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Enhancement of deflection of microcantilever beam for improving the sensitivity of biosensor

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Abstract: A study on increase in deflection of microcantilever beam is necessary for improving the sensitivity of biosensor. The sensitivity of a microcantilever biosensor depends on its deflection that occurs due to antigen-antibody interaction .Therefore, to maximize deflection of microcantilever beam is important for measuring analytes in low concentration and for accurate measurement of analytes in samples which is responsible for diagnosis the disease. The deflection can be increased by increasing the length or reducing the thickness of microcantilever beam but it will reduce the resonant frequency of the beam. This lower resonant frequency makes the cantilever susceptible to thermal noise and low frequency vibrations which directly affect the measurement of deflection. The structural variation is done for improving the sensitivity of microcantilever beam by increase the deflection without much affecting the resonant frequency of microcantilever beam. This study proposes a new cantilever design which is more sensitive than regular rectangular cantilever beam. COMSOL multiphysics software is used to analyze it. The proposed cantilever design shows 140% increase in deflection value with 32% decrease in resonant frequency value when compared to standard rectangular cantilever beam. The deflection and stress analysis of the conventional and proposed cantilever beam is performed.

Keywords: Biosensor, Microcantilever beam, Sensitivity, Deflection, Resonant frequency.

1. Introduction

Microcantilever beams are most ubiquitous structures in the field of micro electro mechanical systems. In past it is used only for atomic force microscopy (AFM) and in the recent years it is employed for biological, chemical and physical, sensing and it has extensive application in the arena of medicine, precisely for screening of diseases, blood glucose monitoring and recognition of chemical and biological agents. The upper surface of the microcantilever is coated with a functionalizing layer (sensing element) which is highly specific to a particular analyte. The surface stress is induced due to interaction between the functionalizing layer and target molecules. This difference in stress of upper and lower surface makes the cantilever to bend [1]. The deflection of the microcantilever depends on the distribution and amount of target molecules adsorbed on the surface which depends on the concentration of target molecules in the sample solution. Henceforth, the deflection of the cantilever represents the concentration of the molecules in the sample solution. Label-free detection of DNA hybridization based on hydration induced tension in nucleic acid films using array of eight cantilevers by [2]. The deflection may be upward or downward depending on the type of molecules involved. By measuring the deflection of cantilever beam, molecular species concentration can be obtained by [3].

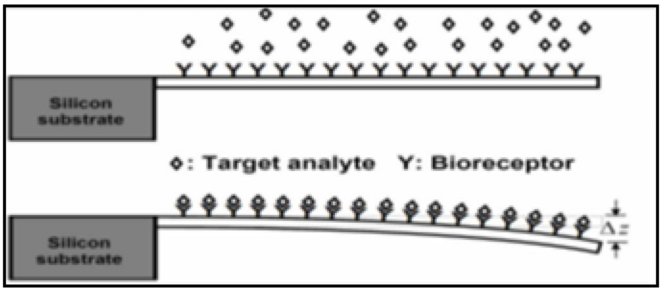

Fig.1. Microcantilever biosensor

It is necessary to increase the sensitivity of microcantilever beam, because the magnitude of force involved is very negligible [4].The cantilever biosensor are deflected generally in the order of nanometer level. These extremely low deflections necessitate use of advanced instruments such as optical and laser deflection detection is used for accurately measuring the deflections. If deflection of cantilever beam is increased, less sensitive readout technique can be used to accurately measure the deflection that will help in decreasing the cost of a biosensor kit. The sensitive cantilever design should efficiently convert the bio molecular stimulus into a large cantilever deflection, deprived of much affecting the resonant frequency of the microcantilever.

1.1. Deflection produced due to surface stress and concentrated load

For the change in surface stress, σ, defined as the reversible work per unit area required to stretch a preceding surface, is correlated to the deflection of the free end of the cantilever, Δz, is given as equation (1),

$$\Delta Z = \frac{4l^3\sigma(1-v)}{Et^2}, \qquad (1)$$

$$\Delta Z = \frac{4Fl^3}{Ebt^3} \qquad (2)$$

Where l and t are length and thickness of the cantilever, respectively; E and ν are Young's modulus and Poisson ratio, respectively. The deflections of a rectangular cross-section cantilever beam with fixed-free boundary condition and subjected to a concentrated load at its free end is mentioned in the equation (2), where b is width of cantilever and F is applied load. By combining the above two equation, we get relationship between induced stress and concentrated load.

$$F = \frac{\sigma bt(1-v)}{l} \qquad (3)$$

The given surface stress can be converted into the concentrated load, so that we can equate the surface stress induced deflection with the concentrated load deflection in the microcantilever beam.

