cantilever beam ultimately improving its sensitivity. The latter method is further improved and used in piezoresistive accelerometers and pressure sensors.

These are the few methods to improve the sensitivity of a piezoresistive cantilever based sensor. The method of optimization of the piezoresistive sensor discussed in this paper is by creating

Stress Concentration region (SCR) on the cantilever beam. SCR are the highly distributed stressed regions that are created with introduction of defects. These defects converge the stress towards itself creating Stress Concentrated Regions near the defects. These Stress Concentration Regions will maximize the differential stresses present on the surface of the beam which will ultimately lead to the optimization of the sensitivity. This way we can successfully optimize a sensitivity of a beam in comparison with a beam with no defects. This method was introduced by Yu Xhang; when he proposed the Finite Element Analysis (FEA) solution to optimize the sensitivity of a piezoresistive sensor used in bio-medical purposes. The SCR is a simple approach with no requirement of high tech equipment (Like deposition equipments LPCVD which are required in doping approach). It only requires a mask of a defect that needs to be etched on the surface of the beam. It was a simple approach with less disadvantages as compared to the optimizing technique like doping with heavily doped boron atoms, designing a supportive beams and other approaches. This paper optimizes the sensitivity of a piezoresistive sensor by creating a new and optimal defect (Star Defect). This defect will ensure the increase in the surface stress around the defect, which will lead to the improvement in the sensitivity of a piezoresistive sensor. Furthermore, it will improve the geometrical aspects of the defect which will enhance the sensitivity to the optimal level requirement.

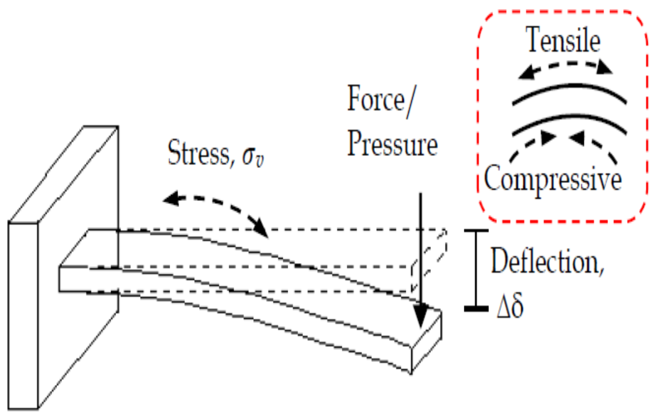


Fig 1: Deformation of a Cantilever Beam [12]

Figure 1shows the simple mechanism of the cantilever beam. A single end cantilever beam bends when an applied force or pressure is applied on the free end of the beam. These causes the tensile and compressive stresses to propagate towards the maximum stress point that is fixed end of the cantilever beam.

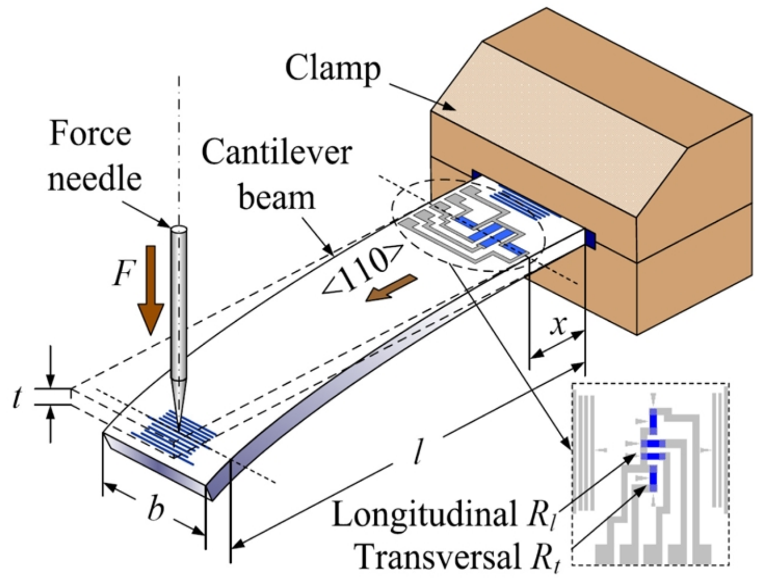


Figure 2: A piezoresistive resistor with a <110> cantilever beam

The above figure shows the mechanism of cantilever beam in contact with the piezoresistive sensor. The force causes the bending and strain at the fixed end. The active regions of the piezoresistive are changed as compared to the passive regions of the piezoresistive sensor. This change is actually the measurable output.

1.2 Terminologies and abbreviations:

The terminologies and abbreviations used in this thesis are as follows:

- SCR- Stress Concentration Region
- MEMS- Micro Electro Machined System
- FEM- Finite Element Modeling
- FEA- Finite Element Analysis
- LPCVD- Low-Pressure Chemical Vapor Deposition
- $\prod_t$- Transverse piezoresistive coefficient
- $\prod_l$- Longitudinal piezoresistive coefficient
- σ_t- Transverse stress
- σ_l – Longitudinal stress
- CAD-Computer Aided Design
- ΔR- Change in resistance

1.3 Thesis statement:

Piezoresistive effect is one of the most exploited effects in the current era of silicon technology. This effect is used in all the application which requires change in resistance with respect to applied load. This change of resistance is a variable and will give respective output depending upon the system integrated with the output (like pressure sensor, electrical output e-t-c). The enhancement approach that is introduced in this research is through creating Stress Concentration Region (SCR). Stress Concentration Regions are created when a defect (through hole) is introduced on a cantilever beam based piezoresistive sensor. This defect disturb the uniform stress regions and creates concentrated stress (principal stresses, normal, transverse e-t-c) regions around the defect. The motivation behind this approach is that it is a simple approach. It doesn't require any high technology equipment and research group. It is also cost effective. It only requires a separate mask which will be fabricated on the beam. This technique can ensure an enhanced sensitive piezoresistor with a simple approach, without usage of any high tech equipment which will make this approach a more cost effective than the previous approach.

1.4 Rationale:

The aim of this research is to design and develop an optimal sensitive MEMS piezoresistive with introduction of low cost enhancement method (No requirement of high tech deposition equipment) which has all the attributes of the MEMS piezoresistive sensors. This research is a simple approach; which include the introduction of Stress Concentration Regions on the cantilever beam of a piezoresistive sensor. This introduction can be made in the cantilever beam of the piezoresistive sensor by any micro-fabrication technique available in MEMS field. This research is basically targeted at microbiological applications where sensitivity matters. For example, there is a stiffness test on the broken or fractured bones of patient. This sensor is attached at the bones. To check the stiffness of the bones, a calculated load or pressure is applied on the bone. The bone will resist that load and that resistance will give the stiffness of the bone as an output. This output is measured by the doctor and with comparison with daily stiffness test; the doctor can state that the patient is recovering. For this test, the piezoresistive sensor needs to be highly sensitive because it has to be sensitive to detect a slightest value of stiffness of the sensitive bones; present in the patient to give the indication of recovering the bone.

Normally by depositing the heavy boron atoms is a very expensive method. A highly doped heavy boron piezoresistive sensor cannot be commercialized in the MEMS market because of the expensive equipment purchase cost and its setup cost. This research will help to design and to fabricate a low cost sensitive piezoresistive sensor which will assist the MEMS market to commercialize this product. This way, MEMS industry will exploit this commercial piezoresistive sensor and will have a chance to flourish in near future

1.5 Objectives:

The objectives of this thesis include:

- A complete design of a piezoresistive sensor
- Designing the cantilever beam of the piezoresistive sensor
- Designing the piezoresistive layer

- Integrating the beam with the piezoresistive layer
- Selecting the boundary conditions, initial values and setting the constratins and loading points.
- Analyzing the beam and calculating the maximum surface stresses which includes longitudinal stress and transverse stress
- Analytically calculating the change in resistance and sensitivity.
- Plotting the results and comparing it with other defects.
- Further improving the defect in case of geometrical aspect and position of the defect.
- Simulate the optimal star defect and compare with the previous one.
- Give the micro fabrication technique to create or develop a defect on the cantilever beam of piezoresistive sensor.

1.6 Research type:

The main focal point of this research is to design and develop an optimal sensitive pieozresistive sensor for bio sensing and bio molecular sensing applications. The main requirement behind this enhancement in sensitivity is for detection of smallest changes happening in bio molecular and bio medical applications. The previous approaches for example doping the piezoresistive layer with heavy n-type atoms (boron, carbon e-t-c); which will increase the linear deflection of the cantilever beam and this deflection will lead to enhanced sensitivity of a piezoresistive MEMS sensor; were too expensive to design and fabricate. It requires expensive equipment with high setup cost and technical support cause. Also the process is too complex for the technical staff to understand it and it will cost more time and money to train the technical staff. So a piezoresistive MEMS based sensor; fabricated by this method cannot be commercialize in the market due to such high equipment and setup cost.

For this reason, a low cost and simpler approach is introduced to tackle this high cost and complexity issue. The enhancement of the sensitivity of a piezoresistive sensor through Stress Concentration region is simpler, low cost and requires no setup time as compared to the method of fabricating it using heavy boron dopants. By this simpler approach, a low cost fabrication approach can be introduced which will help the MEMS market to commercialize this low cost piezoresistive MEMS sensor

1.7 Methodology:

The methodology behind designing the piezoresistive MEMS sensor is to first design the most important feature of this piezoresistive MEMS sensor which is cantilever beam attached at fixed end. Design the cantilever beam and then design the piezoresistive layer. Assemble the piezoresistive layer on the cantilever beam and form a contact pair between them. This assembly would be described more commonly as a “union property” in terms of physical or environmental considerations. By "union property" means that stress, strain, deformation and many other physical properties will be applied equally on both layers. After integrating both layers, introduce a Stress Concentration Region using a defect. For example, introduce a Star defect on the cantilever beam. After that the designing phase is over. Next step is the assignment of materials for both layers. After assigning the materials (material properties are assigned automatically by COMSOL software; although user can change it), the next step is the assigning of boundary loads, fixed constraints, initial values e-t-c. For this step add the values of the boundary load, assigned the fixed constraint and then go to simulation part. Analyze the data. Compare the results with the previous defects and note in tabular form. After that, select the optimal radial area and position of star defect from the fixed end. Simulate it and compare it with previous star defect and state the improvement. Next step is the completed design of piezoresistive MEMS sensor. This design will be used for fabrication. Although you can use this design for accurate result in terms of change of resistivity.

1.8 Resource:

The major resource areas for this thesis paper consist of papers on MEMS based piezoresistive sensor based cantilever beam. This research resource describes the basic objectives and requirements for high sensitive piezoresistive sensor. Another resource is the enhancement of the sensitivity using Stress Concentration Region and its introduction in MEMS. This resource assists this thesis research in terms of enhancing the mechanical properties of peizoresistive sensor. This enhancement will ultimately improve the change in resistivity or sensitivity of a piezoresistive MEMS sensor. It also state the introduction of defect in the cantilever beam and its fabrication method for both defect and piezoresitive sensor. Another resource is the tutorials of COMSOL Multiphysics to help the analysis part of this thesis paper. These tutorials assisted in acquiring the useful results (surface stress, strain, deformation, strain energy and other mechanical properties) required to state the fact that stress concentration regions create a better sensitive piezoresistive sensor as compared with the sensor with no defects. Last resource is the applications that require high sensitivity for piezoresistive sensor. This resource area describes the need for high sensitive piezoresistive sensor for micro-biological purposes where small change needs to be detected for accurate results.

CHAPTER 2: LITERATURE REVIEW

2.1 Research Contribution:

2.1.1. Through embedded membranes:

In MEMS capacitive microphone design, it is very critical to get highest yielding rate and sensitivity as the two major factors dominate structure design of microphone. The central post MEMS microphone is introduced in this paper to differentiate from traditional fixed membrane boundary microphone since the construction is simple and only few masks are required in the process so that the yielding can be greatly enhanced.

2.1.2 By axially stressed tiny cantilever beams:

A high-performance micro machined piezoresistive accelerometer, consisting of two axially stressed tiny beams combined with a central supporting cantilever, is developed for both much higher sensitivity and much broader bandwidth compared with conventional beam-mass piezoresistive accelerometers. With the pure axial-deformation scheme of the tiny beams, the developed accelerometer shows improvements in both sensitivity and resonant frequency. An analytic model is established for the pure axial-deformation condition of the tiny beams by adjusting the distance between the tiny beams and the central supporting cantilever. The specifications of the device, such as sensitivity and resonant frequency etc, are theoretically calculated.

