Mody University International Journal of Computing and Engineering Research
Vol. 1 Issue 2, 2017, pp.104-108
ISSN: 2456-9607 (Print) 2456-8333(Online)

Design and Simulation of Micro-cantilever Based Sensor for Glucose Detection

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Received 15 Oct. 2017, Published 05 Nov. 2017

Abstract: Proper management of blood glucose levels is a major challenge in diabetes therapy. To avert further complications in diabetes, glucose level detection is essential. In this work, ZnO-thin film driven micro-cantilever based sensor is designed to determine the blood sugar. The sensor is a Con A/aminopropylsilatrane (APS)-modified piezoelectric cantilever which detects the blood sugar level and estimates the change in mass by monitoring the resonance frequency shift of the cantilever. The finite element modeling of the sensor was carried out using Comsol Multiphysics (ver. 5.2) and results demonstrate that by observing the frequency shift of the cantilever, this sensor can detect glucose level from 50 mg/dL to 500 mg/dL. The mass sensitivity of the proposed sensor is 1.94×10^{-15} g/Hz.

Keywords: *Glucose, Zinc oxide, cantilever, frequency, Piezoelectric.*

1. INTRODUCTION

Diabetes mellitus (DM) is a metabolic disorder characterized by a fluctuation in the blood glucose level outside the normal range that affects blood vessels and nerves and therefore causes and death throughout the world. Clinical diabetes therapy requires precise monitoring and maintaining of blood glucose levels as close to normal as possible to reduce the risk of emergency complications such as the retinopathy, nephropathy, and hypo-and hyperglycemia [1–3]. So far, existing sensing techniques have been validated, such as glucose-based non-invasive glucose sensors and enzyme-based biosensors; however, impaired responses and unpredictable drift make these unsuitable for long-term therapeutic practice [3]. Therefore, the control of diabetes still remains a great challenge. In order to solve these problems, microcantilever-based sensors have been proposed, which have high sensitivity and broad application in the fields of implantable biosensors, nano- robotics, detection, and environmental monitoring sensors [4-8]. A number of glucose biosensors with various transduction techniques have been reported, including electrochemical, optical, and electromagnetic spectroscopy biosensors. Among these types, electrochemical biosensors are the most widely accepted for the detection of glucose level in blood.

Piezoelectric cantilevers can be configured in variety of ways for sensing and actuation applications [6]. Usually, micro-cantilever based sensors, works at their mechanical resonance frequency. The change in resonance frequency is sensitive to bio- or chemical events happening on cantilever surfaces. Frequency based sensor has advantage compared to their counterparts (capacitive or piezoresistive), because frequency change (Δf) is easy to measure, compared to other techniques. Self-actuation of piezoelectric cantilever is possible by applying voltage signal across the piezoelectric layer and this can be very useful in blood sugar detection.

In the present work, zinc oxide (ZnO) thin film based micro-cantilever is designed for glucose level detection. Lead Zirconate Titanate (PZT) or Aluminium Nitride (AlN) thin films are the alternative piezo material choices. Rather, ZnO thin films have low dielectric constant and have other key practical advantages like bio-compatible, low cost, easy fabrication process, MEMS process compatibility and environment friendly nature [9, 10]. Further, these piezoelectric cantilevers may be functionalized with various probe molecules (e.g., DNA, proteins, and antibodies) and used as biosensors for target molecules (e.g., DNA and antigens) [11]. In this paper, Con A/aminopropylsilatrane (APS) coated ZnO cantilever is designed in Comsol Multiphysics. This sensor is further specialized to act as a functional glucose sensor, where by the resonance frequency of the piezo-cantilever shifts with mass loading when glucose molecule absorbs on a treated surface. The simulated and analytical results are compared and correlated.

2. THEORY

After the initial step, the sensor nodes are responsible for self-organizing and forming an appropriate network infrastructure with multi hops connections between sensor nodes. After this the sensor nodes starts gathering data in form of seismic, infrared etc. about the surrounding environment, using either continuous or event-driven working nodes. It often provides location information using global positioning system (GPS) or some of the location based algorithm. All the information is gathered and is analyzed by forming global view of the monitoring objects [2]. The WSN are deployed over wide area and thus uses large number of nodes. If the nodes lost all the energy, it is wasted. We do not consider it to recharge and reuse sensor node and hence because of this reason the cost of node for practical uses are high deployed in harsh and complicated environment, the sensor nodes are difficult to recharge once their energy is consumed. The nodes even have limited communication capacity and computing power. So how to optimize the communication path, improve energy-efficiency as well as load balance and increase the network lifetime has become an important consideration while designing of routing protocols of WSN. Hierarchical based routing protocols are widely used for their high energy-efficiency and good expandability. The main idea of them is to choose some nodes in charge of certain routing region. These selected nodes have greater performance as compared to other nodes which leads to the incompletely equal relationships between sensor nodes.

