I. E. SACU and M. ALCI/ IU-JEEE Vol. 13(2), (2013), 1641-1645

DESIGN OF A BASIC PIEZORESISTIVE MICROCANTILEVER BIOSENSOR

Ibrahim Ethem SACU[1], Mustafa ALCI[2]

[1]Department of Biomedical Eng., Erciyes University, Melikgazi, Turkey
[2]Department of Electrical & Electronics Eng., Erciyes University, Melikgazi, Turkey
iesacu@erciyes.edu.tr, malci@erciyes.edu.tr

Abstract: *Microcantilevers are one of the basic micromechanical structures. They are fixed at one ends and the other ends can move freely like a diving board. Their sizes are in the micrometer and nanometer ranges. Microcantilevers are called microcantilever sensors when their surfaces are functionalized to detect specific molecules. Since these sensors have offered remarkable possibilities in detection, they have been used in many fields such as clinical diagnosis, drug screening and pathogen detection. In the microcantilever sensors, various detection methods are available such as piezoresistive, optical, capacitive and piezoelectric. Each sensing method holds own advantages and disadvantages. By the advantage of allowing integration of the read-out electronics on the same chip, piezoresistive detection becomes prominent. So piezoresistive detection is chosen in this work and a basic piezoresistive microcantilever biosensor design is introduced. Furthermore, by making geometrical alterations on microcantilever and piezoresistive layer, effects of these variations upon sensitivity, vertical displacement and change in resistance are investigated. Additionally, effects of different shaped holes upon sensor are studied.*

Keywords: *Microcantilever, piezoresistive detection, biosensor.*

1. Introduction

In recent years, microcantilever sensors have attracted great attention because of their considerable potentional of detecting molecules. Microcantilevers are miniature structures like diving boards which are fixed at one end. They were first used as a force probes in Atomic Force Microscopy (AFM). When a microcantilever surface is functionalized to detect biomolecules, it is called the microcantilever biosensor. Microcantilever sensors are basic micromechanical systems which can be fabricated using conventional micromachining techniques. And their sizes range from micrometers to nanometers [1,2].

Microcantilever sensors have been used in biological sensing, chemical sensing and environmental sensing applications. Examples of biological sensing applications are DNA detection, antigen-antibody binding and gene expression [3,4].

Microcantilever sensors offer high sensitivity, low-cost fabrication, ease of use, mass production, label-free detection and parallel processing within a microarray format. The mentioned properties above are desired by any sensor technology. So microcantilever sensors can be ideal candidates for sensing applications [4,5,6].

Microcantilever biosensors utilize a principle that is chemical binding or physical adsorption of biomolecules on the surface of a cantilever changes the cantilever's mechanical properties [7,8]. In these sensors, one surface of the cantilever is coated with antibodies, proteins or stimuli-responsive polymers, whereas the other surface of the cantilever is not coated. In other words, only one surface of the cantilever is functionalized [4].

In the microcantilever sensors, two working modes are available, that are referred as static or dynamic mode. In the static mode, binding or adsorption of target molecules on the surface of the cantilever induces a surface stress change across cantilever surfaces. As shown in Figure 1, the induced surface stress cause bending of the cantilever. The bending can be positive or negative direction depending on molecular forces. On the other hand, working in dynamic mode, binding or adsorption of the molecules on the cantilever surface changes total mass and this mass change cause a shift in cantilever resonance frequency [5,9].

Response of a microcantilever sensor working in static mode or dynamic mode can be monitored by capacitive, piezoresistive, piezoelectrical, optical and electron-tunneling detection methods [10]. Although optical methods is very sensitive and commonly used, it has several disadvantages. These disadvantages are requirement of external devices, periodical alignment and calibration, being not portable and inability to work within a microarray format [11,12]. On the other hand, all of these drawbacks are unavailable in the piezoresistive method. Additionally, in piezoresistive method, signal

Received on: 03.05.2013
Accepted on: 07.08.2013

processing step is very easy due to electrical signal characteristics [13].

In this study, a basic piezoresistive microcantilever biosensor design is introduced. In addition, effects of geometrical alterations of microcantilever and piezoresistive layer upon sensitivity, vertical displacement and the change in resistance are investigated.

