Analytical study of MEMS/NEMS Force Sensor for Microbotics Applications

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Abstract. The purpose of this paper is design, virtual fabrication and simulation of microcantilever based force sensor using Comsol Multiphysics Software version 5.3a to perform analytical analysis of MEMS/NEMS based sensor for microbotic applications. Piezoresistive MEMS force sensor having dimension of fixed part is 1000 μm² with height of 50μm and movable part is 600 μm length, 500μm breadth and 20 μm height. The analysis of force sensor is observed by plotting a curve between force and voltage, displacement and voltage and sensitivity. The range of force measured by this sensor is from 10N to 1µN, the simulating result shows that a very wide range of force can be measured by this single sensor. The force measurement at microscale has been very common in microbotics for micromanipulation. The simulated MEMS force sensor having resolution 0.1µN using piezoresistive sensing which is improved than the previous work. This range of force, resolution and sensitivity can be used for the application of two-fingered microgripper in microbotic system. Mathematically, dynamic frequency range for microcantilever based force sensor is calculated in range of 1.477076 KHz to 467.935969 KHz, along with its different frequency harmonics for force 10N-100µN. Here, microcantilever is used for the measurement of force by using piezoresistors which are arranged in voltage divider sensing technique to obtain higher resolution, sensitivity and wide and lower range of force.

Keywords MEMS, Microbot, Micronewton, Force sensor

1. Introduction

New ideas and innovation for the development of technology has come a long way in the field of MEMS/NEMS technology. There had been ample work already been done from giant robotic arm[1] to micro and nano robots [2], yet there is enough room for further research in this field. In today’s scenario there is lot of demand of integration [3], to tow this line, in this paper our focus is on analytical analysis of MEMS (Micro Electro Mechanical System) based force sensor for microrobotics application. The most challenging aspect in the development of microbots is the fabrication of micro actuators and micro sensors which can give high efficiency and high stability [4]. A lot of physical quantities are there such as force, pressure, temperature, humidity, acceleration, displacement that needs to be measured with the help of sensors. Absolute force sensing is important constraint in the field of material science, biomaterial characterization, microsystem testing, [5] characterizing animal cells, plant cells, and embryos [6]-[7]. There are various method available for force measurement at microscale such as atomic force microscopes, microscales, piezoresistive cantilevers [8] and capacitive force sensors [9]. As far as microcantilever is concern it is operated in two different modes as static mode and dynamic mode [10]. In case of static mode cantilever bend due to applied force or pressure and in case of dynamic natural frequency sifts due to applied force or pressure on the microcantilever. In this paper, our focus is on designing and simulation of MEMS piezoresistive cantilever based force sensor for Microbotics and microgripper applications [11]. Today’s market demands with MEMS are not only sensors capable of measuring the most minute forces but they should also be able to do it with highest precision [12].
This paper focuses on designing and virtual fabrication of microcantilever based force sensor with piezoresistive sensing element connected in voltage divider configuration using COMSOL Multiphysics version 5.3a software so that variation in resistance can be noted down with applied force on cantilever tip. Micromanipulation using MEMS Force sensor is possible by exploiting the piezoresistive property of silicon [13]. Microcantilever based MEMS sensor is an indirect method of force measurement [14] because in this, the applied force on the tip of cantilever is first of all converted into displacement, with that displacement there is variation in resistance which is mounted on fixed and moving part of cantilever in such a way that maximum stress caused by the applied force is converted into resistance. A displacement of just a few micrometers is sufficient to transform the capacity differences into a signal. Variation in resistance causes a voltage potential to develop across terminal. Analytical study and performance of MEMS/NEMS force sensor is obtained by plotting curves between applied force v/s displacement, displacement v/s voltage and by calculating the better sensitivity then existing.

