Design and Simulation of Feedback Controller for Biosensor

Rupali Jumbadkar
M-Tech Student
Dept. of Electronics Engg.
Shri Ramdeobaba Kamla Nehru
Engineering College,
Nagpur

Jayu Kalambe
Asst. Professor,
Dept. of Electronics Engg.
Shri Ramdeobaba Kamla Nehru
Engineering College,
Nagpur

ABSTRACT

In this paper, we proposed the designing of control system for cantilever based biosensor. In cantilever based biosensor, as the device dimension changes the sensitivity of the device reduces which is of prime important in biosensor. To improve the sensitivity of the device we propose to fabricate the digital feedback control system which will take care of providing the predeflection of the cantilever beam to maintain the constant gap between the electrodes inspite of variation due to fabrication process. We have design digital feedback control system for biosensor. The stability and related issues of the proposed device is discussed.

General Terms

Design, modelling and simulation.

Keywords: Biosensor, Microcantilever, Feedback system, FPGA.

1. INTRODUCTION

Micro-Electro-Mechanical Systems (MEMS) is the integration of mechanical elements, sensors, actuators and electronics on a silicon substrate through microfabrication technology while the electronics are fabricate using IC process sequences (CMOS, Bipolar or BICMOS processes), the micromechanical components are fabricated using compatible micromachining processes that selectively etch away parts of the Si wafer or add new structural layers to form the mechanical and electromechanical devices. MEMS technology has generated a significant amount of interest in the government and business sectors. This interest is happening due to the potential performance and cost advantages with micro-scale devices fabricated based o a silicon processing technology [1].

Since the beginning of micro-electro-mechanical systems in the early 1970s, the significance of the biomedical applications of these miniature systems were realized. Biomedical or Biological Micro-Electro-Mechanical Systems (BioMEMS) are now a heavily researched area with a wide variety of important biomedical applications. MEMS offer great potential advantages over other types of implantable systems for certain applications due to their small size scale, electrical nature, and ability to operate on short time scales. BioMEMS and devices have been used as biosensors and the resulting biochips can allow sensitive, rapid, and real-time measurements. Mechanical detection for biochemical entities and reactions has more recently been used through the use of micro- and nano-scale cantilever sensors on a chip. These cantilever sensors can be used in two modes, namely stress sensing and mass sensing. In stress sensing mode, the biochemical reaction is performed selectively on one side of the cantilever. A change in surface free energy results in a change in surface stress, which results in measurable bending of the cantilever. Since the stress detection method used with cantilevers is based upon a change in surface energy, it can be speculated that the DNA or protein layers are continuous over the area of gold-coated cantilevers, as is the case with Self-Assembled Monolayers (SAMs), and hence result in a uniform surface stress change, resulting in the cantilever bending [2].

Microfabricated cantilever-based sensors are widely used for chemical and biochemical sensing. These cantilevers transduce changes in temperature, mass, or surface stress into a (nano) mechanical response. Antibody immobilization, followed by specific antigen binding or DNA hybridization, induces surface stresses in the cantilever; due to van der Waals, electrostatic, or steric interactions. These surface stresses bend the cantilever. Bending of the cantilever can be detected by various methods as reported in [3,4,5,6].

2. CANTILEVER BASED BIOSENSOR

Cantilevers are used as nanomechanical biosensor, micro fabricated with the standards Si technology. There Sizes are in micrometer or nm ranges.

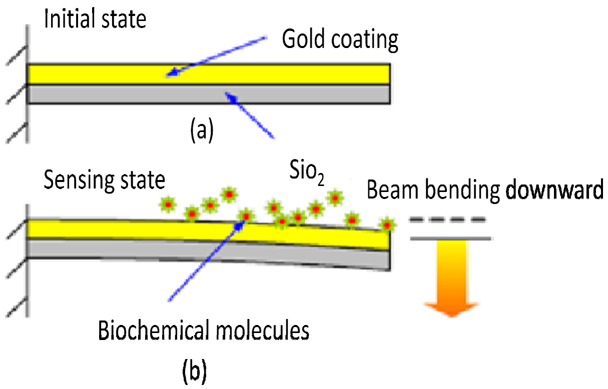

Figure 1. Cantilever beam response.