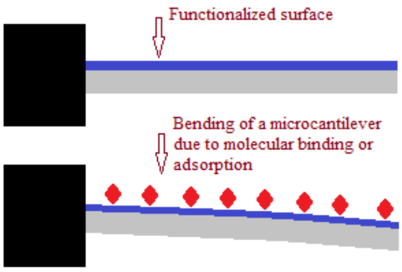

Figure 1. Bending of a cantilever due to the molecular interaction

2. Working Principle of Piezoresistive Detection

When a piezoresistive material such as doped silicon is strained, its electrical conductivity changes and thus its resistivity changes also. So, by incorporating the piezoresistive material into a microcantilever, this effect can be used to monitor stress and therefore deflection of the cantilever. Because, when a functionalized piezoresistive microcantilever is exposed to target molecules, there is a interaction between probe and target molecules. This interaction induces a surface stress which cause cantilever bending and therefore piezoresistive material is undergone a strain. Due to straining of the piezoresistive material, a resistance change occurs. And this resistivity change can be measured easily by using a Wheatstone bridge [3,12]. Consequently, a relationship between resistance change and the number of detected molecules is established. Piezoresistivity is very common transduction mechanism for microelectromechanical systems such as force sensors, accelerometers, pressure sensors, stress sensors, microphones, temperature sensors and chemical sensors [14].

In the piezoresistive microcantilever sensors, when a microcantilever bends due to molecular binding or adsorption, the piezoresistors that are integrated with microcantilever will experience a strain. The experienced strain will result in resistance change and this change is given by the following equation [11,15]:

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

where σ_l and σ_t are longitudinal and transverse stress; π_l and π_t are are longitudinal and transverse piezoresistive coefficients, respectively. As a function of the surface stress change, microcantilever deflection can be described by Eqn (2):

$$\delta = \frac{3L^2(1-v)}{Et^2}(\sigma_1 - \sigma_2) \tag{2}$$

where δ, v, E, L, t and $(\sigma_1-\sigma_2)$ are deflection, Poisson's ratio, Young's modulus, microcantilever length, thickness of microcantilever and differential surface stress, respectively [16]. For a applied force on the free end of the microcantilever, the resulting resistance change is given by:

$$\frac{\Delta R}{R} = \pi_l \sigma_{max} = \beta \frac{6L\pi_l F}{Wt^2} = \beta \frac{3Et\pi_l \delta}{2L^2} = \beta \frac{3\pi_l (1-v)}{t}(\sigma_1 - \sigma_2) \tag{3}$$

where F, W and β are the applied force, width of the microcantilever and a correction factor between 0 to 1, respectively [16,17,18].

From Eqn (3), it can be seen that there are ways for increasing the resistance change: one of them is increasing the differential surface stress, and the second one is decreasing the thickness of the microcantilever. Material properties also effect the resistance change.

3. Simulations

The simulations are conducted in three steps. In the first step, by altering thicknesses of microcantilever and piezoresistive layer separately, effect of the applied force on the deflection of the microcantilever and change in pizeoresistance are observed. In the second step, for appropriate layer thicknesses that are determined by using results of the first step, sensitivity and resistance change is tried to increase by placing a rectangular hole with changing position on the surface of the microcantilever [19]. In the third step, influences of different shaped holes on the sensitivity and change in piezoresistance are indicated.

The sensor model used in the first step and its dimensions are shown in Figure 2 and material properties used in the simulations are listed in Table-1. In the sensor models, SiO_2 is selected for the microcantilever because of the low Young's modulus and Si is selected for the piezoresistive layer. Evaluation version of the Intellisuite have been employed during simulations.

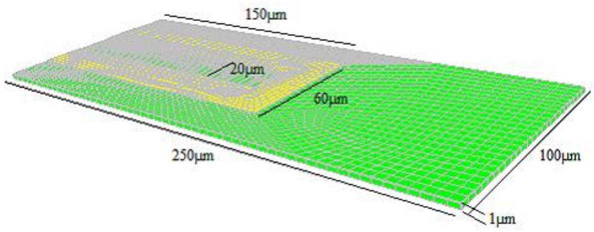

Figure 2. The sensor model used in the first step

Table 1: Material properties used in the simulations [20,21].

Material	Material

property	Si	SiO_2
Young's modulus	130 GPa	70 GPa
Poisson's ratio	0.278	0.17
Piezoresistive coefficients	π_{11} = 6.6e-11 π_{12} = -1.1e-11 π_{44} = 138.1e-11	-
Density	2.328 g/cm^3	2.2 g/cm^3

3.1. The First Step: Effects of layer thicknesses upon sensitivity

In this step, while the piezoresistive layer thickness is kept fixed at 0.2 µm, the microcantilever thickness have been varied from 0.5 µm to 2.5 µm. Therefore, the effect of microcantilever thickness on the deflection of the cantilever and the resistance change is monitored. The applied pressure on the surface of the microcantilever is 40 Pa which corresponds to 1 µN (40 Pa x 250 µm x 100 µm). As shown from Figure 3, the simulation results show that the resistance change increases as the microcantilever thickness decreases. So it can be inferred that in order to make the resistance change maximum, the thickness of the microcantilever should be made as tiny as the fabrication process permits.

