Robust Design of Horn Shaped Piezo-Resistive Mems Pressure Sensor

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Abstract **– The effective use of Micro Electro Mechanical Systems (MEMS) based cantilever sensor is application dependent and it is revolutionary for sensing pressure with improved sensitivity at modest fabrication design in research oriented projects. Micrometer scale piezo-resistive cantilever pressure sensors of two different shapes are modeled by using Bulk and Surface micromachining techniques on the Intellisuite simulation software. The layout of the Piezo-resistors is aligned along <110> orientation of p-type Silicon substrate with Aluminum interconnect to form a Wheatstone bridge configuration where output voltage is read out. A comparative study on different parameters such as displacement, von-mises stress and output voltage for the applied pressure is done by simulation, for the two different shapes of cantilever beams. The sensitivity of rectangular shaped sensor is 111mV/MPa. The sensitivity of horn shaped sensor is 185mV/MPa which is notably higher. This sensor can be used to measure contact pressure between surgical tool and organs during the surgery and for manipulation of living cells.**

Keywords - Cantilever, Piezo-resistors, Pressure Sensor, Displacement, Von-mises stress, Output voltage, Sensitivity, MEMS.

I. INTRODUCTION AND BACKGROUND

Micro Electro Mechanical Systems (MEMS) has drawn wide attention of researchers for its efficient, multifunctional, low cost devices. In the 21st century, the technology of MEMS promises revolution in different fields of applications [1, 2]. The demand of MEMS structures for sensing pressure is still increasing owing to its better performance with improvement in technology which is becoming more significant day by day [3,4]. MEMS cantilever pressure sensor is a device that has support at one end to make it rigid and on application of pressure, the device exhibits maximum displacement at freely movable end. The principle involved in the piezo-resistive cantilever pressure sensor is, the device will undergo deflection causing measurable changes in the resistance of the piezo-resistors on application of pressure. By using Wheatstone bridge configuration, output can be read out in terms of voltage corresponding to the resistance change of piezo-resistive element. For different applications such as for force measurement, acceleration measurement, chemical sensing and bio-sensing; different shapes and sizes of MEMS cantilevers were used [5].Rectangular beam with piezo-resistive transduction showed a sensitivity of 100V/N and 540 V/N for lateral and vertical configuration respectively for force measurement [6]. For force measurements and in case of Atomic Force Microscopy (AFM), high aspect ratio cantilever structures are used for optimal results when compared to low aspect ratio cantilevers [7]. Other than piezo-resistive deflection detection method, capacitive and optical methods can be used to sense pressure [8-10]. Optical detection methods have the advantage of detecting deflection at sub-nanometer range, but the disadvantage is that external opto-electronic set up such as laser source and position sensitive detector are needed which tends to be extremely expensive [11]. Incorporation of capacitive detection technique in cantilever beam makes the fabrication process of sensor complex owing to the requirement of counter electrode [12]. Cantilever based pressure sensor provides higher sensitivity for the reason of fact that only one side is fixed and all other three sides are freely movable which is not in case of diaphragm based pressure sensor [13]. The orientation of the p-type piezo-resistors along <110> direction of <100> Silicon wafer during bulk micro manufacturing contributes to improved sensitivity [14]. Notably, an elliptic diaphragm capacitive pressure sensor achieved wider low pressure sensing range at lower supply voltage compared to commercial pressure sensors and MEMS pressure sensor was successfully fabricated and characterized for high sensitivity [8]. In this regard, the various design considerations for diaphragm based and SOI integration for silicon piezo-resistive pressure sensor are elaborated in detail. Numerous types of sensor structures have been presented in the earlier literatures are often designed to optimize the sensor's performance [15, 16]. In this paper, we proposed horn shaped piezo-resistive MEMS pressure sensor design based on bulk and surface micro matching techniques.

The remainder of this paper proceeds as follows. In Section 2, the micro fabrication process of proposed MEMS pressure sensor has been thoroughly discussed. The performance analysis of the proposed design using Intellisuite simulation is clearly discussed in Section

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3.Finally, the concluding remarks are provided in Section 4.