A micro-cantilever is mechanically fixed on one end and free to vibrate at the other end. Figure 1 shows the schematic sketch of micro-cantilever, where ZnO piezoelectric layer is sandwiched between two electrodes and utilized to self-actuation. This can be considered sinusoidally driven forced harmonic oscillator.

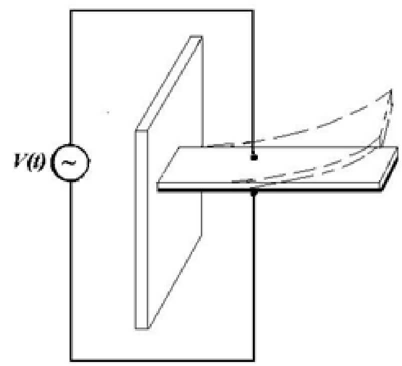

Figure 1: Cantilever in self-actuation mode

The cross-section of a unimorph piezoelectric cantilever consisting of five layers i.e. substrate, oxide, bottom electrode, piezoelectric, isolation and top electrode is shown in figure 2.

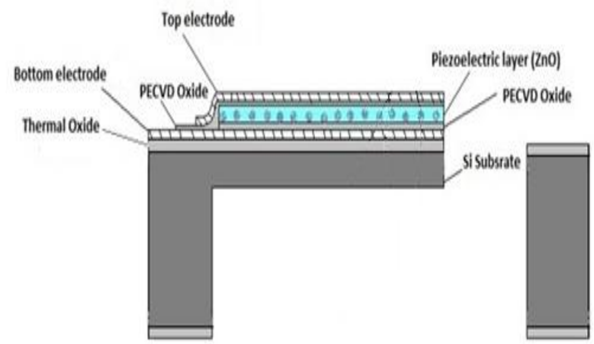

Figure 2: A schematic drawing of the cross section of a piezoelectric cantilever

The modeling of a piezoelectric cantilever to be used for glucose detection is carried out in the present work. The piezoelectric cantilever is chemically modified with APS followed by absorption of glucose specific lectin concanavalian A (ConA) onto the APS modified sensor as shown in figure 3.

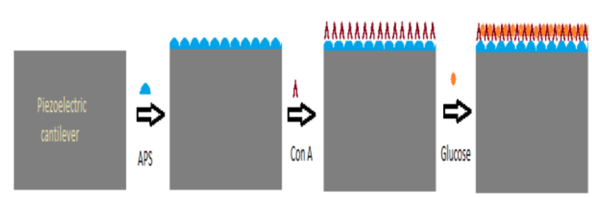

Figure 3: A schematic sketch of cantilever modification

Con A has a strong affinity for glucose. Therefore, upon absorption of glucose to the Con A/APS modified sensor, the resonance frequency of the micro-cantilever shifts due to the added mass. By measuring the shift in the resonance frequency of the cantilever, one can detect the glucose level. The length and width of the cantilever is identical for all the layers. The properties of materials used in the model are listed in table 1.

Table 1: Material properties used in COMSOL simulations.

Material	Density (Kg/m^3)	Young's modulus (GPa)	Poisson's ratio	Thickness (μm)
Si	2329	170	0.28	25
SiO_2	2650	73.1	0.17	1
Pt	21450	168	0.38	0.4
ZnO	5680	211	0.303	2
PECVD oxide	2300	85	0.25	0.15

The first natural frequency of a simple cantilever can be calculated by equation 1.

$$f = \frac{3.51}{2\pi}\sqrt{\frac{EI}{mL^4}} \qquad (1)$$

where E, I, m and L are the elastic modulus, the moment of inertia about the neutral axis, the mass per unit length and the beam length, respectively. The fundamental resonant frequency for a multi-layered rectangular cantilever beam is given as:

$$f = \frac{3.51}{2\pi}\sqrt{\frac{E_e\, I_e}{L^4\, m_e}} \qquad (2)$$

Where E_e, I_e and m_e are the effective young's modulus, equivalent rational inertia and effective mass per unit length of the cantilever beam, respectively. The equivalent young's modulus can be calculated by

$$E_e = \sum_{i=1}^{N} \frac{E_i h_i}{h_i} \qquad (3)$$

where N is the no. of layers of the composite structure and h is the thickness of each layer.