On the other hand, while the microcantilever thickness is kept fixed at 1 µm, the piezoresistive layer thickness have been varied from 0.2 µm to 1.5 µm. Thus, the effect of the piezoresistive layer thickness on the deflection of the cantilever and the resistance change is examined. It can be seen from Figure 4 that, the resistance change increases as the piezoresistive layer thickness decreases. So the piezoresistive layer thickness could be chosen as tiny as possible. But there is a point to keep in mind that even though sensitivity is increasing by making the piezoresistive layer thickness tiny, thermal and other noise sources are also increasing with decreasing layer thicknesses [20].

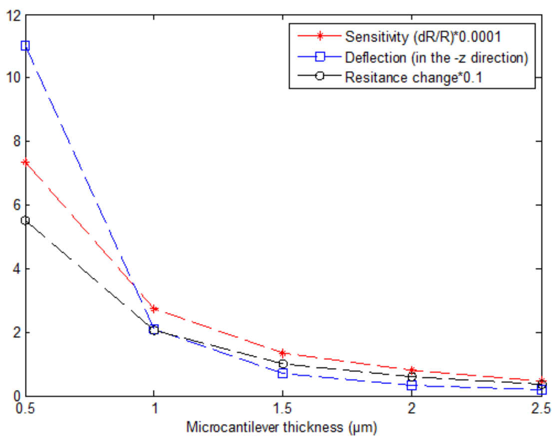

Figure 3. Microcantilever thickness versus resistance change, sensitivity and deflection.

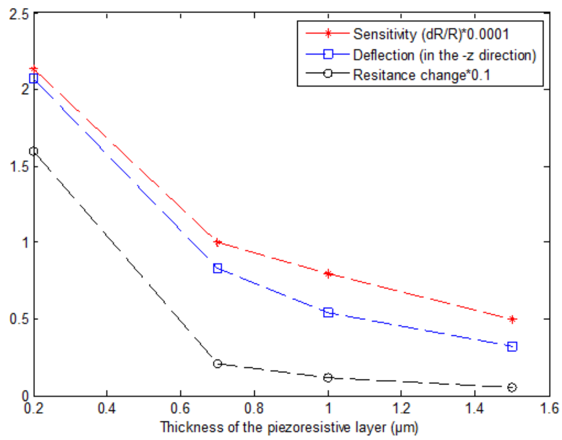

Figure 4. Piezoresistive layer thickness versus resistance change, sensitivity and deflection

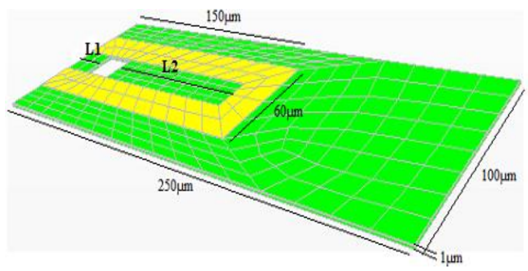

Figure 5. The sensor model used in the second step

3.2. The Second Step: Effect of rectangular hole position on sensitivity

In this step, the sensor model shown in Figure 5 is used. The piezoresistive layer thickness and the microcantilever thickness are 0.2 µm and 1 µm, respectively. The dimensions of the placed hole on the sensor model are 20 µm x 20 µm. 250 nN in the direction of –z is applied on the free end of the microcantilever. Under this loading condition, the position of the hole is changed and the effect of the hole position on the deflection of the cantilever, the sensitivity and the resistance change is investigated.

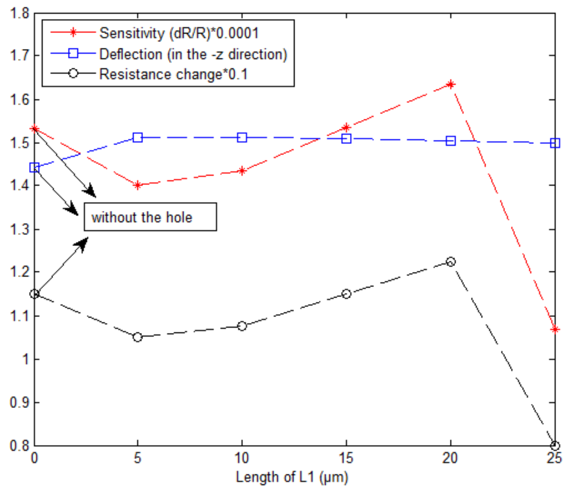

Figure 6. The L1 length versus the resistance change, sensitivity and deflection

The simulation results of the second step displayed in the Figure 6 indicate that when the position of the hole is 20 μm far from the fixed end of the microcantilever, the maximum sensitivity and the resistance change are reached. On the other hand, placing the hole on the cantilever can not always contribute to the sensitivity positively; on the contrary, sometimes it has a negative effect on the sensitivity. As a result, while designing a piezoresistive microcantilever sensor, the shape and the position of the hole should be chosen carefully.