II. DEVICE DESCRIPTION

The fabrication process is modeled using Intellifab and Blueprint modules of Intellisuite. The device structure of the cantilever is illustrated in Figure 1. Micro fabrication process such as bulk and surface micromachining techniques [17] [18] were used to create the MEMS cantilever structures as shown in Figure.2. A Czochralski Si 100 wafer of thickness 50um is used as a substrate. The next process includes ion implantation of 500nm thick piezo-resistors on the substrate. Boron ions are implanted along <110> directions to make the substrate as p-type Silicon (Si). Among the four implanted piezo-resistors two are used for sensing. Aluminum interconnects are deposited on the Silicon substrate to form Wheatstone bridge configuration which is isolated from the substrate by Silicon Nitride layer. Finally Deep Reactive Ion Etching (DRIE) of Si is carried out at the bottom side to reveal the structure of the cantilever beam.

The piezo-resistive Wheatstone bridge configuration shown in Figure 3 is inscribed in the Silicon wafer. The bridge consists of 2/4 active element for transduction of stress into resistance. The other pair of passive element is used for temperature compensation. Young’s modulus is an important mechanical parameter for the design. During FEM simulations and during fabrication, in case of <110> design orientation on a <100> Silicon wafer, the elementary matrix are not aligned along X-Y axes of fundamental elasticity matrix. The design in the workspace has to be rotated in order to obtain the orthotropic elasticity parameters. The young’s modulus is 130 GPa for design in off-axis direction along the diagonal on a <100> Silicon wafer [19]. In order to obtain the alignment of piezo-resistors along <110> direction the mask layers corresponding to the piezo-resistor are rotated 45° during photolithography process.

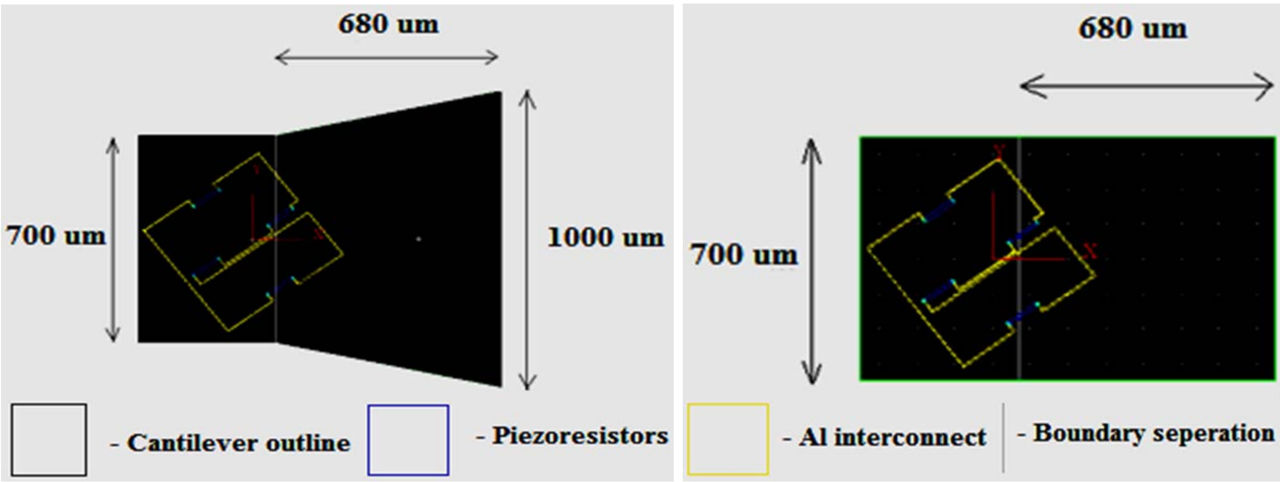

Figure 1: Structure of horn shaped and rectangular cantilever beam and their cross sections.