2.1.3 By using Finite Element Analysis of cantilever beam by introducing Stress Concentration Region:

This paper uses finite element method to obtain the optimal performance of piezoresistive microcantilever sensor by optimizing the geometrical dimension of both cantilever and piezoresistor. A 250 μm x 100 μm x 1 μm SiO_2 cantilever integrated with 0.2 μm thick Si piezoresistor was used in this study. The sensor performance was measured on the basis of displacement sensitivity and surface stress sensitivity.

2.1.4 Through doping concentration:

This paper investigates the characteristics of silicon piezoresistors with various doping concentrations and Length/Width dimensions at micro level. The silicon cantilever beam has been produced by conventional fabrication methods. But for deposition of boron concentration; LPCVD equipment is introduced. By depositing the boron concentrated layer we enhanced the mechanical properties of the beam. This enhancement will ultimately lead to the optimal sensitivity.

2.1.5 SCR and their effect on sensitivity:

These are the few methods to improve the sensitivity of a piezoresistive cantilever based sensor. The method of optimization of the piezoresistive sensor discussed in this paper is by creating Stress Concentration region (SCR) on the cantilever beam. SCR are the highly distributed stressed regions that are created with introduction of defects. These defects converge the stress towards itself creating Stress Concentrated Regions near the defects.

2.2 Research Methodology:

Stress Concentrated Region SCR is the discontinuous shapes introduced in the beam to create enhanced stresses around these defects. These defects can be in shape of grooves, sharp edges and key ways e-t-c. The main theme of this approach is to distribute the maximum stress at the end of the beam and converge it to the position where defects are created so that the surfaces stresses can be enhanced [3]. These surface stresses tend to increase the resistivity of a cantilever beam piezoresistive sensor [4]. According to the text book "Analysis and Design Principles of MEMS" Ref: Chapther 6, the change in resistivity can be calculated by using following formula:

$$\frac{\Delta R}{R} = \pi_l \sigma_l + \pi_t \sigma_t \tag{1}$$

Equation 1 is the generic form of the resistivity relation with the stresses. In this paper, n-type piezoresistor case is discussed. If the piezoresistive thickness and length is very small as compared to the cantilever beam, then stress over the area can be approximated as point stress. As shown in figure 2, a <110> direction of cantilever beam [4]. By <110> direction cantilever beam piezoresistor means that the cantilever maximum perimeters are in <x axis> and in <y axis> which are in this case length and width. The load in this case will be applied in <z axis>. In equation 1, $\prod_l$ is the longitudinal piezoresistive coefficient, σ_l is the longitudinal stress, $\prod_t$ is the transverse piezoresistive coefficient and σt is a transverse stress. Equation 1 is further simplified by putting the values of piezoresistive coefficient:-

$$\frac{\Delta R}{R} = \frac{(\pi_{11} + \pi_{12} + \pi_{44})}{2} \times \sigma_l + \frac{(\pi_{11} + \pi_{12} - \pi_{44})}{2} \times \sigma_t \tag{2}$$

As can been seen from the equation 2 that the change in resistance depends upon the surface stresses. When the SCRs are created, it distributes the surface stresses and converge them around the defect proximity [7]. This convergence of stresses will boost the change in resistance. As the cantilever beam is deformed (because of the load applied at the free end of the beam), the change in the linear strain will increase. This change in linear strain is proportional to change in resistivity of the beam. So as the linear strain will increase, so will the change in resistance. This increase in strain tends to increase the change in resistance of the piezoresistive sensor which is the ultimate objective of this paper.

The optimization technique (Stress Concentration Region) proposed in this paper, is a simple but effective approach. Instead of wasting time and cost on expensive equipment to optimize the piezoresistive sensor, this approach can achieve the required optimized sensitivity. Stress Concentration Regions are the defects that are introduced in a cantilever beam, which distribute the surface stresses. These distributions of surface stresses increase the linear strain which ultimately increases the resistivity. The piezoresistive layer is either deposited or doped on the silicon wafer beam. The optimization feature that is discussed in this paper; is the introduction of a new defect (Star defect) and to change the geometrical parameters of the star defect. This technique optimizes the change in resistivity as compared with the previous SCR's shapes. The process flow of this whole research methodology in form of flow chart is shown below:-

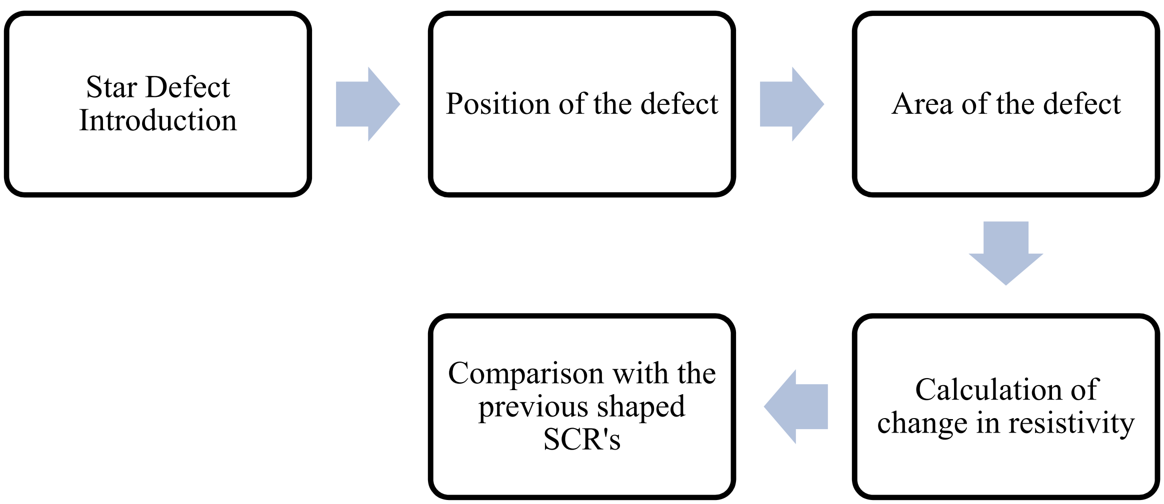


Figure 3: Flow Process of the methodology

Figure 3 shows the process flow of the discussed approach.

CHAPTER-3: METHODOLOGY

3.1 Design process:

The SCR effect of SCR on resistivity of Piezoresistor has been simulated and analyzed using COMSOL Multi physics 4.3a. The design parameters selected to create and test this simulation are shown as:

3.1.1 Design Parameters:

Design Parameter for this process are specified as below

1. A rectangular beam as shown in Fig 3 of specification: 20µm long, 3.2µm wide and 0.2µm thick.
2. The material selected for the beam is Poly silicon with Young's modulus
3. Young's modulus of 170GPa and Poisson ratio of 0.22
4. Piezoresistive layer selected is lightly doped n-type silicon with perimeters of 3µm long, 3.2µm wide and 0.1µm thick
5. The boundary load is a applied pressure on half of the beam is calculated as 3.07 Pa, 6.14 Pa and 9.21Pa
6. Star defect of dimension 2.42µm*2.42µm*0.2 µm

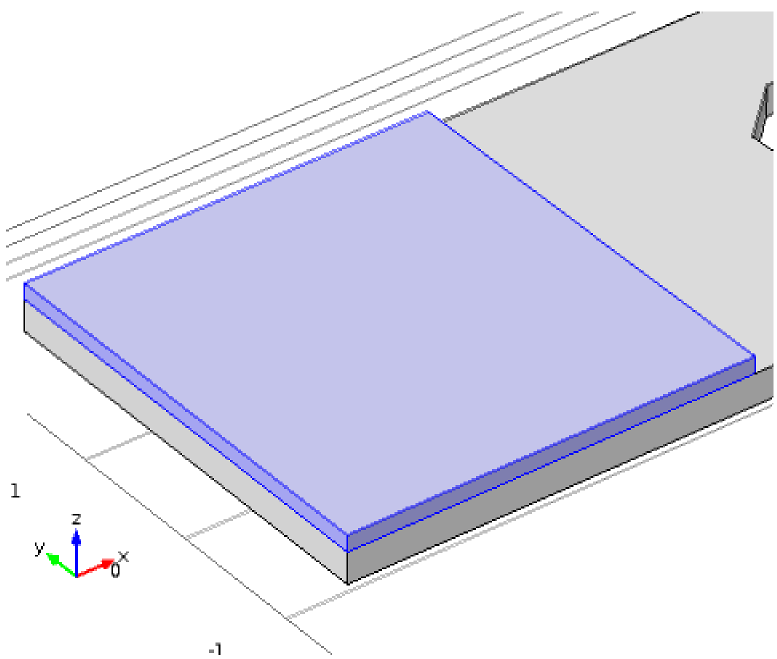


Figure 4: Piezoresistive layer

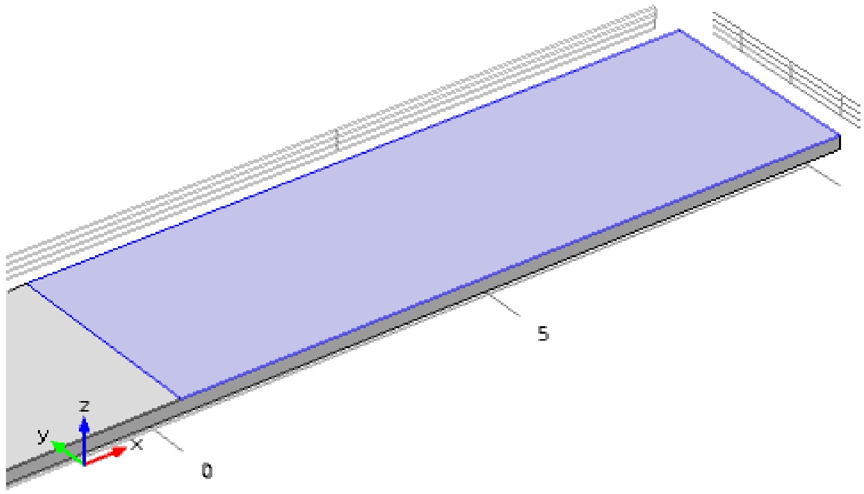


Figure 5: Boundary load Area

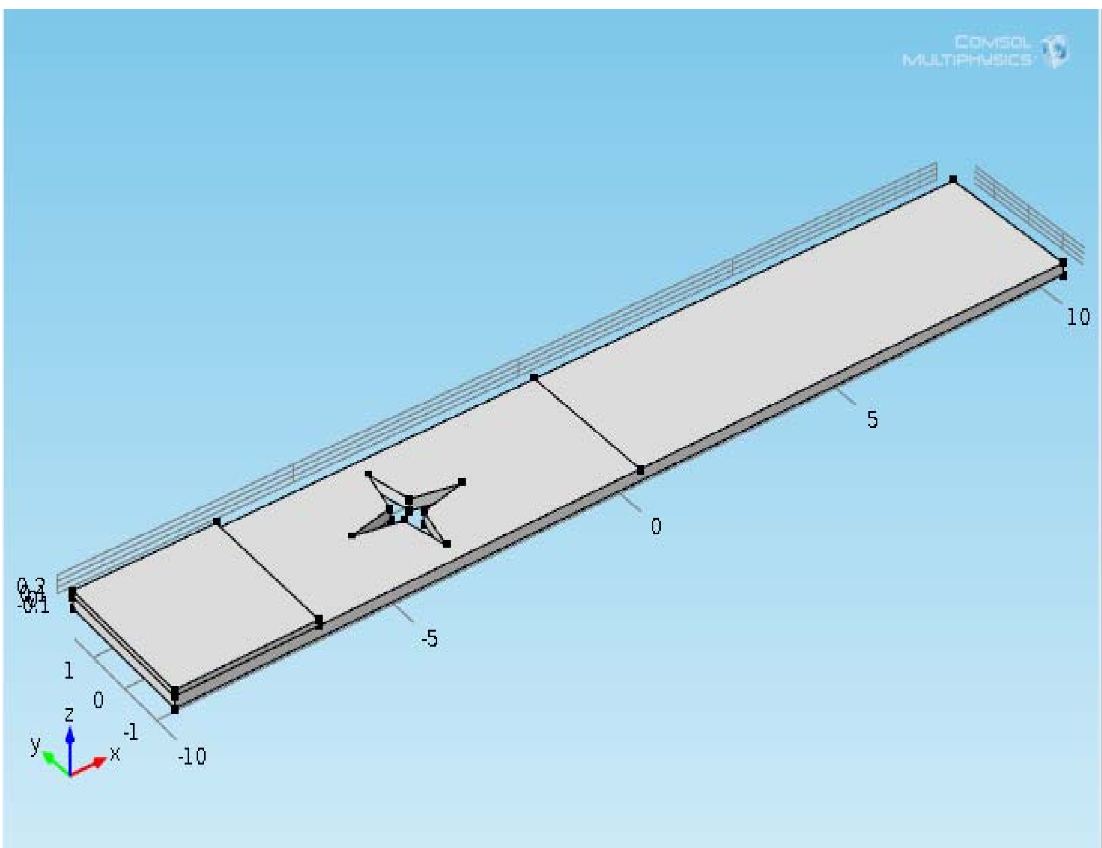


Figure 6: CAD model of the piezoresistive sensor

Figure 6 is the Star defect beam design. As can be seen from the figure that a 2.42µm*2.42µm*0.2 µm star shaped defect has been created on the beam. Figure 4 is the piezoresistive layer embedded on the silicon cantilever based piezoresistive sensor. As you can see from the figure, the blue highlighted squared layer is of the piezoresistive layer. Figure 5 is the boundary surface of the beam where the load 30ng will be equally distributed. The blue highlighted surface is the boundary surface condition for the 30ng load. These boundary surface perimeters are 10µm*3.2 µm; which is equivalent to half of the section of the cantilever beam of this piezoresistive sensor.