2. Details of Analysis

This study used the microcantilever properties and the experimental data reported in Arntz *et al*. [1]. Using an array of eight conventional microcantilevers it is stated that a maximum surface stress of 0.05 N/m is produced upon injection of 50 μg mL^{-1} myoglobin proteins onto the functionalized surface of the silicon microcantilever, which produced a deflection of 0.9 μm at the free end. The cantilever size was 500×100×0.5 μm, and the elastic modulus and Poisson ratio was 130 GPA and 0.28, respectively. This experimental data and cantilever model will be used as reference in this study.

2.1. Finite element modelling (Numerical analysis)

The finite element modelling is done for the same dimension and same material as reported in Arntz et al [1] in finite element analysis COMSOL MULTIPHYSICS software. The given surface stress 0.05 N/m is converted into force which acts in free edge of cantilever.

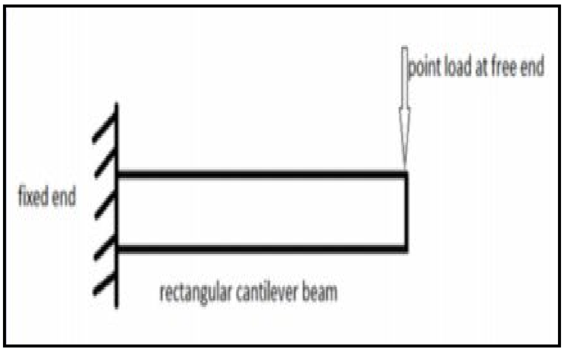

Fig.2. Boundary condition of microcantilever beam

The surface stress can be converted into the force by equation (3). The force calculated is $3.6*10^{-9}$ N.

The deflection value produced using Comsol multiphysics software is 0.93 µm.

2.2. Theoretical analysis

The deflection of rectangular microcantilever beam is calculated theoretically by Stoney's equation. Dimensions of rectangular cantilever beam $500x100x0.5µm^3$.

Young's modulus=130 Gpa

Poisson's ratio are = 0.28

$$Z=\frac{3(1-\nu)\,\Delta\sigma}{E}\left({}^{l}/_{t}\right)^2 \qquad (4)$$

In Stoney's equation, all the values are substituted

The deflection value obtained is 0.83 µm.

2.3. Validation of numerical result

Table 1 Comparison between experimental, simulation and theoretical result

Max surface stress (N/m)	Max. deflection(µm)		
	Experimental	Simulation	Stoney's equation
0.05	0.9	0.93	0.83

For same surfaces stress of 0.05 N/m the simulation result show a maximum deflection of 0.93 µm. The simulation result is about 3% higher than experimental. The theoretical result shows that 7% lower than the experimental results and the 10% lower than the simulation result. Thus, above table validate that numerical analysis has good accord with experimental and theoretical result.

3. Studying the effect of various parameters on sensitivity of micro cantilever beam biosensor

The sensitivity of biosensor depends on the sensitivity of transducer. The design of transducer plays a major role in enhancing the biosensor sensitivity. The microcantilever beam is a transducer for biosensor. Its sensitivity depends on deflection and resonant frequency of microcantilever beam. The influence of various parameters on sensitivity of microcantilever beam is studied.

3.1. Influence of length on sensitivity of microcantilever beam

The thickness and the material of the microcantilever beam are kept constant as reported in Arntz and the length is changed gradually from 100-1000 µm. It is found that increase in length, the deflection of microcantilever beam gets increased but the resonant frequency of microcantilever beam gets decreased.

3.2. Influence of thickness on sensitivity of microcantilever beam

The length and material are kept constant as reported in Arntz and thickness is increased gradually from 0.5-1.5 µm. The corresponding deflection and resonant frequency value are calculated. It is found that increase in thickness increase the resonant frequency, but it will reduce the deflection of microcantilever beam.

3.3. Influence of material on sensitivity of microcantilever beam

The length and thickness are kept constant as reported in Arntz and material is changed. The corresponding deflection and resonant frequency value are calculated. The material which has low young's modulus produce high deflection and low resonant frequency.