2. Design Parameter Consideration

The designing of microcantilever based MEMS force sensor consist of fixed part having dimensions 1000µm² with height 50 µm and cantilever part having length, breadth and height as 600 µm, 500 µm and 20µm respectively. The basic principle behind the virtual fabrication of sensor is the voltage divider rule. Concept behind voltage divider rule is that “The voltage is divided between two resistors which are connected in series in direct proportion to their resistance”. The dimension of contact pads is 50µm², Piezoresistors value is of 2KΩ each with length of resistor 400µm and width 10µm. The metal lines used for the connection between contact pads and piezoresistors having width 20µm. In the designing of sensor one of the series resistance are arranged at maximum stress region of sensor so that variation in resistance due to applied force can easily be detected and converted to voltage output. The sensing method for the detection of microforce can be capacitive, optical/laser and piezoresistive, but in the proposed model, sensing mechanism used in piezoresistive [15].

The proposed design of MEMS force sensor with piezoresistive sensing element is shown below:

Fig. 1- D model of Microcantilever based MEMS Force sensor

Above Fig. 1 shows Microcantilever having chip of 1400µm with 20µm height for the purpose of force sensing, the displacement of moving part in terms of voltage. Two resistor are mounted on cantilever in voltage divider configuration so that one out of them can experience minimum stress and other experience maximum stress.

Below Fig. 2 shows meshing of Microcantilever based Force sensor in tetrahedral configuration. In meshing Finite element method analysis is performed which is a numerical method of solving mathematical physics. Smaller the mesh better will be the simulation.
Fig. 2 Tetrahedral Meshing on Microcantilever for FEM Analysis

Fig. 3 shows simulation results of microcantilever based for force sensor through Von Mises Stress diagram which shows effect of force applied on cantilever in form of color variation from blue to red defining minimum and maximum stress respectively.

The dimension of sensor is 1600 µm with depth 50µm with the range of applied force is from 1 Newton to micronewton.

The two-fingered microgripper is the application for which this MEMS force sensor is designed. Below diagram shows the schematic diagram of micromanipulation system which is composed of actuating mechanism and measuring mechanism.

In the Fig. 4 two-fingered microgripper having actuator attached to its one of the arm and MEMS force sensor is attached to Measuring finger. Here in this case, MEMS force sensor is used to measure the gripping force acting on object which is placed at free end of the actuating and the measuring Fig. The length of both the actuating and measuring is equal.
Material and Methods: - The MEMS force sensor is virtually fabricated using COMSOL Multiphysics software [16]. The material used in designing of sensor are silicon as substrate material, piezoresistor made up to polysilicon, Connecting wires and contact pads are made up of gold. The properties of these material are as follows:-

Silicon Substrate: - Silicon is the primary substrate material used in microelectromechanical sensors. The Properties of silicon using as substrate material in fabrication of force sensor is shown below in table 1.

| S. No | Properties                      | Values                        |
|-------|---------------------------------|-------------------------------|
| 1.    | Relative Permeability           | 1                             |
| 2.    | Electrical Conductivity         | $1 \times 10^{-12}$ [S/m]    |
| 3.    | Coefficient of Thermal Expansion| $2.6 \times 10^{-6}$ [1/K]    |
| 4.    | Relative Permittivity           | 11.7                          |
| 5.    | Density                         | 2329[kg/m³]                   |
| 6.    | Thermal Conductivity            | 130[W/(m*K)]                  |
| 7.    | Young’s Modulus                 | $170 \times 10^{9}$[Pa]       |
| 8.    | Poisson’s Ratio                 | 0.28                          |

Polysilicon: - This material is used in the designing of piezoresistors which is mounted on microcantilever acting as sensing element having following properties. Polysilicon is a polycrystalline form of silicon which is most commonly used for surface micromachined devices. Polysilicon has material properties similar to single crystal silicon and can be doped via introducing impurities.
Table 2. Properties of Polysilicon

| S. No | Properties                  | Values         |
|-------|-----------------------------|----------------|
| 1.    | Relative Permittivity       | 4.5            |
| 2.    | Electrical Conductivity     | $1 \times 10^{-12}$ [S/m] |
| 3.    | Density                     | 2320 kg/m$^3$  |
| 4.    | Young’s Modulus             | $169 \times 10^9$ [Pa] |
| 5.    | Poisson’s Ratio             | 0.22           |
| 6.    | Reference Resistivity       | $2 \times 10^{-5}$ |

**Gold**: Connecting wires and contact pads used in designing of sensor are made up gold, as gold is one of the best conducting material. The properties used by COMSOL software for simulation are shown below in table 3