After selecting the optimal design, next part in the process tree; comes the placement and size of the defect on the cantilever beam. Distance of defect and size of the defect matters a lot in altering the mechanical properties of a cantilever beam. These factors can readily create effects on maximizing the stress to optimal conditions. The final part is to put these values in equation no. 2 and compare these defects. The change in resistance per load will describe how much sensitive a beam has been made by these defects.

3.2 Sensitivity enhancement (Changing the position of the defect)

The second method we discuss in this paper is to change the geometrical parameters of the defect. In this experiment, we took the parameter of the position of the defect. We conduct the following test of the defect at seven different positions from the fixed end of the beam that are: a. 4.5µm, b. 5µm, c. 5.5, d. 6, e. 6.5, f. 7 and 7.5µm. The results are quite clear that as the defect's position is away from the fixed end of the beam, the resistivity decreases. This method inclined us to the fact that the position of the defect must be selected nearest to the fixed end for better sensitivity. This change of effect in surface stresses is simulated in a figure shown below:

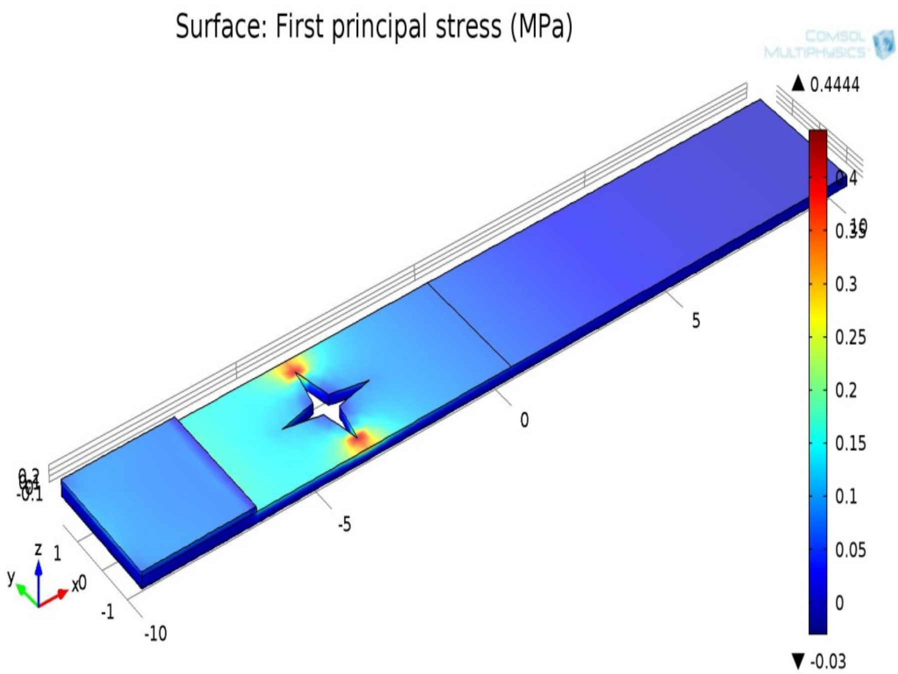


Figure 7: Stress plot of star beam (units in MPa)

Figure 7 the stress analysis of star defect under 30ng of load applied at the free end of the cantilever beam

3.3 Sensitivity enhancement (Changing the Area of the defect)

To optimize the sensitivity performance of the cantilever based piezoresistive sensor, another way is by changing the area of the defect. In this case, discuss the star defect beam and the change effect of Stress distribution by changing the area (radius normally because area of circle is πr2) of the central circle of the star defect. We have conducted this experiment using three data areas which are listed as: a. R=4.5μm, b. R=5μm, c. R=5.5μm, d. R=6μm, e. R=6.5, f. R=7and c. R=7.5μm using load as 30ng. After simulating the result in COMSOL Multiphysics for these three data values; following result summarized as: The resistivity increases with increase in the radius of the central circle of the star defect till it reaches at point 6μm. Here the stress distributed is maximum because the ends of the star are still effective to create maximum stress at the edges of the cantilever beam. After that radius, it decreases with different slope as the shape tends to change more towards polygon (For example Decagon, Octagon, Hexagon etc). The effect of change of area with respect to the applied load is shown as:

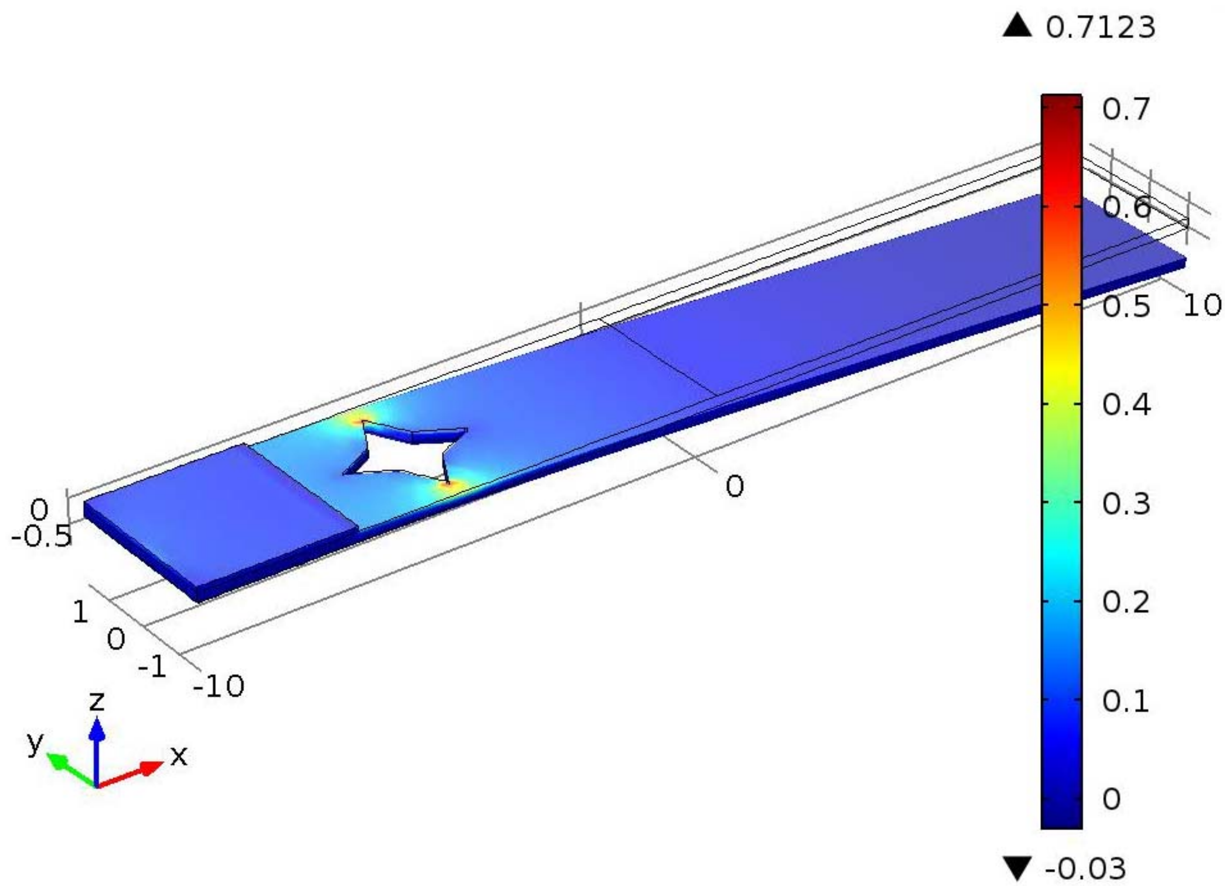


Figure 8: Stress at 6µm radius central circle

The above figure shows the improvement in stress after we increased the radial area of the defect while keeping the geometrical position, applied load and perimeters as constant

3.4 Complete Piezoresistive Sensor Design:

After creating the experiments to test the statement that "whether surface stresses increases when a Strength Concentration Region is introduced in a cantilever beam", the next step is to design the experiment with complete piezoresistive sensor design instead of only a cantilever beam. For that, the beam is first designed in modeling software "PRO-E". The design parameters selected to create the complete piezoresistive sensor are shown as:

- Piezoresistive MEMS senor CAD model perimeters: Length=26mm, Width=20mm, thickness=5µm
- Material: Poly silicon
- Inner perimeters: Length=18mm and width= 12mm
- Piezoresistive layer perimeters: Length=3.5 µm, Width=3.2µm and thickness 0.2µm

- Material of peizoresistive layer: Slightly doped n-type piezoresistive layer
- CAD designing software: Pro Engineering 5 and COMSOL Multiphysics
- Analysis Software: COMSOL Multiphysics
- Load: Fixed pressure at the half of the beam i.e 3.07 MPa, 6.14 MPa and 9.21MPa.