3.3. The Third Step: Effects of different shaped holes on sensitivity

In this step, a 250 nN is applied to free end of the microcantilever in the negative z direction. Rectangular, diamond-shaped, circular, hexagonal and star-shaped holes depicted in Figure 7 are placed on the microcantilever, independently and separately. By doing this, five different sensor models are obtained. For each model, separate simulation is conducted.

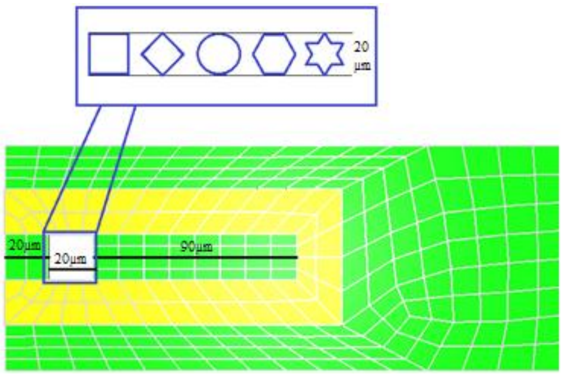

Figure 7. The sensor model with different shaped holes for the third step

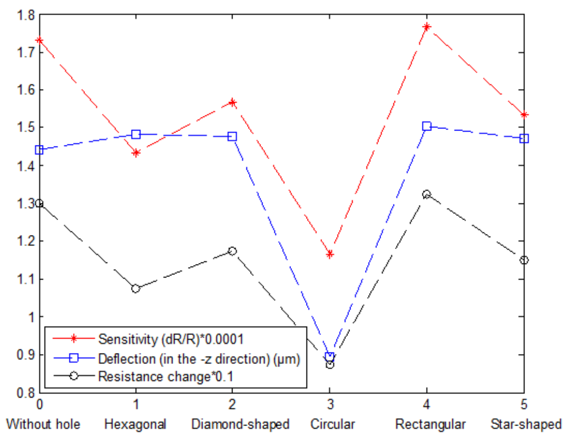

Figure 8. Sensitivity, deflection and resistance change plot of different shaped holes

It is clearly demonstrated in Figure 8 that from the point of sensitivity, just the rectangular hole can increase sensitivity and other shaped holes decrease sensitivity. On the other hand, from the point of deflection, just circular hole decreases deflection, whereas the other shaped holes increase deflection. When it is considered from both of sensitivity and deflection point, only rectangular hole increases both sensitivity and deflection, for this reason we suggest using of the rectangular holes on microcantilever biosensors. But it should not be forgotten that we have conducted our simulations employing only five different shaped holes, so there can be different shaped holes which are better than rectangular one.

4. Conclusion

In this study, a basic piezoresistive microcantilever sensor is designed. And the effects of the geometrical changes of the microcantilever and different shaped holes on the sensitivity are investigated. The simulation results show that the thicknesses of the microcantilever and the piezoresistive layer should be chosen as tiny as possible. Moreover, according to the position and the shape of the hole, placing the hole on the microcantilever can be increase the sensitivity. But there is a point to mention that Si and SiO_2 materials are selected in our simulations. So selection of different materials may change simulation results and graphics

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Ibrahim Ethem SACU was born in Kayseri, Turkey. He received the B.Sc. and M.Sc. degrees in Electrical & Electronics Engineering from the Erciyes University in 2010 and 2012, respectively. Since 2010, he has been a member of academic staff with Erciyes University, Engineering Faculty, Biomedical Dept., Kayseri, Turkey. His current research interests include medical electronics, biosensors and circuit design.

Mustafa ALCI was born in Kayseri, Turkey, in 1957. He graduated at the Electronic Dept. of the Technology Faculty, Gazi University, Ankara, in 1979. Then he received the B.Sc. degree from Erciyes University, Kayseri, in 1983, M.Sc. degree from the Middle East Technical University, Ankara, in 1986 and Ph.D. degree from Erciyes University, Kayseri, in 1989, respectively, all in Electrical & Electronics Engineering. Since 1979, he is a member of academic staff with Erciyes University Engineering Faculty, Electronic Engineering Dept., Kayseri, Turkey. His current research interests include image processing, noise and coding artifacts suppression, fuzzy systems, medical electronics, chaotic systems and circuit design.