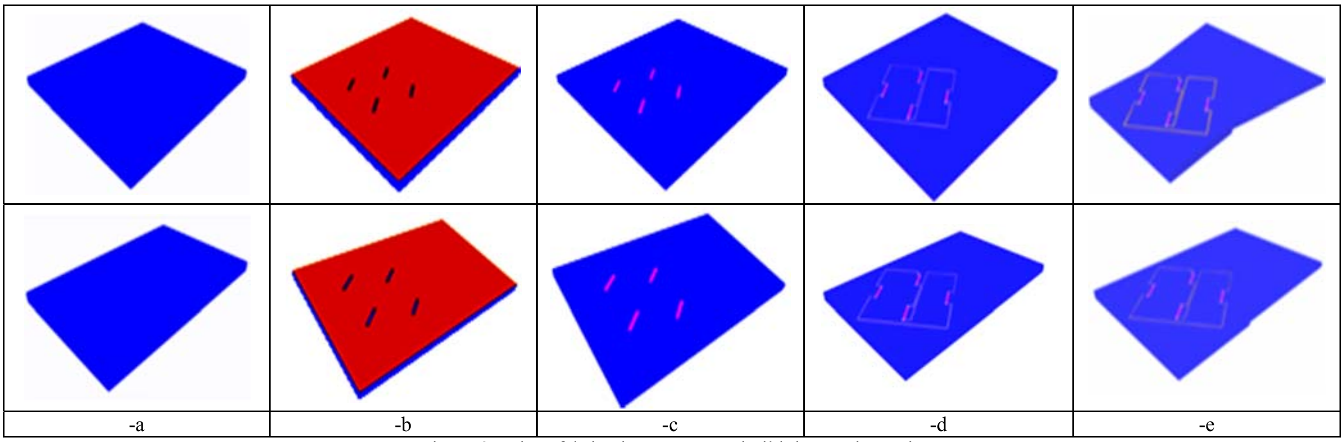

Figure 2: Micro fabrication process to build the sensing unit.

a) Substrate definition b) Photolithography exposure c) Boron ion implantation d) Aluminium interconnects for Wheatstone bridge configuration e) DRIE Etch at the bottom to reveal the free standing cantilever beam

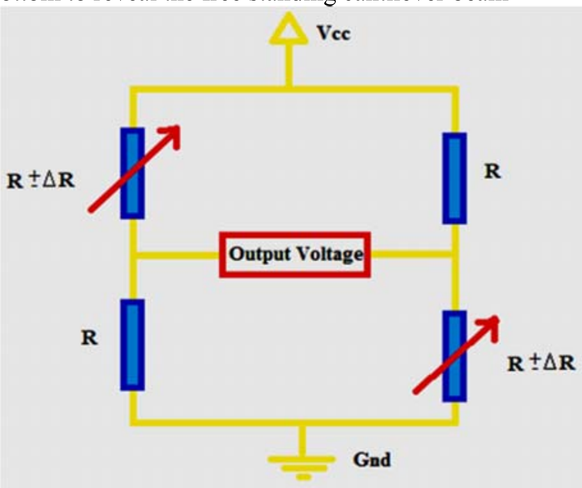

Figure 3: Wheatstone bridge configuration

The piezo-resistive coefficients of p-type Silicon are $\pi_{11}=6.6e^{-5}/MPa$, $\pi_{12}= -1.1e^{-5}/MPa$, $\pi_{44}=0.00138/MPa$ [20]. Table 1 shows set of values used for simulation.

TABLE 1: VALUES OF DIFFERENT PARAMETERS USED FOR ANALYSIS

Symbol	Parameter	Values
b_r	Width of rectangular cantilever	700 µm
t_r	Thickness of rectangular cantilever	30 µm
a_r	Length of the rectangular cantilever	680 µm
k_r	Stiffness of rectangular cantilever	1953.52 Hz
b_h	Width at centroid of horn shaped cantilever	850 µm
t_h	Thickness of horn shaped cantilever	30 µm
a_h	Length of the hypotenuse line of horn shaped cantilever	696 µm
k_h	Stiffness of horn shaped cantilever	1769.81
E	Young's modulus of Silicon	130 GPa
P	Density of cantilever	2328 kg/m^3