Per unit length equivalent mass m for the micro cantilever is given by

$$m_e = W \sum_{i=1}^{N} t_i \rho_i \qquad (4)$$

where W is the width of the cantilever, t_i and ρ_i are the thickness and density of each layer, respectively. The effective mass of inertia is expressed as:

$$I_e = \sum_{i=1}^{N} I_{ci} + A_i\,(y_c - y_{ci})^2 \qquad (5)$$

Where $I_{ci} = \frac{E_i w h^3}{12 E_1}$ (6)

$$A_i = \frac{E_i w h_i}{E_1} \qquad (7)$$

$$y_{ci} = \frac{h_i}{2} + \sum_{j=1}^{i-1} h_j \qquad (8)$$

When a cantilever beam is subjected to harmonic excitation acting at the tip of the beam, the equivalent spring constant is obtained from the following equation:

$$K_{eq} = \frac{3EI}{L^3} \qquad (9)$$

where E, I, and L are equivalent young's modulus, equivalent moment of inertia and effective length of the cantilever beam, respectively.

The mass sensitivity is a key parameter representing the sensor performance. It can be defined as the variation in a measurable parameter as a function of added mass to the sensing surface. The mass sensitivity of the glucose sensor is given by the following equation [12]:

$$\frac{\Delta m}{\Delta f} = R^{-1} = -\frac{2m_{eff}}{f_o} \qquad (10)$$

Where R is the mass responsivity of the sensor and m_{eff}, f_o are the effective mass and resonant frequency of the sensor before mass loading, respectively.

3. FINITE ELEMENT MODELING

The glucose sensor is designed and simulated using finite element method (FEM) COMSOL mutiphysics [13]. FEM gives information about resonance frequency and quality factor of the cantilever. Procedure is initiated by selecting physics and defining geometry of micro-cantilever structure. Materials listed in table 1 are added from MEMS library and allocated to appropriate layer. The length of the senor is 200µm and width is 60µm. The thickness of each layer is given in table 1.

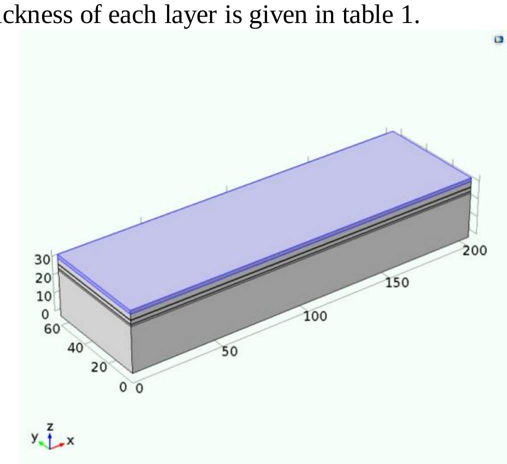

Figure 4: 3D model of self-actuated cantilever based sensor

Figure 4 shows the 3D model of the designed sensor. Using solid mechanics module the mechanical boundary conditions are applied to appropriate layer structures i.e. one end of the model is fixed and the other end is made to move freely.

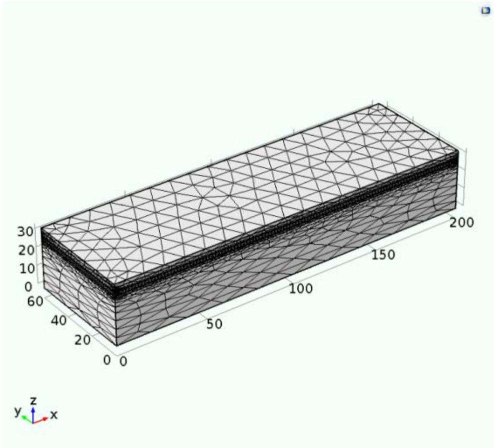

Figure 5: Meshed model

After that, step for setting up the physics was done. The mesh element of cantilever beam is selected as fine tetrahedral. The 3D meshed geometry as shown in figure 5 is submitted for the eigen frequency study. After computing the model by, different plots can be observed in the result section.