3.4. Influence of structural modification

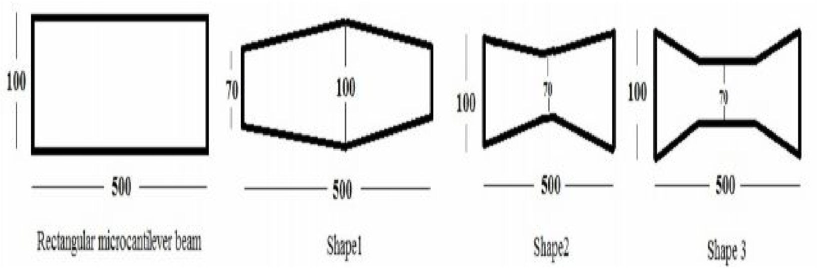

Fig.3. Different shapes of microcantilever beam

The structure which shows maximum resonant frequency and deflection is selected. The resonant frequency to be maximum, which will reduce the vibration of microcantilever beam, thus we make a measurement accurately. The reason for changing the shape of microcantilever beam is to, increase the deflection of the microcantilever beam. The deflection can be increased by reducing the bending stiffness of the microcantilever beam. The reduction in bending stiffness can be done by reducing the cantilever thickness or by reducing cross section area at fixed end. Further, reduction in cantilever thickness will affect the structural integrity for fabrication. Hence, the cross sectional area is reduced by providing notches in the fixed end.

Table 2: Deflection and Resonant frequency value for different shape

Shape	Deflection (µm)	Resonant frequency (KHz)
Shape 1	1.107	2.609
Shape 2	1.094	2.603
Shape 3	1.143	2.760

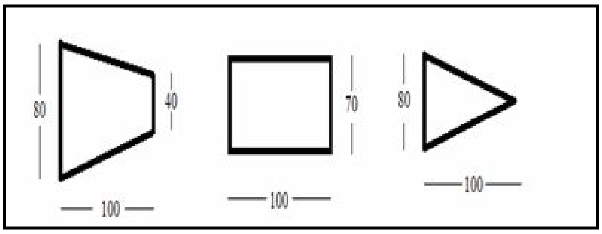

Fig.4. Different notch shapes

The different type of notches is introduced at the fixed end of microcantilever beam. Among this trapezoidal notch shows better trade-off when compared to triangular and rectangular notch.

Table 3: Deflection and resonant frequency for different notch shapes

Notch	Deflection (µm)	Resonant frequency (KHz)	Stress (MPa)
Trapezoidal	2.367	1.732	2.233
Rectangle	2.278	1.568	2.291
Triangle	1.914	1.931	2.408

Proposed design

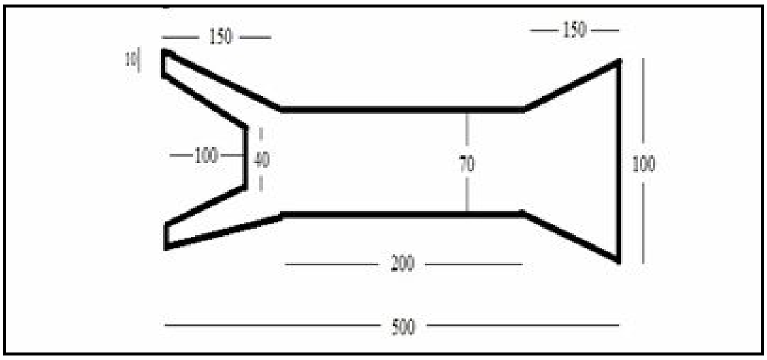

Fig.5. Proposed design of microcantilever beam

4. Design of experiments

To determine the effect of different parameters on sensitivity of microcantilever beam is identified by the taguchi's orthogonal array concept. This study investigates the influence of various parameters and we can find out the most influencing factor on sensitivity of microcantilever beam. MINITAB software is used for the analysis of taguchi method.

4.1. Different values of parameter

From the trial experiment, the six factors are chosen for determining the most influencing factor which affects the sensitivity of microcantilever beam. Three geometric parameters and three material properties are considered for analysis. The five different levels of each factor are chosen and orthogonal array is framed.

Table 4: Different levels for the six factors

Input considerations	Levels				
Length	100	200	300	400	500
Thickness	0.5	1	1.5	3	10
Width	50	100	170	200	300
Young's modulus	70	150	230	5	10
Poisson ratio	0.17	0.23	0.27	0.30	0.33
Density	2200	2330	3100	1190	1300

The simulation is carried out for a combination of L25 orthogonal array design and the response is calculated for the orthogonal array design. After the calculation of result, design is analyzed.