III. SIMULATION RESULTS AND DISCUSSION

Analysis is done using TEM module of Intellisuite software. First mode resonant frequency and spring constant of the cantilever can be obtained by using Laser Doppler Vibrometer (LDV) [21]. The spring constant or stiffness of the cantilever is the ratio of applied force to the deflection of the cantilever and so when the stiffness increases, less will be the deflection of the beam. This stiffness in turn is also a function of the Young's modulus and dimensions of the beam. Equation (1) and Equation (2) gives the formula for stiffness and resonant frequency (f_0) of the beam [22]. Figure 4 shows plot of resonant frequency varied as a function of thickness of the beam.

$$k_r = \frac{E\, b_r t_r^3}{4\, a_r^3} \tag{1a}$$

$$k_h = \frac{E b_h t_h^3}{5 a_h^3} \tag{1b}$$

$$f_0 = \sqrt{\frac{k}{0.24\, \rho\, a\, b\, t\, (2\,\pi)^2}} \tag{2}$$

where k_r and k_h are stiffness of rectangular and horn shaped cantilever beam, b_r and b_h are width of the rectangular and width at centroid of horn shaped cantilever beam, t_r and t_h are thickness of rectangular and horn shaped cantilever beam, a_r and a_h are length of rectangular cantilever and length of hypotenuse line of horn shaped cantilever, respectively, E is the young's modulus of silicon, k is the stiffness of the cantilever beam, ρ is the density of the cantilever beam, a is length of the cantilever beam, b is the width of the cantilever beam and t is the thickness of the cantilever beam.

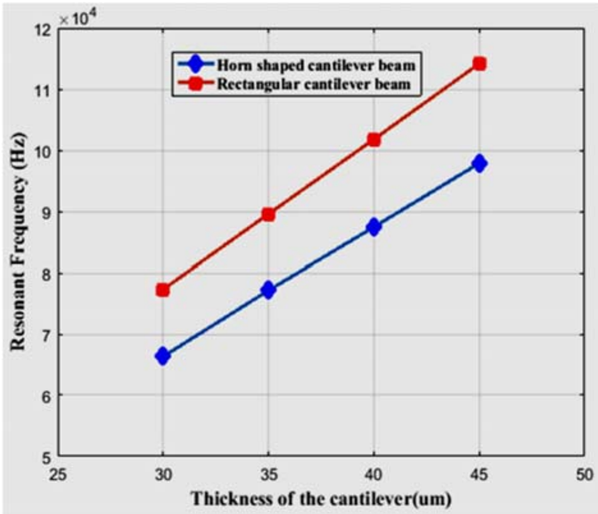

Figure 4: Resonant frequency v/s thickness for rectangular and horn shaped cantilever beam

On applying pressure, the cantilever bends. Displacement is more at the free end of the cantilever since the other end being fixed. The displacement at the free end (y) as a function of pressure (ρ) is given by [12].

$$y = -1.5\, p\, \frac{a^4}{E\, t^4} \tag{3}$$

The surface of the cantilever will be influenced by stress due to the applied pressure. Based on the stress change will be the resistance change of the piezo-resistive element. Since stress value is variable along the length of the cantilever beam, the location of piezo-resistors plays a

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major role in sensor output. Since resistive change of the piezo-resistive element is based on the strain it experiences, more resistance change will be encountered when piezo-resistors are placed in location contributing to the cantilever area where influential stress of the cantilever is more. The maximum displacement and von-mises stress for applied pressure of rectangular and horn shaped cantilever beam is shown in Figure 5 and Figure 6. <110> direction oriented piezo-resistor on <100> Silicon wafer exhibits longitudinal piezo-resistive coefficient (π), which is given by [6] as,

$$\pi = 0.5\ (\pi_{11} + \pi_{12} + \pi_{44}) \tag{4}$$

where π_{11}, π_{12} *and* π_{44} are independent components of first-order piezo-resistive tensor.

