1. Introduction

Biochemical sensing technique has become vital in finding surface stress changes in solid substances. MEMS based cantilevers are being considered as potential candidates for biochemical sensing due to the facts that they have small size, low fabrication cost and better sensor characteristics. There were different detection methods being used for biochemical sensing viz., optical levers, piezoresistive, capacitive and piezoelectric. MEMS based piezoresistive micro cantilevers offer a prominent future for the advance of innovative physical, chemical, electrical and biological sensors. Among various different detection approaches, piezoresistive cantilevers are widely investigated due to their significant advantages like direct fabrication, simple signal-conditioning circuitry, more dynamic range, tiny sensor area, a label-free detection method and compatibility with read-on chips. Piezoresistive cantilevers contain a strain sensitive layer is placed between two conducting layers those were treated as prominent structural and encapsulation layers. Selective immobilization of specific biomolecules on the top surface alters surface stress at opposite faces that enable cantilever to bend. The bending due to binding of molecules on the top surface leads to change of resistance that used for calculating sensitivity. These cantilevers offer prominent advantages over other transducers: No requirement of external devices for performing sensing,
no periodic alignment or calibration required, ability to work in a microarray format and signal processing step is very easy due to electrical signal characteristics etc. Along with above mentioned advantages, piezoresistive detection system has the limitation on sensitivity due to its low resolution in comparison with optical readout system. In this scenario, various attempts have been made to improve the sensitivity of the piezoresistive cantilever beam. Yin et al. have reported the stripe-patterning of sensing layer to improve the output of piezoresistive cantilever sensor and also effective sensing surface area. Yang et al. have investigated the enhancement in the detection sensitivity with the introduction of SCRs by increasing surface stress. Sacu et al. have studied the influence of dimensional changes and location of different punched objects on the performance of cantilever. Sung et al. reported an improvement in the sensitivity of piezoresistive cantilever and also noticed that efficiency and force sensitivity factors are effected by design and process parameters. However, very limited number of simulation studies were available on SiO2 based piezoresistive cantilevers with SCRs. Hence, it is felt that, still there is lot of scope to improve the sensing ability by overcoming the low resolution of cantilever with different innovative approaches. Thus, the present study is mainly focussed to design a simple piezoresistive cantilever punched with different shaped objects in the concept of SCR. In addition, effects of geometrical changes, materials and applied load were simulated to find optimum conditions resulting high sensitivity. The reasons for improvement in the sensitivity were discussed in detail by means geometrical alterations and materialistic conditions. Finite element approach was used in this research to get optimal displacement sensing performance of SiO2 piezoresistive microcantilever. COMSOL MultiPhysics v 5.2a, MEMS software tool was used to build the proposed finite element model.

2. Materials and Methods

2.1 Theoretical Background

When the piezoresistive cantilever is loaded, change in resistance takes place due to deflection of the cantilever. Stoney's formula in combination with resistance change equation are used to evaluate the displacement sensitivity of the cantilever.

\[ \frac{\Delta R}{R} = n_1 \sigma_1 + n_2 \sigma_2 \]  

where, \( \sigma_1 \) and \( \sigma_2 \) are longitudinal and transverse stress; \( n_1 \) and \( n_2 \) are longitudinal and transverse piezoresistive coefficients, respectively.

\[ \delta = \frac{3L^2(1-\theta)}{Et^2}(\sigma_1 - \sigma_2) \]  

where, \( \delta \), \( v \), \( E \), \( L \), \( t \) and \( (\sigma_1 - \sigma_2) \) are deflection, Poisson's ratio, Young's modulus, micro cantilever length, thickness of micro cantilever and differential surface stress, respectively. The stress at the base of the cantilever can be calculated using the following equation which is found to be maximum that at the centre.

\[ \sigma_{max} = \frac{6L}{Wt^2}F = \frac{3Et}{2L^2} \delta \]  

For an applied force on the free end of the micro cantilever, the resulting resistance change is given by:

\[ \frac{\Delta R}{R} = n_1 \sigma_{max} = \beta \frac{6L \pi F}{W^t} = \beta \frac{3n_1(1-\theta)}{W^t} (\sigma_1 - \sigma_2) \]  

where, \( F \), \( W \) and \( \beta \) are the applied force, width of the micro cantilever and a correction factor between 0 to 1, respectively. From the above equations, it was very clear that the resistance can be increased by increasing surface stress \( (\sigma_1 - \sigma_2) \) or assigning different materials or decreasing the thickness of the cantilever or placing punched objects in the SCR.