Table 3. Properties of Gold

| S. No | Properties                        | Values            |
|-------|-----------------------------------|-------------------|
| 1.    | Relative Permeability             | -16.5             |
| 2.    | Electrical Conductivity           | $45.6 \times 10^9$ [S/m] |
| 3.    | Coefficient of Thermal Expansion  | $214.2 \times 10^{-6}$ [1/K] |
| 4.    | Density                           | 19300 kg/m$^3$    |
| 5.    | Thermal Conductivity              | 317 [W/(m*K)]     |
| 6.    | Young’s Modulus                   | $70 \times 10^9$ [Pa] |
| 7.    | Poisson’s Ratio                   | 0.44              |

The basic method used behind the designing of this sensor is the property of microcantilever as it is one of the simplest mechanical structure, which is fixed at one end and free from other end. Microcantilever is a microfabricated rectangular bar shaped structure, longer as compared to width, and has a thickness much smaller than its length or width[10]. In addition to it the piezoresistive phenomena for the detection of applied force is used, in which resistor are arranged in voltage divider configuration so that one of them experience maximum force and other one experience no force and proportionally output voltage across its two terminals can easily be calculated.

3. Sequential Steps for Simulation

The following sequential of steps to be followed for simulation is shown below:

1. Set up model Wizard environment.
2. Creating Geometrical object.
3. Specifying material properties to the created object.
4. Define physics and boundary condition for the created object.
5. Creating Mesh for Finite Element analysis.
6. Computing results for the designed model

Initially model wizard choose with 3D space dimension. The physics used while designing
the sensor is Solid Mechanics, Electric Current, Piezoelectric effect and Boundary condition.
In Solid Mechanics Linear elastic material along with its free, initial and boundary load is defined.
In Electric Current, Shell physics Current conversion, electric insulation, initial values piezoresistive
material along with electric potential and ground and defined in sensor. Two resistors are connected
in voltage divider configuration so piezoresistive effect along with boundary condition is also
considered. Assigning of material to different part of sensor is the next stem in simulation, in this
force sensor material used for substrate material is silicon, the resistors are made up of polysilicon,
connecting wires and contact pads are made up of gold. After material assigning, meshing is the next
step and two important considerations in meshing is its size and shape. There are different levels of
size such as extremely fine, extra fine finer, fine, Normal, Coarse, Coarser, Extra Coarse, Extremely
Coarse. The shape choose for mesh in is tetrahedral and size is finer in fixed part of microcantilever
and extremely finer on moving part of cantilever and near piezoresistors. Meshing help in Finite
element analysis which is a numerical method of solving mathematical physics. Smaller the mesh
better will be the simulation. For computing the results study is performed by selecting stationary
study[17].Software used for the simulation for force MEMS sensor is COMSOL Multiphysics
version 5.3a

4. Mathematical Modelling for analytical analysis
The resonance frequency in dynamic mode is obtained by performing analytical analysis of
microcantilever based force sensor. Bending of movable part of cantilever depend upon the amount
of force applied on cantilever.

The resonance frequency of oscillating cantilever is given below

\[ F = \frac{1}{2n} \left( \frac{K}{m} \right)^{1/2} \]  

F= Resonance frequency of Microcantilever
K= Lever stiffness depend upon absorption
m= mass of Beam

\[ K = E \frac{h^3}{4l^3} \]  

E= Young’s modulus of Elasticity
m= \( \rho \) V

Where, \( \rho \) is the resistivity of material, V is the volume

\[ V = L \times B \times H \]  

L= Length of cantilever
B= Breadth of cantilever
H= Height of cantilever

Moment of Inertia

\[ I_g = \frac{b^3 h^3}{4l^3} \]  

Natural frequency of micro cantilever

\[ F_n = \frac{K_n}{2n} \left( \frac{E I_g}{l^4} \right)^{1/2} \]  

Where n is mode of vibration
The analytical analysis of the voltage divider concept used for the sensing in MEMS based force sensor is explained below:

\[ V_{\text{out}} = V_{\text{in}} \cdot \frac{R_2}{R_1 + R_2} \]  \hspace{1cm} (7)