The Piezo-resistors embedded in the cantilever, due to its property of piezo-resistivity undergoes resistance change due to influential localized stress on applied pressure. Resistance changes as a function of lateral and transverse piezo-resistive coefficients. Since transverse stress is negligible, it can be neglected in analysis due to the fact of deflection being much lesser than the length of the cantilever.

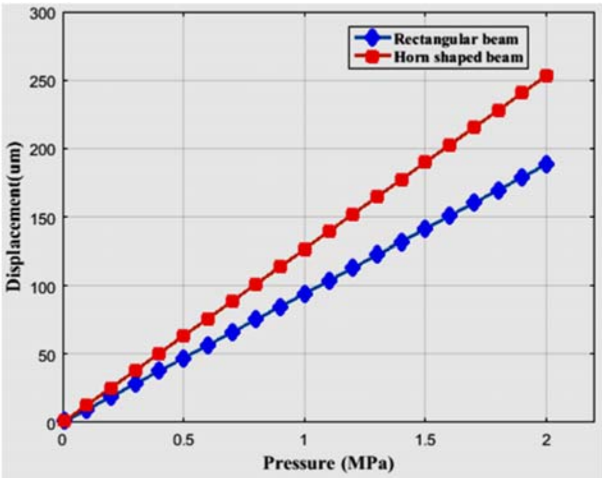

Figure 6: Von- Mises Stress v/s Pressure

Resistivity change to the zero stress resistivity ($\frac{\Delta\rho}{\rho}$) at one point along the length of the cantilever as a function of longitudinal stress is given (σ) by [6, 22] as,

$$\frac{\Delta\rho}{\rho} = \pi\ \sigma \tag{5}$$

The piezo- resistor resistance (R) as a function of electrical resistivity in sensing arms piezo- resistors (ρ) is computed by [6] as,

$$R = \int_0^{a_s} \frac{\rho(x)}{S}\, dx \tag{6}$$

where S is the area of cross section of the piezo-resistors and a_s is the distance from the fixed end of the of the cantilever to the tip of the piezo- resistors.

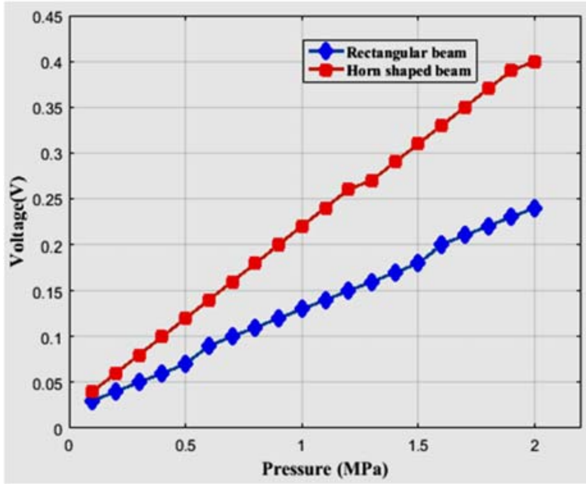

Figure 7: Voltage v/s Pressure

Aluminum is deposited on the Silicon wafer in a Wheatstone bridge configuration which directly converts this resistance change into voltage output for applied pressure values as shown in Figure 7. The Wheatstone bridge configuration is in such a way that the two active arm resistance values are either increased or decreased to $R \pm \Delta R$.The output voltage (V_0) of the bridge configuration is given by [6] as,

$$V_0 = V_{in}\left(\frac{1}{\left(\frac{2R}{\Delta R}\right)^2 - 1}\right) \tag{7}$$

where V_{in} is the input voltage given to the Wheatstone bridge configuration, R is the resistance of the piezo-resistor under no load condition, ΔR is the effective resistance change of piezo-resistor under the influence of pressure.

IV. CONCLUSION

In this work, performance of horn shaped and rectangular shaped MEMS cantilever structures with fabrication process were modeled and its deflection, von-misses stress and output voltage for applied pressure have been reported. Results shows that horn shaped cantilever beam's sensitivity is higher when compared to rectangular cantilever beam for sensing pressure.

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