5. Results and Discussion

The eigen frequency simulation of Con A/APS modified piezoelectric cantilever is carried out to find out the natural frequency of the sensor.

Table 2: Simulated and analytical result

Cantilever Type	Simul. res. freq. (kHz)	Exp. res. freq. (kHz)	Deviation (%)
ConA/APS modified ZnO Cantilever	1060.18	1062.08	0.17
Glucose/ConA/APS modified ZnO cantilever	1060.03	1061.93	0.17

The simulation is repeated when glucose is added to the cantilever. Figure 6 shows the simulated plot of the cantilever for glucose level of 500mg/dL and simulated natural frequency of the sensor is 1061.9 KHz .The simulated and analytical results are listed in table 2 for comparison. It is observed that simulated result differs very slightly from the analytical value of the resonant frequency for glucose sensor. The recommended range of blood sugar without diabetes is 70 to 130mg/dL and in the present work, the designed sensor can detect 50 to 500 mg/dL.

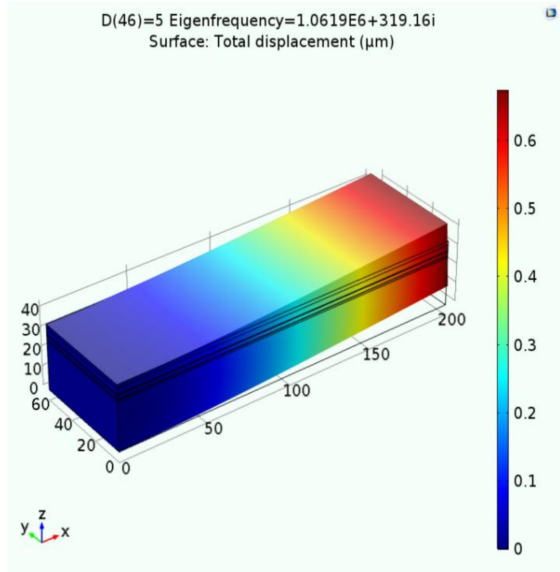

Figure 6: Eigen frequency plot at 500mg/dL glucose level

In Comsol multiphysics when glucose is added to the cantilever as added mass, a slight shift in the resonant frequency of sensor takes place. It should be noted that the resonant frequency of the cantilever is inversely proportional to the effective mass as given in equation (2). Therefore, it decreases with increasing the mass of the sensor. The Frequency shift vs glucose level is plotted in the figure 7. It can be observed that the shift in the resonant frequency is proportional to the added mass, so a linear plot of Δf vs glucose level is obtained. Further, the Δf can be used to detect the level of glucose present in the blood. For 500 mg/dL glucose level, a shift of 147.65 Hz is attained. Hence, using equation (10) the mass sensitivity of the proposed sensor is 1.94fg/Hz.

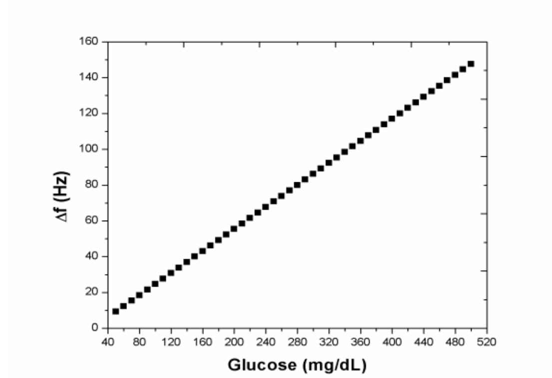

Figure 7: Shift in the resonant frequency plotted with glucose level

5. CONCLUSION

A micro-cantilever based glucose sensor is designed and simulated in comsol. Here, piezoelectric ZnO thin film was used as a self-actuation layer. The proposed sensor can detect the blood sugar level from 50 mg/dL to 500 mg/dL. With femtogram mass sensitivity, this sensor shows a great promise for the development of frequency detection bio-sensors.

ACKNOWLEDGMENTS

Authors are thankful to Prof. Santanu Choudhary, Director CSIR-CEERI Pilani for continuous support and encouragement.

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