(a) Initial state and

(b) Sensing state

Figure 1. shows a schematic diagram for the cantilever based biosensor, where a target biochemical species absorbing on a functionalized surface of the MEMS cantilever beam. When the biochemical sample is applied to the MEMS cantilever sensor, some of molecular sample is binding with gold layer, the gold surface is either tension or compressive. This causes the MEMS cantilever to deflect and its deflection founds to be exponential to the biochemical concentration. When the gold layer expands, the beam bends and gives deflection in range of nm[1].

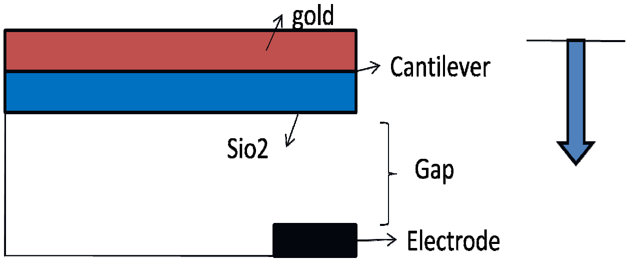

Figure 2. Cantilever beam with biosensor

Figure 2 shows basic schematic diagram for cantilever based biosensor with electrode. When the deflection due to antibodies antigen interaction occurs, the cantilever beam touches the electrode, resulting in increasing current as the contact area between electrode and cantilever beam increases.

When biomolecule attached to antibodies changes the surface stress leading to a bending of cantilever. The surface stress is very small of the cantilever to the tune of a few tens of nanometer. The major issue for the device fabrication is the creation of gap between the electrodes of this order. During etching process there is variation in thickness of about 10% is observed this will affect the sensitivity of the device, i.e. the beam will give less deflection on same amount of antibodies antigen interaction and will affect the resulting current through the same. We cannot measure the response of the device correctly due to this major fabrication problem.

3. DESINGNING OF FEEDBACK SYSTEM

Feedback control of the cantilever that attenuates the thermo-mechanical fluctuations from the observed cantilever motion to minimize vibration of the cantilever tip.Analog components suffer from thermal drift as the ambient temperature changes during an experiment. Also some of the analog components must be replaced to maintain stability and performance [7]. The displacement of the cantilever is detected by an electrical method and the control voltage is applied to the cantilever by the feedback control system[8].

To control displacement i.e. for stability of the system, feedback loop must be employed. Feedback control of the cantilever must be such that it attenuates the thermo-mechanical fluctuations from the observed cantilever motion to minimize vibration of the cantilever tip. Also, as the analog components suffer from thermal drift as the ambient temperature changes during an experiment, some of the analog components must be replaced to maintain stability and performance.
we will employ the digital control system for our sensor.

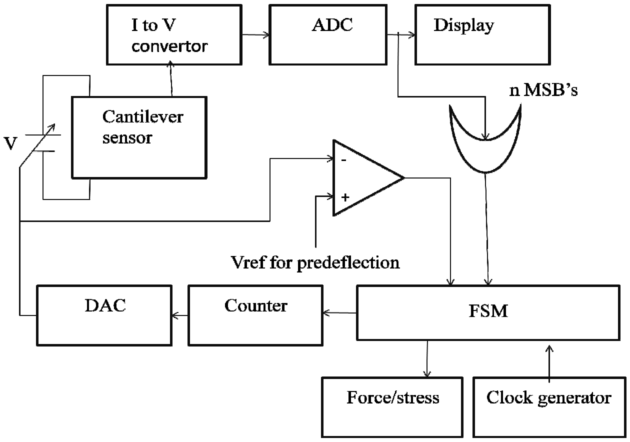

Figure 3. Digital Feedback Control System

3.1 Device Description

Ideally current through the cantilever based sensor will be zero. So, the output of I to V convertor will be zero, which gives zero digital output from ADC, so OR gate output is also zero, applied to the FSM.

FSM will supply the cantilever so as to make contact i.e. to close the sensor, it will increment the counter accordingly. This counter value is then converted into analog voltage by DAC and applied to the cantilever sensor. Due to the applied voltage, the cantilever gets deflected and gap between cantilever and electrode get decreased. As the gap is not reduced to zero, current will be zero and the process gets repeated till the current starts flowing through the cantilever and the electrodes.