3. Results and Discussion

Piezoresistive cantilever of length 150 mm, width 30 mm and thickness 10 mm was designed. In order to evaluate optimal design conditions of piezoresistive cantilever to get better sensitivity, numerous simulation attempts have been performed in three steps through SCR concept. In the first step, different punched objects (Triangle, Rectangle, Circle & T-shape) were placed separately in SCR at a fixed distance of 20 mm from rigid support where different materials (SiO2, Si3N4 and SiC) assigned to cantilever for an applied load of 50 N. Then, resulting changes in the deflection of the cantilever are observed and presented in Figures 1 and 2. The details of cantilever displacement for different punched objects with the assigned materials under load of 50 N is shown in Table 1. It is very clear from the tabulated values that the SiO2 cantilever with the punched object ‘circle’ found to exhibit high displacement. It could be due to the fact that the physical properties viz., young's modulus, poison's ratio...
of SiO\textsubscript{2} are very low in comparison with other materials. The maximum space occupied by punched object circle could be another reason for better displacement. By using the above result, optimum displacement sensitivity is evaluated only for SiO\textsubscript{2} cantilever as it has exhibited high deformation out of all the assigned materials for the given load and geometrical conditions.

![Diagram](image1)

![Diagram](image2)

![Diagram](image3)

Table 1. Details of displacements for various punched objects under different applied loads and materials

| Material | Circle | Rectangle | Triangle | T-shape |
|----------|--------|-----------|----------|---------|
|          | 50N    | 100N      | 150N     |         |
| SiO\textsubscript{2} | 15.3  | 30.6      | 45.9     |         |
|          | 29.1   | 43.6      | 13.8     | 14.3    |
|          | 41.4   | 14.3      | 28.6     | 42.9    |
| SiC      | 1.39   | 2.79      | 4.18     | 5.9     |
|          | 11.9   | 17.8      | 1.25     | 2.51    |
|          | 3.76   | 1.30      | 2.60     | 3.91    |
| Si\textsubscript{3}N\textsubscript{4} | 4.27   | 8.55      | 12.8     | 4.06    |
|          | 8.13   | 12.1      | 3.85     | 7.71    |
|          | 11.5   | 3.99      | 7.99     | 11.9    |
Figure 1. Displacement in the circle, rectangle punched PZR cantilever beam with 50 N load for different materials a & d) SiO2, b & e) SiC and c & f) Si3N4.
By using the above result, in the subsequent step, thickness of SiO\textsubscript{2} cantilever is varied for the set of individual punched objects with an applied load of 50 N and corresponding results are shown in Figure 3. Here, it is important to mention that the effect of thickness variation on displacement sensitivity is carried out only for SiO\textsubscript{2} cantilever since it has exhibited predominant displacement in comparison with other materials. As expected, the decrease in thickness of cantilever found to exhibit high displacement sensitivity. The displacement values with respect to thickness variation for various objects at 50 N load are presented in Table 2. Thus, it has suggested another approach to improve the displacement sensitivity of SiO\textsubscript{2} cantilever by placing punched objects either in an ascending or descending order.

Table 2. Cantilever displacement with different punched objects under maximum load of 150 N

| Material | Displacement for punched objects (10\textsuperscript{5} µm) |
|----------|---------------------------------------------------------|
|          | Ascending | descending |
| SiO\textsubscript{2} | 54.1 | 45.3 |
| SiC       | 4.96 | 4.15 |
| Si\textsubscript{3}N\textsubscript{4} | 15.1 | 12.7 |

From all the above simulation results, it has been clearly evidenced that the SiO\textsubscript{2} cantilever with the
dimensions of length 150 μm, width 30 μm and thickness 10 μm with the ascending order of punched holes (circle, rectangle, T-shape and triangle) for maximum applied load of 150 N has exhibited high sensitivity that would be useful for bio-sensing applications where biological species involves similar load. From the simulation results, it is found that the displacement sensitivity has been raised three times when thickness is decreased from 10 μm to 5 μm. It is due to the fact that the spring constant also found to increase with respect to decrease in thickness\(^{10–12}\). When thickness is decreased, spring constant starts decreasing in turn displacement sensitivity due to decrease of total strain energy stored in the cantilever. Hence, it is worth mentioning that cantilever found to exhibit high sensitivity for the optimal thickness of cantilever. This kind of studies open the way for alternative approach to assess biological sensing in context of surface stress loading where biological species involve like load.

### 4. Conclusion

A basic piezoresistive micro cantilever is designed. Geometrical alterations, punched objects, materials addition, variable load and thickness changes of cantilever have been analyzed using finite element analysis technique to achieve optimal performance of piezoresistive micro cantilever sensor. More specifically, the SiO\(_2\) cantilever with punched circle has shown better displacement sensitivity (applied load of 150 N), similarly, punched objects in an ascending order (circle, rectangle, T-shape and triangle based on their individual displacements) has proven to be optimal condition for the improved displacement sensitivity. The cantilever with minimum thickness also yields highest displacement sensitivity, however, it may be possible that depend on fabrication limitations. From the analyses of all simulation results, the SiO\(_2\) cantilever of 5 μm minimum thickness with punched objects in ascending order for maximum load of 150 N shows highest sensitivity.

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