4.2. Responses as per taguchi array

Table 5: Responses as per taguchi array

Length µm	Thickness Mm	Width µm	Young's modulus GPa	Poisson ratio	Density Kg/m^3	Deflection µm	Resonant frequency KHz	Stress MPa
100	0.5	50	70	0.17	2200	0.0936	45.941	0.4870
100	1.0	100	150	0.23	2330	0.0099	133.10	0.2231
100	1.5	170	160	0.27	3100	0.0026	215.670	0.1338
100	3.0	200	5	0.30	1190	0.0027	104.000	0.0058
100	10.0	300	10	0.33	1300	0.0019	479.270	0.0166
200	0.5	100	160	0.30	1300	0.0012	27.587	0.4153
200	1.0	170	5	0.33	2200	0.0933	6.290	0.1967
200	1.5	200	10	0.17	2330	1.0142	12.690	0.1604
200	3.0	300	70	0.23	3100	0.2918	59.980	0.0728
200	10.0	50	150	0.27	1190	0.0072	459.930	0.0410
300	0.5	170	10	0.23	1190	5.3960	1.810	0.4511
300	1.0	200	70	0.27	1300	0.1803	10.070	0.2143
300	1.5	300	150	0.30	2200	0.0353	23.040	0.1356
300	3.0	50	160	0.33	2330	0.0057	54.294	0.0657
300	10.0	100	5	0.17	3100	0.0295	22.946	0.0241
400	0.5	200	150	0.33	3100	0.1803	3.630	0.2143
400	1.0	300	160	0.17	1190	0.1138	14.176	0.2441
400	1.5	50	5	0.23	1300	2.1698	2.980	0.1538
400	3.0	100	10	0.27	2200	0.2508	6.542	0.0725
400	10.0	170	70	0.30	2330	0.0029	56.742	0.0197
500	0.5	300	5	0.27	2330	27.9400	0.485	0.4203
500	1.0	50	10	0.30	3100	3.4531	1.171	0.2070
500	1.5	100	70	0.33	1190	0.2509	4.687	0.1309
500	3.0	170	150	0.17	1300	0.0304	20.959	0.0820
500	10.0	200	160	0.23	2200	0.0016	67.001	0.0223

The response table for signal to noise ratio for deflection and resonant frequency is calculated. For displacement and resonant frequency, The "Larger the Better" model was calculated for S/N ratio. Therefore, young's modulus has the maximum effect on displacement and resonant frequency of microcantilever beam. The design of experiments taguchi method is applied and found that the young's modulus is the most influencing factor for both deflection and resonant frequency.

Based on taguchi analysis, young's modulus of the material plays important role in increase in deflection and resonant frequency of microcantilever beam. For a proposed design, different material are used and analyzed in COMSOL multiphysics software. The polysilicon gives better result when compared to other materials.

Table 6: Deflection and resonant frequency of different materials

Materials	Deflection (µm)	Resonant frequency (KHz)	Stress (MPa)
Silicon	2.367	1.732	2.233
Polysilicon	2.229	1.781	2.231
Siliconoxide	5.089	1.209	2.225

Table 7: Comparison of rectangular cantilever beam and proposed design

Shape	Deflection(µm)	Resonant frequency (KHz)	Stress (MPa)
Rectangle	0.941	2.632	0.49
Proposed design	2.223	1.782	2.231

The proposed design is 140% increase in deflection value with 32% decrease in resonant frequency value compared to standard rectangular cantilever beam.

5. Conclusion

The influence of parameters that is length, thickness and material of the beam are studied. It is found that increasing the length or decreasing the deflection of cantilever beam gets increased, but it results in decrease in resonant frequency. The different shapes are obtained arbitrarily and corresponding deflection and resonant frequency of different structure are calculated among that shape 3 in Fig.3. Shows maximum the deflection and resonant frequency.

The further increase in deflection is obtained by introducing notch in cross sectional area at fixed end which will reduce the bending stiffness of the microcantilever beam. The rectangular, triangular and trapezoidal notch is introduced in cross sectional area at fixed end. Among that trapezoidal notch shows maximum deflection with less reduction in resonant frequency.

The young's modulus is the most influencing factor which affects the deflection and resonant frequency is identified from the taguchi analysis. It is seen that the width, poisson ratio and density does not have that much effect on deflection and resonant frequency when compared to length, young's modulus and thickness of the microcantilever beam.

The different materials silicon, polysilicon and silicon oxide are analyzed for the proposed model it is found that polysilicon gives better result when compared to other materials.

This study proposed and analyzed a new cantilever design which shows high deflection with less reduction in resonant frequency when compared to standard rectangular cantilever beam. The proposed design shows 140% increase in deflection value with of 32% decrease in resonant frequency value when compared to standard rectangular cantilever beam.

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