When the current starts flowing through the cantilever sensor, that means the cantilever beam is attached to the electrode. The equivalent voltage will get generated through I to V convertor and is converted to digital value from ADC. As their will be at least one bit equal to '1', output of OR gate will be '1',so, FSM will get input as logic 1, which we will decrement the voltage at the cantilever through counter and DAC. The cantilever will regain its original position, the current will reduce to zero. To avoid the noise we have to use MSB's of ADC output ignoring 2 or 3 LSB's. Also, instead of OR gate we can use a comparator, where one input will be output of I to V convertor and one will be reference voltage that we will decide from coventor analysis for current Vs voltage.

When the current starts flowing through cantilever that voltage will decide the reference voltage for predeflection for cantilever sensor. Now, the predeflection reference voltage is applied to one input of comparator and second input will be the output of DAC i.e. of counter. Now, again we will increase the voltage across cantilever through counter till we get the equivalent voltage of predeflection voltage value. So, we achieved the predeflection.

FSM will switch to Force/stress and will get displayed that now we have to apply stress on cantilever beam by applying antibodies on it. Depending upon the amount of antibodies antigen interaction applied on beam, the beam starts deflecting, and as it touches the electrode, the current start flowing. As the contact area increased (analysis of contact area on coventor) the current increases and we will monitor the voltage equivalent to the current through cantilever and electrode on the display through I to V convertor. This current is proportional to the amount of antigen attached to the beam surface

4. DEVICE DESIGN

A digital circuit can be implemented using either DSP or FPGA platform for the above control system to minimize the above maintained problems. We will design an ASIC for digital feedback control system. We will use FPGA platform to design Digital feedback control system. The clock generator will reduce the internal clock of the ASIC to reduce the power consumption of the control unit.

4.1 FSM

FSM has been designed to provide supply voltage to the cantilever depending on whether the current is flowing or not. Initially, the current will be zero, so it will increment the voltage through counter to make contact of cantilever. It will increment the counter till current is zero and when contact is made, i.e. when their will be some amount of current through cantilever it decrements the voltage to make current zero. Now as current becomes zero i.e. cantilever regain its original position, again increments voltage across cantilever till predeflection voltage across comparator to achieve predeflection in cantilever. After predeflection of cantilever it activates the stress applied on cantilever. Due to this stress applied on cantilever, it strarts bending and after touching to the electrode, the contact area between cantilever and electrode increases as stress increases. Thus the current across it increases which is to be monitored on display. Figure 4. shows the state diagram for FSM which consists of 4 steps to carry out incrementing and decrementing voltage across cantilever beam.

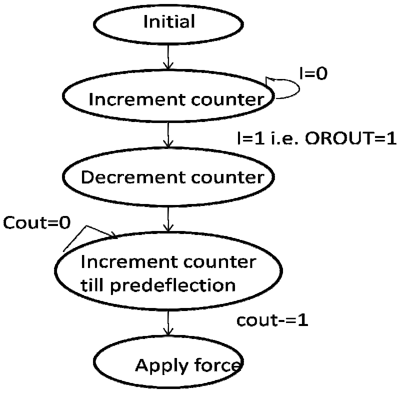

Figure 4. State diagram for Finite State Machine

4.2 DAC

DAC has been designed using R-ladder type DAC. It is having resistive type ladder whos output is expressed by Equ. (1):

$$out = \sum_{N=0}^{n} \frac{Vref}{2^{N+1}} \tag{1}$$

Where, out is the output of DAC; Vref is reference voltage for DAC; n is number of bits required for resolution. R-ladder is used for our design as is simple to design and gives appropriate resolution that we need for our design.

4.3 Comparator

Comparator has DAC output as one input to the positive of comparator, and negative input will have predeflection voltage set by FSM and DAC. When the DAC output is less than predeflection voltage at another input of comparator, the output of comparator remains equal to zero, so FSM will increment the voltage of DAC. When DAC output becomes equal to predeflection voltage, comparator output becomes one, which will stop incrementing of voltage.

4.4 I to V Converter

I to V converter is designed by Equ. (2) as;

$$V = IR \tag{2}$$

Where, I is input to I to V converter from cantilever beam, R is reference resistor set to calculate V which is the output of I to V converter. We will assume R having value of 1Kohm, to make ADC sensitive to small change in current of the cantilever beam.