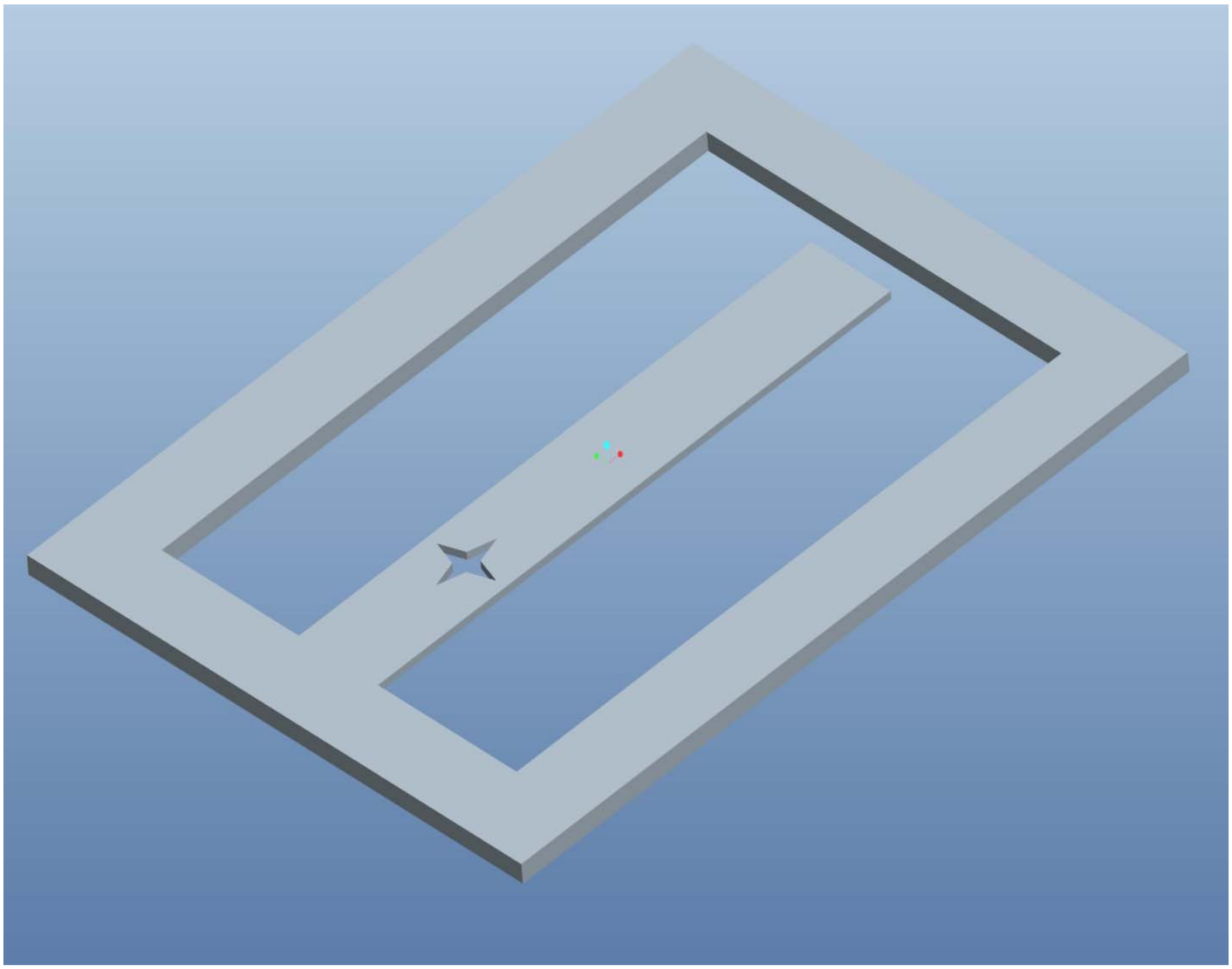


Figure 9: CAD Figure of Piezoresistive MEMS sensor

The above figure is the CAD file which is imported in COMSOL Multiphysics software for further designing. A piezoresistive layer is model at the edge of the beam with the perimeters described above. This piezoresistive layer will have two regions that would be operative in this experiment. One is active region and other is passive region. Active region is the region which would be responsible to vary the change in resistivity. This region will show the change in resistance ΔR in comparison with the resistance present in passive region. The complete CAD file in integration with the piezoresistive layer is shown below:

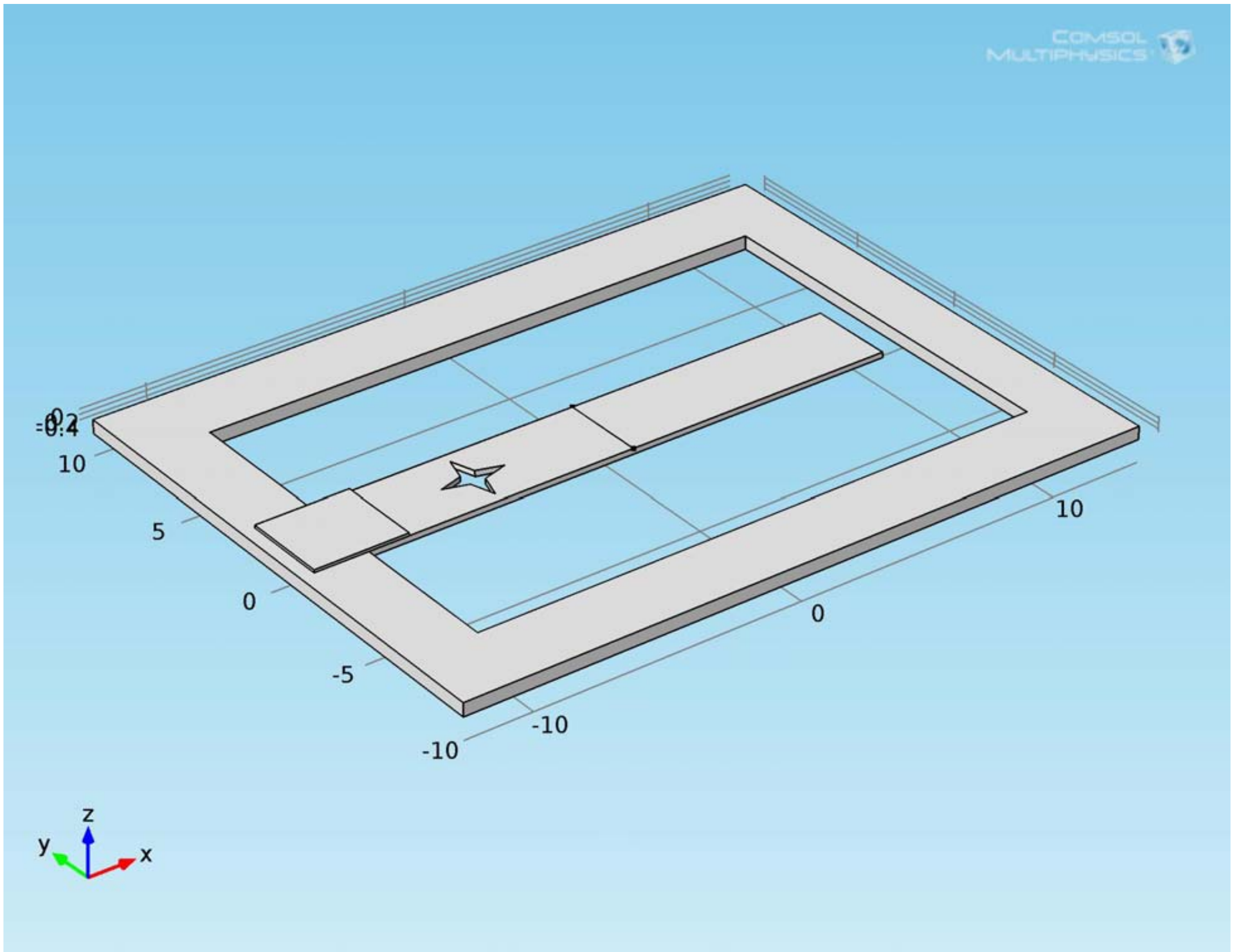


Figure 10: Complete CAD figure MEMS piezoresistive sensor

Figure 10 consist of complete assigned CAD file with previous CAD file; with a piezoresistive layer for analysis. After this, this CAD file undergoes simulation experiment. First step is the material assignment. The whole MEMS body including cantilever beam is assigned as Poly silicon material. Then the piezoresistive layer is assigned as slightly doped n-type piezoresistive layer and both of these materials are integrated with each other. The second step is the assigning boundary loads and fixed constraints. After assigning these loads and constraint, the third step is initiated; to simulate the results of respective inputs. The experimental results, Simulation results, Graphs and tables are displayed in the next chapter.

3.5 Mask Design and Fabrication Limits:

Before the fabrication process for piezoresistive sensor, mask designing phase holds great importance for fabricating the precise and accurate cantilever beam and the defect (which in this case is star defect). In this section, fabrication through photolithography process is discussed. For designing the mask of both cantilever and star defect, first we have to select the field of the mask. For that dark field mask designing is used with positive photo resist. Two masks have been designed for this fabrication process. One for the cantilever beam and other for the star defect. The beam would be fabricated at the top/front of the wafer as layer.

Figure 11: Side view of cantilever beam on wafer

Figure 11 shows the fabricating of cantilever beam on the top of the wafer. After developing the cantilever beam, the next step is to fabricate the beam. The cantilever beam is etched from top side to bottom side till a hollow defect is fabricated on the cantilever beam. For this case, alignment error and other mask developing are not considered. So the mask design is shown as:-

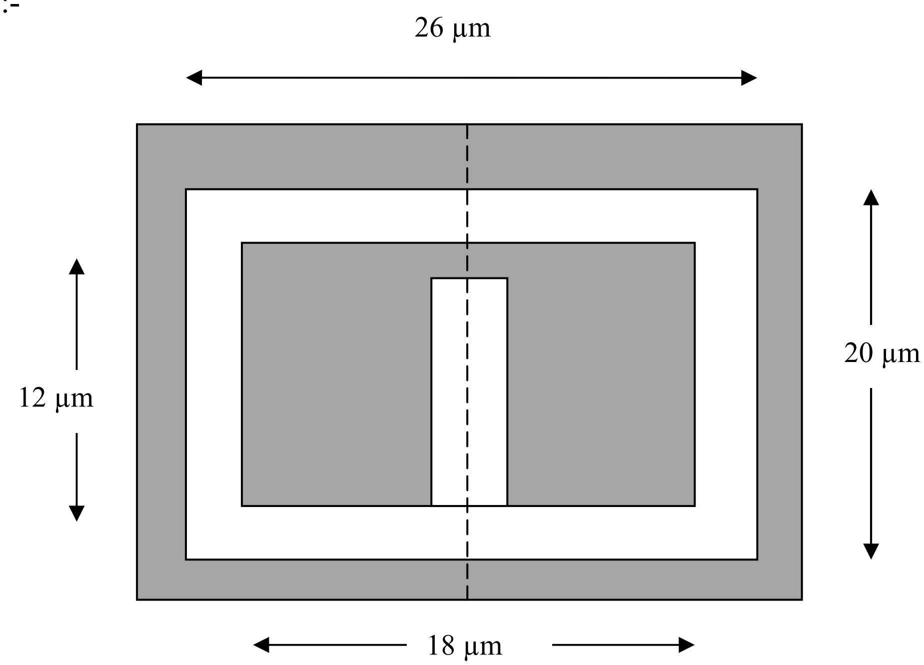


Figure 12: Top view of cantilever mask design

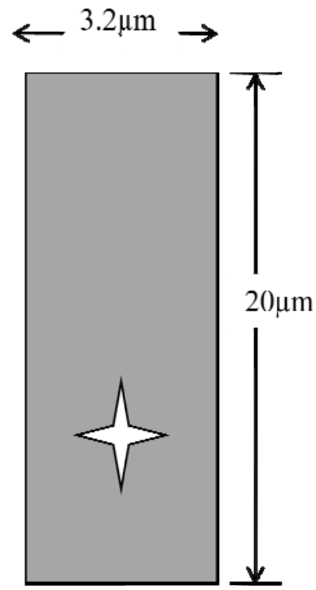


Figure 13: Star Defect Mask design

Figure 12 is the Mask design for the cantilever beam. In the end, the light shaded piece would be extracted and developed. Figure 13 is the mask design for the star defect that will later be fabricated on the cantilever beam.

The process of any fabrication starts with a selection of a silicon substrate. First decision to make is the direction of the cantilever beam that is going to be etched. In this case it would be in <110>. Then a layer of SiO_2 as thermal oxidation is deposited on the silicon wafer [22]. Then the layer of photo resistive is deposited on the wafer. The main aim of this layer is its interaction with Ultraviolet source. The photoresist layer gets excited from U.V source. Only the mask area doesn't get excited because the mask area prevents the U.V exposure on the photoresist layer. So after etching, the mask would be deposited on the substrate and the unexposed area would be removed [23]. So a cantilever beam with defect introduction is fabricated. After this, a piezoresistive layer is deposited on the top surface of the beam, positioned at the fixed end. The last step is the deposition of the metal layer on the beam as a metal contact with the required electronics. In this case, an aluminum layer is made in contact with piezoresistive layer and with the other side of the beam.