Where, \( V_{\text{out}} \) = Output voltage 
\( V_{\text{in}} \) = Input voltage applied to MEMS sensor which is 3.3mV 
\( R_1 \) = Resistance across which \( V_{\text{in}} \) is applied 
\( R_2 \) = Resistance across which output voltage \( V_{\text{out}} \) is calculated

Simplification of equation (7) as following cases

Case I: - If \( R_1 = R_2 \)
\[ V_{\text{out}} = V_{\text{in}} \cdot \frac{R}{2R} = \frac{V_{\text{in}}}{2} \] \hspace{1cm} (8)

Case II: - If \( R_2 \gg R_1 \)
\[ V_{\text{out}} = V_{\text{in}} \cdot \frac{R_2}{R_2} = V_{\text{in}} \] \hspace{1cm} (9)

Case III \( R_2 \ll R_1 \)
\[ V_{\text{out}} \approx V_{\text{in}} \cdot \frac{a}{R_1} = 0 \] \hspace{1cm} (10)

5 Results and Discussion

For the analysis of the results there is need to categorize the applied force into three groups i.e. 1N-10N, 0.1N-1N, 0.01N-0.1N, 0.001N-0.01N, and 0.0001N-0.001N so that precise and accurate results while plotting curves between force v/s displacements can be obtained.

Below Fig. 5 shows simulated output of force v/s displacement in the range of force 1N - 10N. For analytical analysis of linearity applied force on the microcantilever moving part and corresponding displacement of microcantilever in micrometer has been noted down plotted.

![Fig. 5. Relation between Force & Displacement for the range 1N - 10N](image)

Below Fig. 6 shows simulated output of force v/s displacement in the range of force 0.1N-1N. For analytical analysis of linearity applied force on the microcantilever moving part and corresponding displacement of microcantilever in micrometer has been noted down plotted.
Fig. 6. Relation between Force & Displacement for the range 0.1N-1N

Below Fig. 7 shows simulated output of force v/s displacement in the range of force 0.01N-0.1N. For analytical analysis of linearity applied force on the microcantilever moving part and corresponding displacement of microcantilever in micrometer has been noted down plotted.

Fig. 7. Relation between Force & Displacement for the range 0.01N-0.1N

Below Fig. 8 shows simulated output of force v/s displacement in the range of force 0.001N-0.01N. For analytical analysis of linearity applied force on the microcantilever moving part and corresponding displacement of microcantilever in micrometer has been noted down plotted.
Below Fig. 9 shows simulated output of force v/s displacement in the range of force 0.0001N-0.001N. For analytical analysis of linearity applied force on the microcantilever moving part and corresponding displacement of microcantilever in micrometer has been noted down plotted.
Fig. 10. Relation between Force & Displacement for the range 0.00001N-0.0001N

Below Fig. 11 shows simulated output of force v/s displacement in the range of force 0.000001N-0.00001N. For analytical analysis of linearity applied force on the microcantilever moving part and corresponding displacement of microcantilever in micrometer has been noted down plotted.

Fig. 11. Relation between Force & Displacement for the range 0.000001N-0.00001N

Fig. 5-Fig. 11 shows the simulated results of MEMS Force sensor using COMSOL Multiphysics Software 5.3a for varied range of forces. It can be seen from these figs there is a linear relation between the applied force and displacement of microcantilever. Range of force applied and corresponding movement opens new horizon of application for mems Force sensor in the field of microbotics and microgripeer applications.
Below Fig. 12 shows Simulated input with respect to output. In this microcantilever based force sensor output is obtained in the form of voltage, because piezoresistors are connected in voltage divider configuration. Simulation results shows that there is an linear relation between force and output voltage. With the increase in force the voltage developed across the voltage divider configuration also increases.

![Graph showing linear relationship between force and output voltage](image)

**Fig. 12.** Relationship between Force & Output Voltage

**Conclusion**

MEMS based piezoresistive micro-force sensor are low cost, highly sensitive leads to improvement in reliability, repeatability and cost effectiveness technology, and which makes it suitable for micromanipulation application such as microgripper in microbotics. Universally microcantilever sensors are, extremely powerful and highly sensitive tool to evaluate various, physical, chemical and biological phenomena’s. Increase in overall sensitivity of microcantilever sensor depend on, both deflection and resonant frequency of the cantilever. MEMS Force sensor has been successfully designed and virtually fabricated using COMSOL Multiphysics 5.3a software with measured value of sensitivity and resolution were found to be 264400V/N and 0.1µN, respectively. Simulated results also shows linear realtion between force and displacement.