4.5 ADC

ADC is designed using Resistive type, as given in Equ. (3);

$$ADCcode = \left(\left(\frac{2^{M}}{Vrefhi - Vreflow} \right) (Vin - Vreflow) \right) \tag{3}$$

Where, ADCcode is output for ADC; M is number of bits for resolution; V_{RefHi} is higher value of reference voltage; V_{RefLow} is lower value of reference voltage usually zero for unsigned ADC; and Vin is input to the ADC. We have employed Resistive type ADC, as it converts the digital input in one clock period only and fulfill the requirnment of resolution for our design.

5. SIMULATION

The code for the design is written in Verilog language and the results are verified using Xilinx ISE 9.2i.

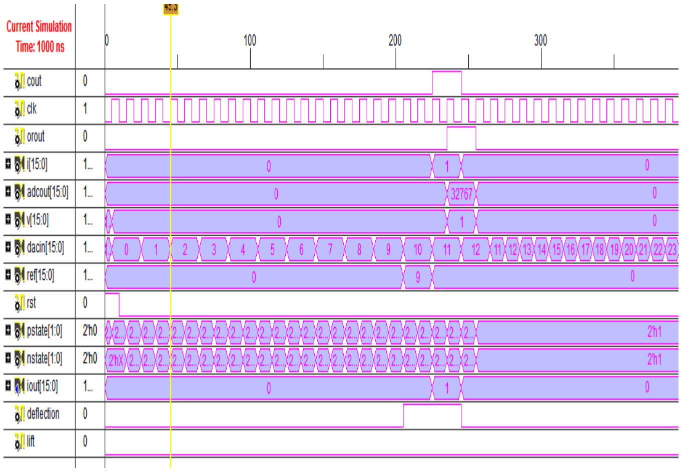

Figure 5. Simulation results for design

Simulation results in Figure 5. shows, according to clock signal the DAC output increases using the FSM states. The predeflection is achieved at voltage of 9 volt, when deflection becomes one which shows that cantilever is touched to electrode. Predeflection voltage gives current to I to V converter, which gives ADCout. ADCout sets OROUT, which decreases DAC output.

Accordingly the DAC output i.e. the voltage applied to cantilever is controlled.

6. STABILITY

To achieve stability for the system, feedback loop must be employed to control displacement. Large displacement are successfully obtained over the pull-in limit up to 80% of the gap, however, it becomes unstable when the target displacement is set to be 90% of the gap. This is mainly due to the approximation of the system such as linearization of the electrostatic force. There are some considerations for stability as:

1. If the oscillation amplitude A is smaller than the distance D, the tip never touches the surface.
2. If amplitude is larger than D, the tip exhibits intermittent contact situations.

   The time during which the tip touches the surface touches the surface depends on several parameters as

   i. For very soft material, tip speeds half of the period into the substrate.
   ii. For hard material, time during which tip touches the surface is negligible compared to oscillation period. So the selection of the material is also important part of the design.

   When intermediate contact situation occurs various assumption are required to describe the contact between tip and the surface.

3. An open loop MEMS cantilever system with electrostatic operation exhibits a snapping instability when the gap between two charged plates is decreased by one-third of its initial value.

   The gap between electrode in our case is 2μm, so instability occurs when gap reduces to 0.66 μm.

4. Electrostatic and Casimir interactions can limit the range of positional stability of electrostatically actuated or capacitively coupled mechanical devices.
5. Poincar`e map method can be used to study the stability of cantilever system [11].

A real MEMS cantilever with dimensions of 100μm × 35μm ×0.5μm. As shown in figure 2, our MEMS cantilever is modeled as a nonlinear mass-spring-damper (m, k, b) system with external electrostatic actuation. The initial gap between the two parallel electrodes is $g = 2\mu$m. The normalized equation of the motion for the dynamic system is as in Equ. (4);

$$\ddot{x} + \gamma . \dot{x} + x = \frac{V_n^2}{(1-x)^2} \qquad (4)$$

Where, $x = z/g$, $\gamma = b/\sqrt{mk}$, $\omega_0 = \sqrt{k/m}$ and $\tau = \omega_0 t$, where, ω_0 is the the cantilever's natural frequency, τ is the normalized time and $\dot{x}$ and $\ddot{x}$ are respectively the first- and second-order derivatives of x with respect to τ . The right hand side of the equation represents the nonlinear electrostatic actuation force, where, $V_n = V\sqrt{\varepsilon_0 A/2kg^3}$, and V denotes the voltage applied across the electrode gap. The absolute dielectric constant of vacuum is ε_0 = 8.854 ×10^{-12} F m^{-1}, and the plate area is A=1.75×10^{-12} m^2.