3.5.1 Concave under cutting:

There is a limitation for the suggested fabrication process known as "Concave under cutting". This fabrication cavity arises with the increase in etching time. This limitation causes the small and sharp edges/points to undergo round profiles. In this case, the sharp points at each end of star defect and edges will tend to go to round profile. The size of round profile depends upon the minimum feature size of the fabrication technique. For this purpose, e-beam fabrication is used. The minimum feature size for case of e-beam fabrication is around 0.7μm. A round profiled star beam is shown as below:-

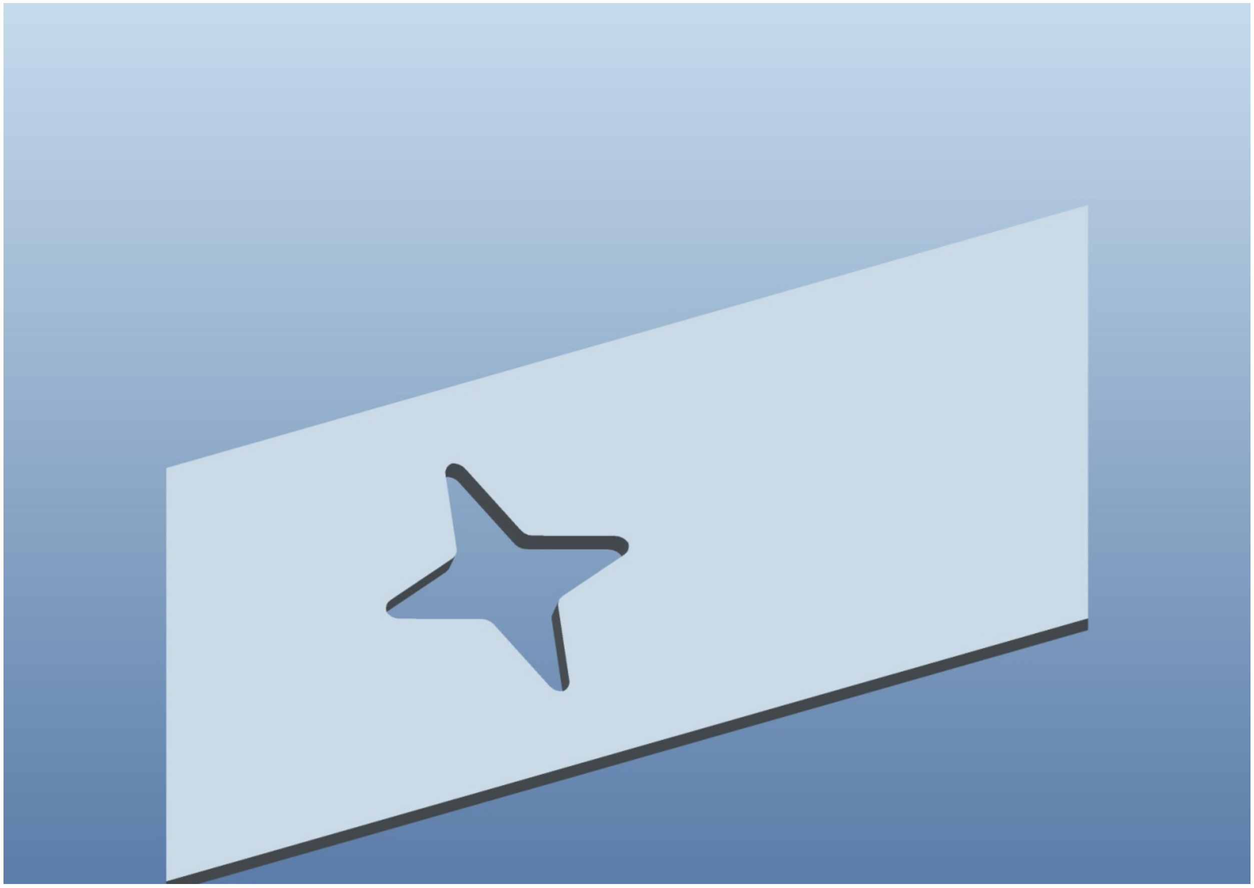


Figure 14: Round profile of star defect

As can be seen the round profiles of the pointy edges of the star defect in the above figure. This cavity problem reduces the surface stresses and the overall resistivity is changed. The relative error between ideal fabricated and real time fabricated cantilever beam is calculated to be around 7.75%. This error must be taken into consideration because in the real time scenarios, this concave under cutting problem will change the results. This error can be reduced by using Excimer laser technique (which has minimum detectable size of 130nm) or any advanced fabrication technique in future.

3.6 Micro fabrication process for piezoresistive MEMS sensor:

In this paper, the defect is introduced in the beam. So for the fabrication of a cantilever based system, a n-type silicon <110> direction piezoresistor is selected [8]. Then a beam of 20μmx3.2μmx0.2μm is fabricated using masking [11]. Another mask of defect is also designed. For star beam, a 2.42μmx2.42μmx0.2μm star defect is masked on the photo resistor layer. U.V exposure will engrave these two masks on the photo resistor layer for photolithography [10]. Then it is etched and the photo resistive layer is removed. After this etching, we would have a cantilever beam as shown in fig 5 process 6. Then we will make a metal contact of aluminum. This metal contact will actually act as the change of resistance against the change in the displacement of the beam. The basic deposition of the mask on the cantilever beams; viewed from top is shown in figure below.

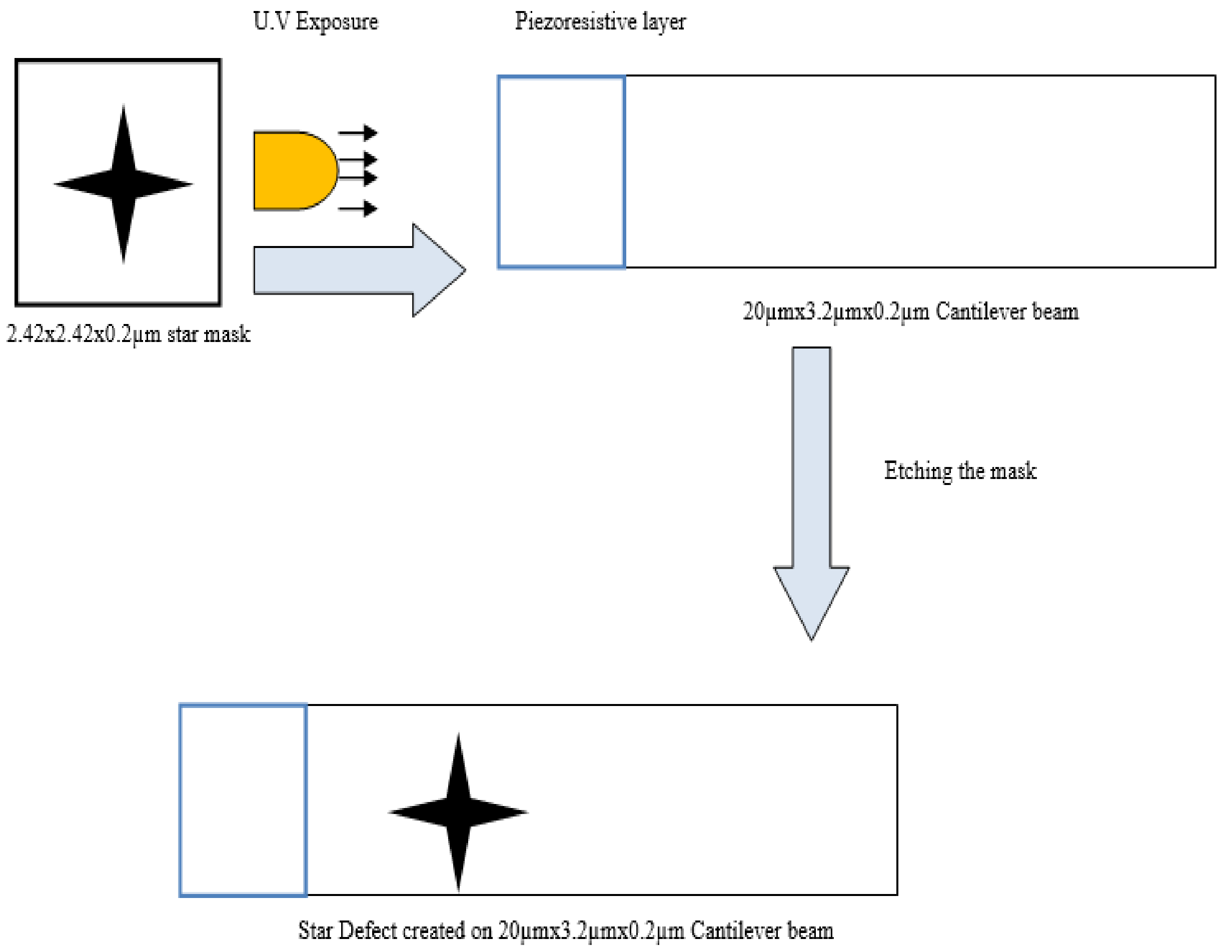
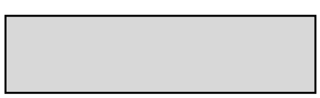
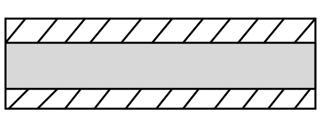
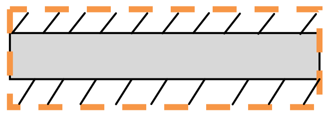
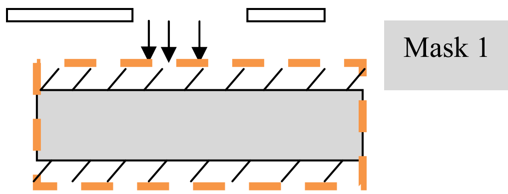
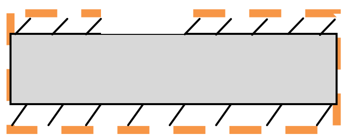
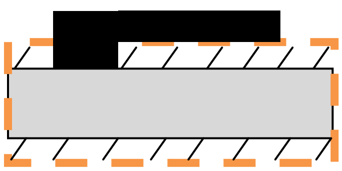
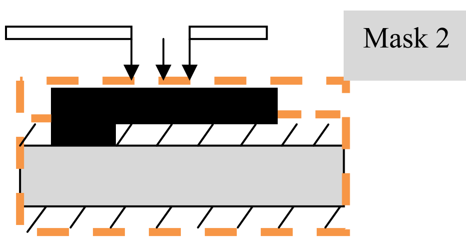


Figure 15: Creation of defect on the cantilever beam

1. 	N type silicon <110> has been selected as substrate
2. 	Thermal Oxidation layer for SiO_2 growth as sacrificial layer

3.		Photo resistive layer for photolithography process
4.		Mask 1 is introduced to fabricate the cantilever beam.
5.		The exposed photoresistive layer is etched so that cantilever beam would be fabricated on the etch area on the silicon wafer
6.		Exposed part is removed and cantilever beam is fabricated on the wafer
7.		Mask 2 (star defect mask) is exposed on the cantilever beam
8.		After etching, the defect is etched on the top of the cantilever beam. Sacrificial layer and photoresistive layer is removed and a cantilever beam is fabricated on the top of the wafer

	Silicon Wafer		Photoresistive layer
	Silicon Di Oxide		Cantilever beam

Figure 16: MicroFabrication process Flow

CHAPTER-4: ANALYSIS AND CALCULATIONS

4.1 Analytical/Mathematical Model of Optimized Piezoresistive sensor:

Before displaying the results of simulation, an analytical/mathematical model of this whole research methodology needs to be explained. This model will calculate the theoretical value of the surface stresses which in comparison with simulation results, gives us the relative error in case of surface stress.