**References**

[1] Jahnavi, K., & Sivraj, P. (2017, July). Teaching and learning robotic arm model. In 2017 International Conference on Intelligent Computing, Instrumentation and Control Technologies (ICICICT) (pp. 1570-1575). IEEE.

[2] Qin, J., & Xu, Q. (2014). Functions and application of exosomes Acta Pol Pharm, 71(4), 537-43.

[3] Noda, K., Hashimoto, Y., Tanaka, Y., & Shimoyama, I. (2009, June). MEMS on robot applications In TRANSDUCERS 2009-2009 International Solid-State Sensors, Actuators and Microsystems Conference (pp. 2176-2181). IEEE.

[4] D’Souza, R. D., Sharma, S., & Jacob, A. (2016). Microrobotics: Trends and technologies. American J Eng Res, 5(5), 32-39.

[5] Guggenheim, J. W., Jentoft, L. P., Tenzer, Y., & Howe, R. D. (2017). Robust and inexpensive six-axis force-torque sensors using MEMS barometers. IEEE/ASME Transactions on Mechatronics, 22(2), 838-844.
[6] Sun, Y., & Nelson, B. J. (2004). MEMS for cellular force measurements and molecular detection. International Journal of Information Acquisition, 1(01), 23-32.

[7] Arai, F., Sugiyama, T., Fukuda, T., Iwata, H., & Itoigawa, K. (1999). Micro tri-axial force sensor for 3D bio-micromanipulation. In Proceedings 1999 IEEE International Conference on Robotics and Automation (Cat.No. 99CH36288C) (Vol. 4, pp. 2744-2749). IEEE.

[8] Beyeler, F., Muntwyler, S., & Nelson, B. J. (2009). A six-axis MEMS force–torque sensor with micro-Newton and nano-Newtonmeter resolution. Journal of Microelectromechanical Systems, 18(2), 433-441.

[9] Fahlbusch, S., & Fatikow, S. (1998). Force sensing in microrobotic systems-an overview. In 1998 IEEE International Conference on Electronics, Circuits and Systems. Surfing the Waves of Science and Technology (Cat.No. 98EX196) (Vol. 3, pp. 259-262). IEEE.

[10] D. S. A. M. and D. V. R. A. GOPINATH. P. G., “MEMS Microcantilevers Sensor Modes of Operation and Transduction Principles,” Int. J. Comput. Eng. Sci., vol. 4, no. 2, pp. 1–11, 2014.

[11] Boudaoud, M., Haddab, Y., & Le Gorrec, Y. (2010, October). Modelling of a MEMS-based microgripper: application to dexterous micromanipulation. In 2010 IEEE/RSJ International Conference on Intelligent Robots and Systems (pp. 5634-5639). IEEE.

[12] S. Russi and M. Aeschbacher, “Measuring forces in the micro range,” vol. 23, no. 2, pp. 1–2, 2016.

[13] Delic, N., Deter, H., Brenner, W., Popovic, G., Vujanic, A., & Hannenheim, W. (1996). Development of Force Sensor for Microhandling Purposes. In Micro System Technologies 96 (pp. 363-368).

[14] Pandya, H. J., Kim, H. T., Roy, R., & Desai, J. P. (2014). MEMS based low cost piezoresistive microcantilever force sensor and sensor module. Materials science in semiconductor processing, 19, 163-173.

[15] Duc, T. C., Creemer, J. F., & Sarro, P. M. (2006). Lateral nano-Newton force-sensing piezoresistive cantilever for microparticle handling. Journal of Micromechanics and Microengineering, 16(6), S102.

[16] A. Qaiser, “Designing a Capacitive Sensor using COMSOL,” p. 16, 2010.

[17] A. Vasudev, “Microcantilever-Based Sensors,” vol. 59, no. 6, pp. 98–99, 2006.