The MEMS cantilever can be unstable because of the nonlinearities in electrostatic actuation. The electrostatic potential energy has a minimum and a maximum when a constant voltage is applied to the cantilever system. For a large enough voltage, the maximum disappears and the system becomes unstable. As a result, the cantilever plate snaps to the top plate; that is, a snapping instability occurs.

Stability has different characteristics for linear and nonlinear systems. For a linear control system, the loop gain, phase margin and gain margin can be obtained by standard methods. The Poincar`e mapping method to investigate the nonlinear dynamics of the controlled cantilever under strong disturbances is suggested in [11].Some modification in the design is required by considering the instability of the system. Once the device become stable the device is of real use as it is used for biosensing application where sensitivity and stability are the important design parameter.

7. CONCLUSION

We have designed Feedback control system for cantilever based biosensor. This method is used for all the readout methods where the gap between electrodes is very small. Our digital feedback control system will solve all the major fabrication issues which is of very small gap in cantilever. The gap between electrode is adjusted by electrostatic actuation. The design is simulated and result is presented to support our design.

Stability related issues are discussed and to achieve the stability the design will be modified further.

8. REFERENCES

[1] Don Klaitabtim and Adisorn Tuantranont, "Design Consideration and Finite Element Modeling of MEMS Cantilever for Nano-Biosensor Applications", Proceedings of 2005 5th IEEE Conference on Nanotechnology Nagoya, Japan, July 2005.

[2] Nabiollah Abolfathi, "BioMEMS", Mechanical Engineering Department of North Dakota State University, April 2006.

[3] Nitin S. Kale and V. Ramgopal Rao, "Design and Fabrication Issues in Affinity Cantilevers for BioMEMS Applications", Journal of Microelectromechanical systems, Vol. 15, No. 6, December 2006.

[4] Mohd. Zahid Ansari and Chongdu Cho, "Design and Analysis of a high sensitive Microcantilever Biosensor for Biomedical Applications", 2008 International Conference on BioMedical Engineering and Informatics.

[5] M.F. Abdullah, L.Y. Khuan, N.K Madzhi, M. Masrie, A. Ahmad, "Development of a Transduction Circuit for Piezoresistive MEMS Sensor for Biosensing", 2009 IEEE Symposium on Industrial Electronics and Applications (ISIEA 2009), October 4-6, 2009, Kuala Lumpur, Malaysia.

[6] United states Patent, Patent no.: US 7,574,327 B2, Date of Patent: Aug.11, 2009.

[7] Y.Tanaka, Y.Hirai, N.Kimura, T.Jin and M.Kabuto, "Large displacement control system beyond pull-in limitation in electro-static micro cantilever", Department of Mechanical System Engineering, Osaka Prefecture University, 1-1 Gakuen-cho, Sakai, 599-8531, Osaka, Japan.

[8] C. L. Degen, U. Meier, Q. Lin, A. Hunkeler, and B. H. Meiera, "Digital feedback controller for force microscope cantilevers". Review of Scientific Instruments **77**, 043707 _2006.

[9] A. Arbat, E. Edqvist, R. Casanova, J. Brufau, J. Canals, J. Samitier, S.Johansson, A. Dieguez, " Design and validation

of the control circuits for a micro-cantilever tool for a micro-robot". Sensors and Actuators A 153(2009) 76-83.

[10] S Liu, A Davidson and Q Lin, "Simulation studies on nonlinear dynamics and chaos in a MEMS cantilever control system" .Institute of Physics Publishing, Journal of Micromechanics and Microengineering J. Micromech. Microeng. **14**(2004) 1064–1073 PII: S0960-1317(04)73833-4