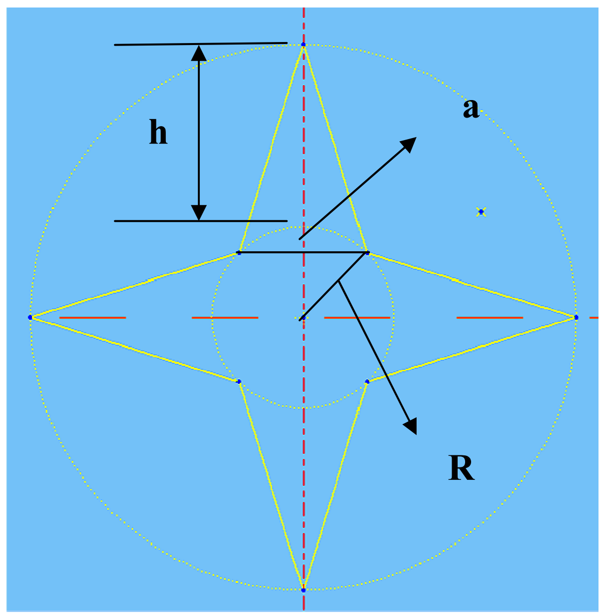


Figure 17: CAD Design of Star defect

The above figure is the top view CAD model of star defect. The overall approach is to find the differential moment of inertia with respect to cantilever beam and star defect. The main difficulty is to calculate the moment of inertial area of the irregular shape (triangle with a curve). So the approach is to divide it into two areas by joining the vertices of the arc. This way; two areas would be separated: 1. Area of Triangle with base 'b' & height 'h', 2. Area of ellipse of height a & base as b. So to calculate the moment of inertia the triangle with the curve, we need to find the difference of the triangle area with ellipse area:

Here x and y are geometrical parameters of star defect in x and y axis respectively

$$I_{tri} = \frac{by^3}{12}$$

$$I_{tri} = \frac{b(h+a)^3}{12}$$

$$I_{tri} = \frac{b[h^3 + a^3 + 3h^2a + 3a^2h]}{12}$$

I_{tri} is the moment of inertial mass for the triangular section of the star defect with base as '*b'* and height as '*h'*

$$I_{elli} = \frac{\pi}{8} ba^3$$

I_{elli} is the moment of inertial mass for the small elliptical section of the star defect with base as '*b'* and height as '*a'*

$$I_0 = I_{tri} - I_{elli}$$

$$I_0 = \frac{b[2h^3 + 2a^3 + 6h^2a + 6a^2h - 3\pi a^3]}{24}$$

The above variable I_o is actually the moment of inertial area for case of the triangle with an arc. As there are 4 triangles; so simply multiply the I_o four times and then add the moment of inertial mass of the centric circle. This whole summation will give us the total moment of inertial area of star defect which is shown below:

$$I_m = 4 \times I_0 + \frac{\pi}{4} R^4$$

$$I_m = \frac{b[2h^3 + 2a^3 + 6h^2a + 6a^2h - 3\pi a^3]}{6} + \frac{\pi}{4} R^4$$

$$\Delta I = I_{cant} - I_m$$

$$\Delta I = \frac{bt^3}{12} - \frac{2b[2h^3 + 2a^3 + 6h^2a + 6a^2h - 3\pi a^3] + 3\pi R^4}{12}$$

$$\Delta I = \frac{bt^3 - 2b[2h^3 + 2a^3 + 6h^2a + 6a^2h - 3\pi a^3] + 3\pi R^4}{12}$$

This ΔI is actually responsible for enhancing the surface stress of the cantilever beam and in the end the sensitivity of a piezoresistive sensor.

$$\sigma = \frac{12FLt}{bt^3 - 2b[2h^3 + 2a^3 + 6h^2a + 6a^2h - 3\pi ba^3] + 3\pi R^4}$$

As the moment of inertial area of Cantilever beam reduces due to the difference between moments of inertial area with star defect, it causes the denominator to decrease and increase the surface stress of the cantilever beam.

The values of the given variables are:

- Applied force at free end: F=10ng
- Length of the cantilever beam: b=20µm
- Width of the cantilever beam: t=3.2µm
- Height of star from the inner circle: h=0.8µm
- Radius of inner circle: R=0.4µm

After substituting the given values; the theoretical surface stress comes out to be around σ=0.131MPa. The maximum surface stress calculated by the COMSOL simulator is around 0.14MPa. So the relative error 6.642% is calculated between theoretical and practical stress results.

4.2 Comparison of different Stress Concentration Region shapes:

Apart from Stress, Strain and deformation; some important material properties needs to be compared with the star defect. This comparison will give a concrete analysis for the best possible Stress Concentration Region shape:

Sr. No	Defect	Maximum Load Capacity (µg)	Fundamental Frequency (KHz)
1	Star	438.7	573.20
2	Octagon	610.6	580.13
3	Square	640.41	590
4	Slit	747	567.32
5	Circle	821	585.31
6	Without SCR	1151	534

TABLE I: Material Properties of different SCR's Shape

Table I shows the only disadvantage of Star defect is the endurance level against loading. The table shows the low loading capacity for the piezoresistive sensor with star defect. This can be improved by increasing the geometrical parameters of the cantilever beam so that the sharp corners of the star defect don't crack with increase in load. Also the area of application discussed in this research is focused on bio-implantable and bio-medical purposes. In these applications, the applied load is very small. The maximum load that is applied is around 5µg. The disadvantage of star defect; can be neutralize for the case of bio-medical, bio-metric or bio implantable applications.

4.3 Simulations and Results:

The simulation of this paper is conducted on COMSOL Multiphysics 4.3a. Five defects have been tested on same load that is 10ng. Then for further results the load has been increased to 20ng and 30ng [6]. After the analysis the following results has been produced after creating the defects in the beam:-

SCR's Defects	Resistivity at 10ng (mΩ)	20ng (mΩ)	30ng (mΩ)	Sensitivity (mΩ/Pa)
Octagon	8.6	17.56	25.8	2.684
Slit	6.94	13.88	20.12	2.26
Square	8.45	17.11	24.95	2.48
Circle	6.54	12.32	18.12	1.88
Star	10.866	20.2	30.4	3.32

TABLE II: Resistivity and sensitivity of different SCR

Table II shows the complete supremacy of the star defect as compared with the previous defects at constant physical and material properties.

4.3.1. Results of geometric position of the defects experiment:

The resistivity calculated at these seven different points (a. 4.5µm, b. 5µm, c. 5.5, d. 6, e. 6.5, f. 7 and 7.5µm) are plotted on a graph shown below:

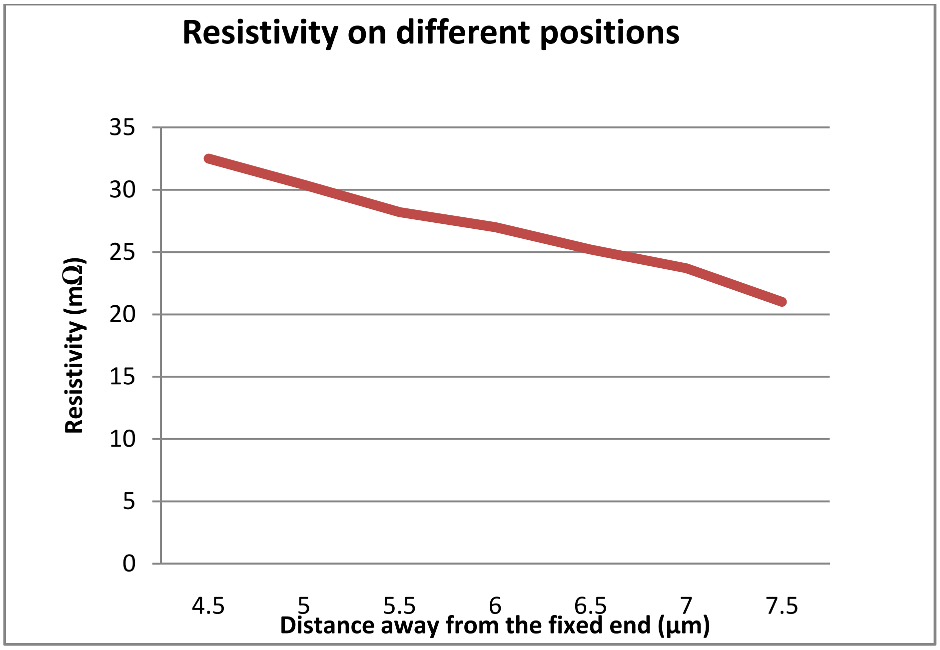


Figure 18: Graph of Max Stress at three points

As can be seen from the Figure 18, the resistivity at 30ng of load decreases with the increase in distance from the fixed end. This shows us the fact that if the defect is farther from the fixed end of the cantilever beam, the maximum stress of the beam at same load decreases. The decrease in this stress affects the resistivity slope and it decreases with increase in distance from fixed end.

4.3.2 Results from Defect's Geometrical Area experiment:

The resistivity increases with increase in the radius of the central circle of the star defect till it reaches at point 6µm. Here the stress distributed is maximum because the ends of the star are still effective to create maximum stress at the edges of the cantilever beam.

After that radius, it decreases with different slope as the shape tends to change more towards polygon (For example Decagon, Octagon, Hexagon etc). This result has been graphed as shown below:

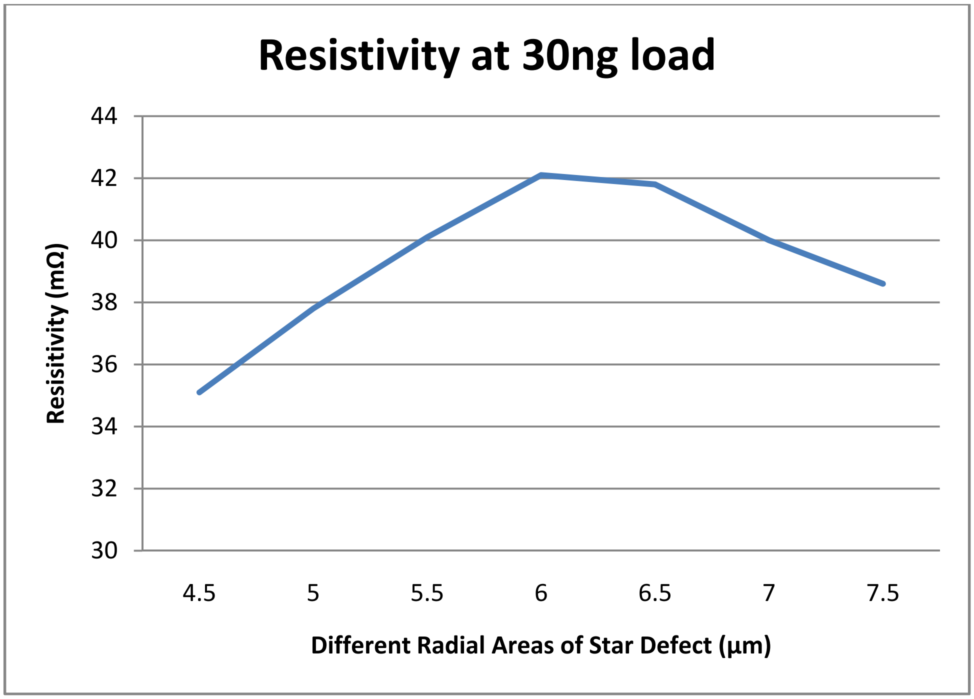


Figure 19: Graph of different radial areas against maximum stress

As can be seen from the graph, the resistivity curve boost up to 6μm distance from the fixed end and then decreases. So by conducting this experiment, we have improved the resistivity on the cantilever beam surface up to 16.6%.

These are the few parameters to boost the surface stress of the cantilever beam. This boost will help us to obtain a better sensitive piezoresistive sensor than the previous defect and previous approach.

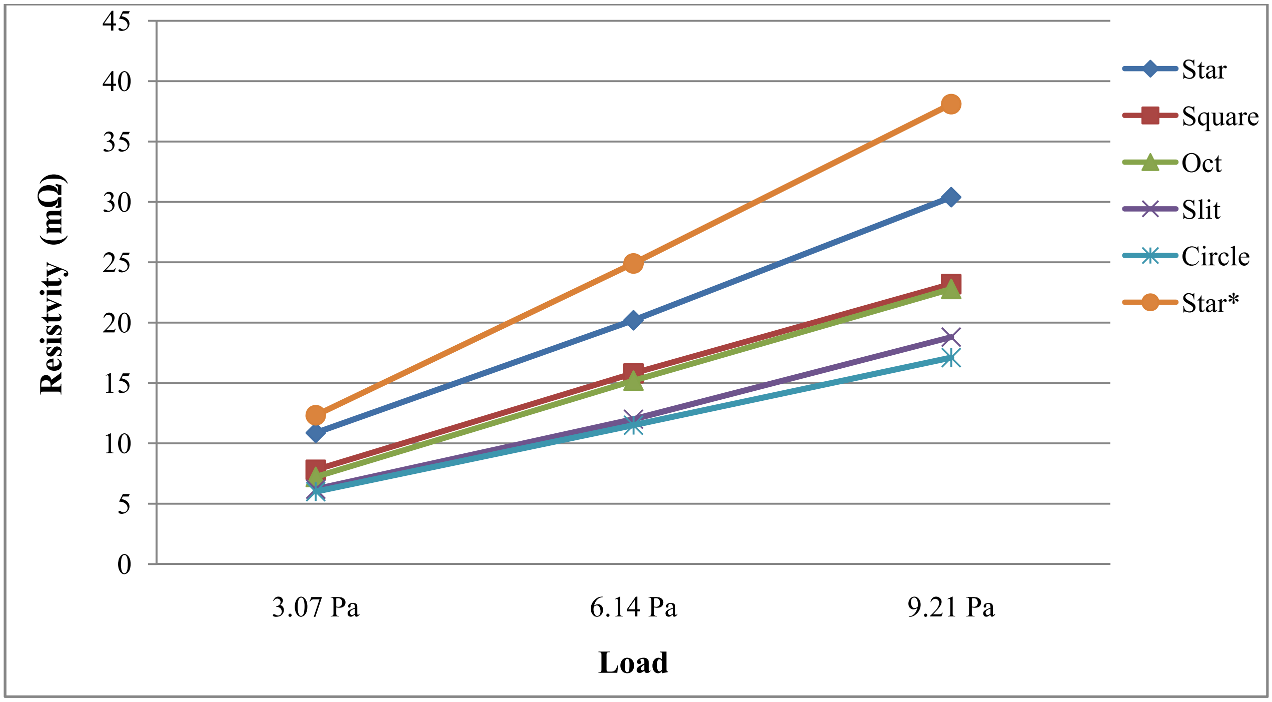


Figure 20: Resistivity graph of different SCR shape

The above graph shows the improvement of star defect* as compared with the previous defects. Star defect* improvement clearly shows that the modifications in geometrical position and radial area are successful.

4.3. Generic overview of effect of SCR on different size beam:

The above results are for one cantilever beam with fixed dimension of 20µm of length, 3.2µm wide and 0.2µm of thickness. To give a generic overview of the effect on stress if the length or width is changed; while keeping the other parameters constant. For that purpose, two major parameters (length and width) have been changed simultaneously while keeping the rest of the parameters as constant. There are 5 different length cantilever beams (ranging from 10µm to 30 µm with equal intervals of 5µm) and 5 different wide cantilever beams (ranging from 1.6µm to 4.8µm with intervals of 0.8µm). The results are displayed in separate graph as:

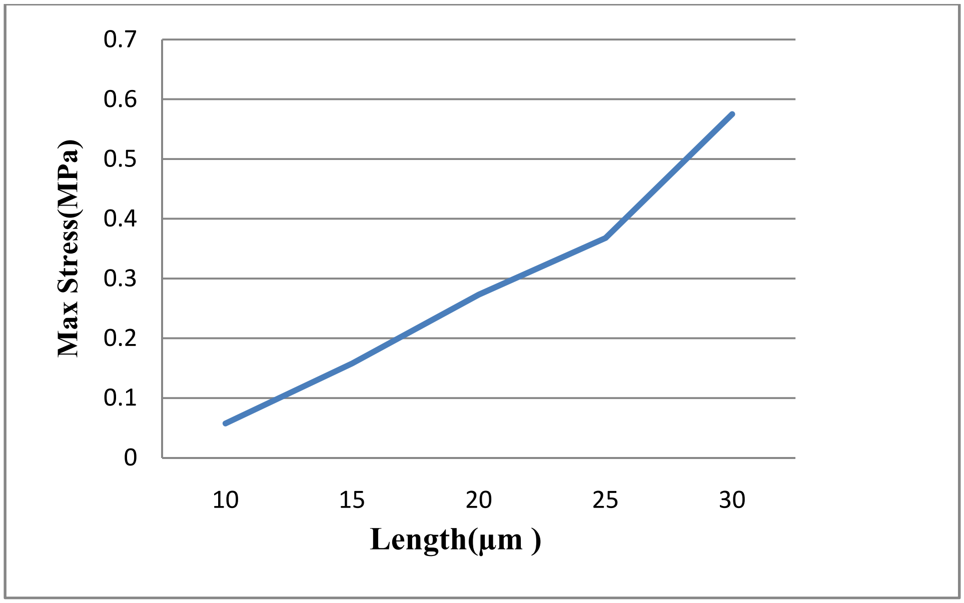


Figure 21: Stress curve against different length cantilever beam

This graph explain the fact that with increase in length, the surface stress of the cantilever beam also increases the surface stress of the cantilever beam. The other two parameters width and thickness are kept constant. The maximum rise in stress is calculated between length 25 and 30 of around 39.64%. This generic overview in case of length can tell us the fact that the increase in length of the cantilever beam improves the surface stress.

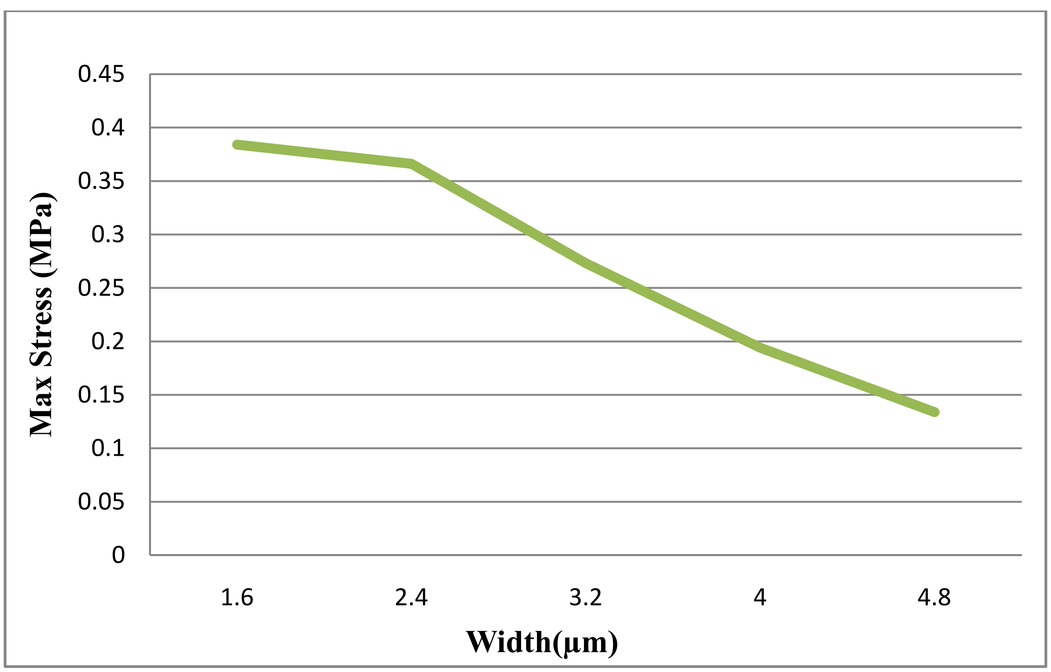


Figure 22: Stress curve against different width cantilever beam

The above graph states the declination of surface stress curve of the cantilever beam with increase in the width of the beam. That means the surface stress decreases with increase in width of the cantilever beam.

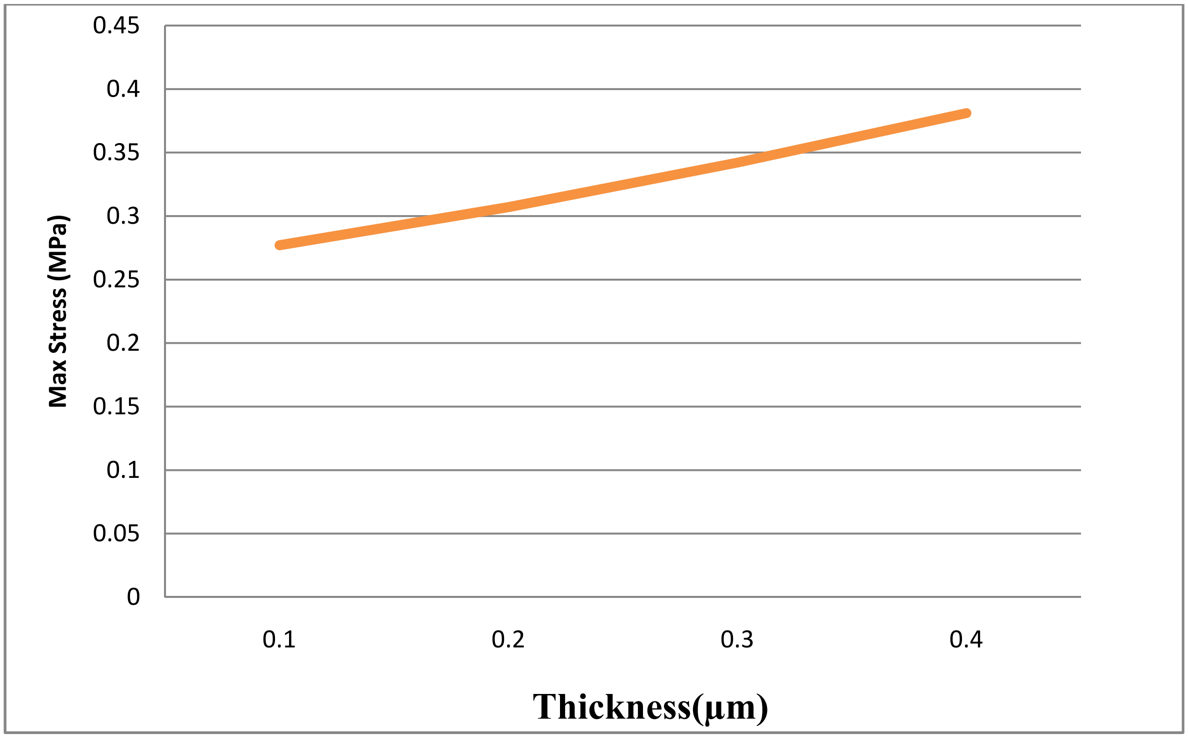


Figure 23: Thickness curve against different thick beams

The above figure shows the slow inclination curve. As compared to other two parameters (width and length), thickness doesn't have that dramatic effect. The surface stresses show a slight improvement if we increase the thickness of the cantilever beam. The curves of length and width states the fact that the difference in stress per unit change is far much greater than the thickness curve. However, the improvement by the thickness cannot be denied and one should keep in mind the effect of change of thickness on the surface stress of the cantilever beam.

The purpose for this generic overview is to help us in selecting the perfect perimeters to fabricate a sensitive piezoresistive MEMS based sensor.

CHAPTER-5: COMPARISON AND DISCUSSION

Table-III shows the comparison of different sensitivity techniques used on piezoresistive sensor up to this date. All of this research papers/journal has some advantages and disadvantages. The parameters used for comparison:

- Weight of the sensor including anchor and cantilever beam.
- Maximum capacity of the cantilever beam to endure the load.
- Fundamental Frequency of the sensor
- Sensitivity of the sensor
- Maximum lateral strain shown by beam
- Maximum deformation/deflection from fixed end to free end of the beam

Sr. No	*Papers/ Journals*	*Published date*	*Weight (ng)*	*Loading Capacity (µN)*	*Fundamental frequency (kHz)*	*Sensitivity (mΩ/Pa)*	*Max strain (µ)*	*Max Deformation (nm)*
1	A Low Cost CMOS piezoresistive accelerometer with large proof mass	2011	105	1035.8	1.48	0.46	0.027	4.37
2	Piezoresistive Sensitivity, Linearity and Resistance Time Drift of Polysilicon Nanofilms with Different Deposition Temperatures	2009	0.0024	12.37	1353.2	1.26	1.3	0.01225
3	High Sensitive Piezoresistive Cantilever MEMS Based Sensor by Introducing Stress Concentration Region (SCR)	2007	9.45	747	567.32	1.76	5.3	0.913
4	Design of Piezoresistive MEMS-Based Accelerometer for Integration	2003	52.45	814.2	13	1.24	0.012	0.845

	with WSU for Structural Monitoring							
5	A Multi Axial BioImplantable MEMS Array Bone Stress Sensor	2007	162	1250	1200	0.17	0.4	0.623
6	Performance Improvisation of Cantilever-type Silicon Micro Acceleration Sensors Using Stress Concentration Regions Technique	2007	12.23	845.2	288	1.312	4.32	0.624
7	High-performance piezoresistive pressure sensors for biomedical applications using very thin structured membrane	1996	8	614	300	0.06	0.22	0.096
8	Half Cut Stress Concentration (HCSC) Region Design on MEMS Piezoresistive Cantilever for Sensitivity Enhancement	N.A	15	452	432	2.12	4.8	0.508
9	Design and Analysis of MEMS Piezoresistive SiO2 Cantilever-based Sensor with SCR for Biosensing Applications	2008	76	580	680	1.3	3.82	1.82

10	Optimization of a piezoresistive sensor using SCR's orientation	N.A	6.25	438.7	573	4.2	4.85	1.23

Table-III: Comparison of piezoresistive sensors

Table III is the overall comparison of the previous approaches used by the researchers. All of these 9 papers have emphasized on achieving a sensitive piezoresistive sensor. There are many other techniques beside Stress Concentration Region; that have been used to enhance sensitivity. All of these papers have some strong point and some weak point. For example, in case of a piezoresistive accelerometer using large proof mass has some strong deformation and loading capacity as compared to our approach but due to large proof mass; it is not suitable for medical or bio implantable purposes. Likewise for case of high sensitive piezoresistive sensor using thin structured membrane is light weighted, low cost and has good loading capacity but due to embossed membrane; the piezoresistive show poor performance in sensitivity and deformation department. Every technique is unique and its own pros and cons but the decision for the best approach would be cleared in figure of merits table.

5.1 Figure of merit:

The figure of merit is a quantitative analysis required to find out the "best" design per given list which in our case, is the 10 papers given in table-II. The methodology is to devise a formula in which each quantity is given certain percentile score and each of the paper is rated according to that score.

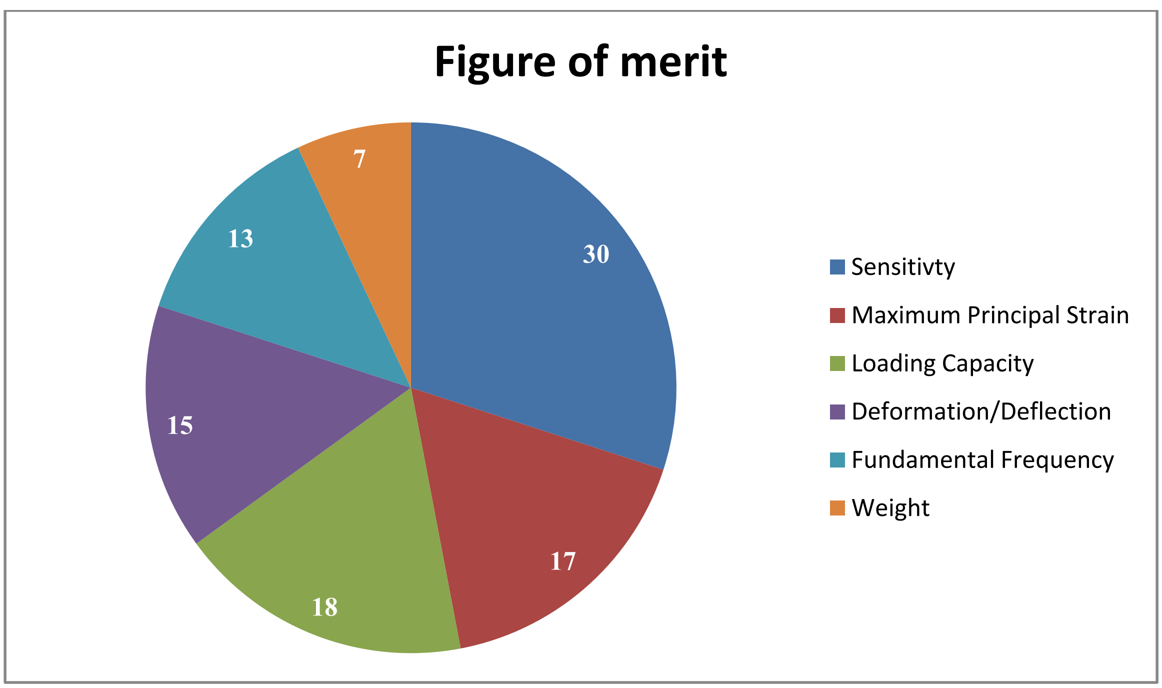


Figure-24: Figure of merit of different quantity out of 100

Figure 24 shows the distribution of the major parameters that will be discussed in table IV as figure of merits.

Now by entering the scores of different quantities as per the figure-25 we can develop a score of over-all best exoskeleton design.

Sr. No	Papers	Sensitivity	Strain	Loading Capacity	Deflection	Frequency	Weight	Total out of 100
1	A Low Cost CMOS piezoresistive accelerometer with large proof mass	10	6	14.91	15	3	1	49.91
2	Piezoresistive Sensitivity, Linearity and Resistance Time Drift of Polysilicon Nanofilms with Different Deposition Temperatures	18.6	10.4	5.2	6	13	5	58.2
3	High Sensitive Piezoresistive Cantilever MEMS Based Sensor by Introducing Stress Concentration Region (SCR)	20.57	17	11.27	6.5	6.3	4	65.64
4	Design of Piezoresistive MEMS-Based Accelerometer for Integration with WSU for Structural Monitoring	17.57	6.2	12	7.4	5	3	51.17
5	A Multi Axial BioImplantable MEMS Array Bone Stress Sensor	10.8	7.45	18	6.225	12.1	2.1	56.675

6	Performance Improvisation of Cantilever-type Silicon Micro Acceleration Sensors Using Stress Concentration Regions Technique	19.27	14.58	12.52	6.3	6.8	3.95	56.62
7	High-performance piezoresistive pressure sensors for biomedical applications using very thin structured membrane	9.45	7.1	10.22	5	6.92	4.2	42.89
8	Half Cut Stress Concentration (HCSC) Region Design on MEMS Piezoresistive Cantilever for Sensitivity Enhancement	25.1	15.12	9.4	5.9	7.1	3.78	68.4
9	Design and Analysis of MEMS Piezoresistive SiO2 Cantilever-based Sensor with SCR for Biosensing Applications	19.4	12.8	9.8	8.5	7.6	2.74	60.84
10	Optimization of a piezoresistive sensor using SCR's orientation	30	12.1	8.89	7.82	7.32	4.52	70.55

Table-IV Figure of merits of 10 papers of piezoresistive sensor

The above table shows that our current approach has the highest figure of merit as compare with the previous approaches.

CHAPTER-6: CONCLUSION & FUTURE WORK

So far in this paper, the objective discussed is how to increase the sensitivity of a piezoresistive sensor for bio- medical and bio-molecular applications. The conclusion of this paper has reached to the selection of an optimal defect design that can maximize the sensitivity [9]. So through the whole flow of process, the maximum stress has been computed. Each defect produced their respective change in resistance against 10ng (3.07 Pa), 20ng (6.14 Pa) and 30ng (9.21Pa) load against these maximum surface stress.

These changes in resistivity are plotted in figure 3 with respect to the applied load 3.07, 6.14 and 9.21 Pa pressure applied on the boundary load surface. Each of the defects sensitivity is plotted in the graph shown below with an addition of a piezoresistor with no SCR and an optimized Star defect. The optimized star defect is the further improvement and modification of the star defect. This improvement includes geometrical position of the star defect from the fixed end and the perfect selection of radial area of the star defect. These parameters have boosted the sensitivity of the piezoresistive sensor using star defect to a further and improved point.

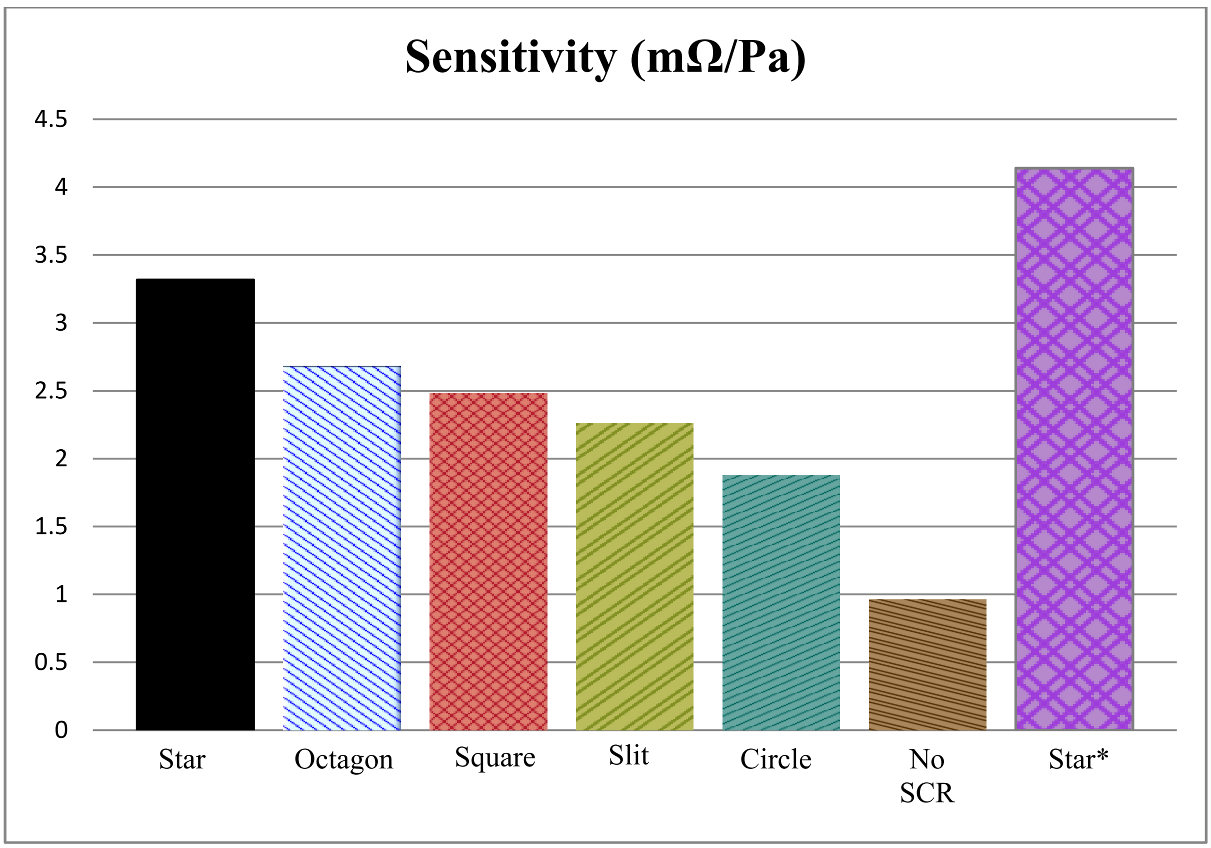


Figure 25: Sensitivity graph of different defects

As can be seen from the graph, the star design has clearly surpassed the octagon, circle, square and rectangular slit design. The sensitivity calculated in case of star is 3.34mΩ/Pa; octagon is 2.475mΩ/Pa, Rectangular slit 2.214mΩ/Pa, Square defect is 2.41mΩ/Pa and for circle is 1.85mΩ/Pa. The Star defect* has the highest sensitivity of 4.14mΩ/Pa and piezoresistive without SCR has around 0.96mΩ/Pa. This result explains one fact that star design* has exceeded square design, octagon design, rectangular slit design, circle design and no SCR design by 41.7%, 40.2%, 46.5%, 55.314% and 76.8% respectively. This comparison of these five defects (Star defect, Octagon defect, Square defect, Circle Defect and Rectangular slit defect) indicates the optimal defect that can lead to the highly sensitive piezoresistive sensor. Now at this point this fact can be stated that star design is an optimal design to be used as Strength Concentration Region (SCR) for the sensitivity application in today's silicon industries.

6.1 Future Work:

The current objective of this thesis was to improve and optimize the sensitivity of a piezoresistive MEMS based sensor. However, there are few more aspects that need to be modified or improve in future. For example, piezoresistive sensor with Stress Concentration Region shows poor performance against cyclic and static load. Due to hollow defect, it increases the stress but reduces the endurance limit against static and dynamic load. A research is needed to increase the endurance limit of the piezoresistive sensor using Stress Concentration Region. This can be done by selecting a perfect set of length; width and thickness of the cantilever beam which will increase the yield strength of the cantilever beam without reducing the surface stresses and sensitivity.

Also a research should be conducted in selecting a silicon wafer that has excellent material properties. The wafer can withstand high cyclic load in those areas of application where dynamic load is applied. Future research on fabrication technique needs to be conducted; improvised and improved. The convex cutting cavity error can be reduced by using the high technology equipment with minimum feature size (for example excimer laser technology). If the minimum feature size can be reduced, it will affect the surface stress created by Stress Concentration Region. This research will help to reduce the error and the difference between theoretical calculation and practical calculation.

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<u>Completion Certificate</u>

It is to certify that the thesis titled "**Optimization of the Sensitivity of a Piezoresistive Sensor using SCR's Orientation**" submitted by Regn. No. **2011-NUST-MS-PHD-Mts-33**, **Muhammad Tayyab Shahid** of **MS-70Mechatronics Engineering** is complete in all respects as per the requirements of Main Office, NUST (Exam branch).

Supervisor: _____________

Dr. Umer Izhar

Date: ____ Oct, 2014