Design and Simulation of Micromachining Membrane Flow-Meter

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Abstract— **In this paper a new piezoresistive flow-meter has been proposed. For enhancement of sensitivity, a large membrane is placed vertically against the flow direction to maximize the air drag force. In the new proposed structure supporting beams do not scale up the total die-size, and due to large torsion spring constant, considerable incensement in mechanical stability is achieved. The range of measureable flow is 0-6m/s, and maximum variation of piezoresistors is 3.6 percent. Bulk micromachining technology is proposed for fabrication process and total die-size of flowmeter is 1.5×1.5 mm^2.**

Keywords-component: Piezoresistive; MEMS; Flow Velocity ;Flowmeter; Sensitivity

I. INTRODUCTION

Measuring the velocity of gas flows is an essential requirement in many commercial and industrial applications, including Energy (Fuel cells, Welding), Building automation (Gas leak detectors, Combustion control), Medical (CPAP, Anesthesia, Respiratory, Oxygen concentrators), Laboratory (Clean boxes, Gas analyzers), Industrial (Pick and place machines, Cable monitoring, Process control) [1] and city natural gas metering which are commercially available [2,3]. The MEMS-based flow sensing technology offers many advantages over traditional diaphragm gas flow measurement, including High measureable range (turn-down ratio), High accuracy, Low pressure drop and very low power consumption [4].

The flowmeter has various measuring mechanisms, which can be broadly classified as either thermal or non-thermal, depending on their mode of operation.[5,6]

Thermal flowmeters have some advantages including high accuracy in low flow velocity and no moving part (element) is required, but for permanent heating of heater up to hundreds mW power is consumed.[7]

Moreover, the external temperature has an influence on the temperature measurement, and the additional compensation unit is required [8, 9].

Furthermore, non-thermal sensors can be further categorized as either differential pressure-based, lift force-based, or cantilever-based [5].

In non-thermal flowmeters resistive and capacitive techniques are used for detection, which resistive one requires simpler processing circuits.

One of advantages of non-thermal flowmeters compared to their thermal counterpart, namely the requirement for a heating element is removed and therefore the device tends to be more easily fabricated and more power efficient. The main issue in developing high performance non-thermal flow sensors is to enhance the low flow rate sensitivity, because system includes a moving part, which needs air drag force to move, and trivial drag force is obtained in low flow velocity.

A wide series of cantilever beam flowmeters have been presented among nonthermal flowmeters so far, that majority of them use curve structure. The curved structure requires proper residual stress, and the process should be tightly controlled. [10, 11] The drag force decreases in those flowmeters since the main device is not perpendicular to the air flow. Therefore, they show some weak point in the resolution and sensitivity, and they are usually applied for the detection of over 2 m/s or faster air flow [12, 13]

The other main drawback of cantilever beam flow meters is their tendency to be mechanically less stable, as they are supported by only one beam, for instance if the gas flows in unexpected directions it will causes aerodynamic force which can crack the cantilever beam [14].

The proposed flowmeter includes a membrane structure which is perpendicular to the air flow direction to maximize the air drag force. Membrane has suspended by four supporting beams symmetrically which results in extra large torsion spring constant, so torsional or lateral deformation decreases, and mechanical stability is increased. Die-size of the structure is not increased by supporting beams due to the new proposed architecture. The p-type piezoresistor is used due to its higher sensitivity in comparison with n-type.

II. DESIGN

Fig.1 presents a schematic illustration showing the basic structure of the micro-membrane flow-rate sensor developed in the current study.

The device is vertically located against the air flow, so the air drag force is maximized. As indicated in Fig. 1 the resulting downward force created by the pressure difference between the upper and lower surfaces of the membrane causes the four supporting beams to be deflected in the downward direction, thereby producing a measurable change in the resistance of the piezoresistors.

To obtain more stable structure compared to previous works [15-17], four beams support membrane. Membrane displacement is in perpendicular direction and lateral and torsion bending is negligible.

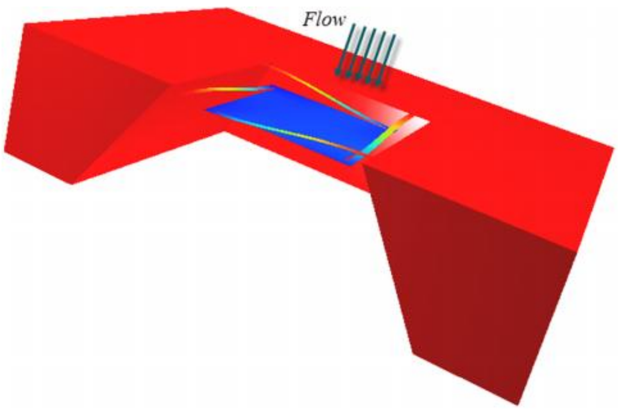

Figure 1. Schematic of proposed structure with applied air flow

Supporting beams are modeled by springs with spring constant equal to k; these springs are in parallel configuration. Hence, the equivalent spring constant is 4k. The equivalent supporting beam width (considering thickness, length and Young's Module to be constant) in fig.2b is 4 times of each beam in fig.2a

The width of each supporting beam is 25µm, so the equivalent beam width is 100µm.

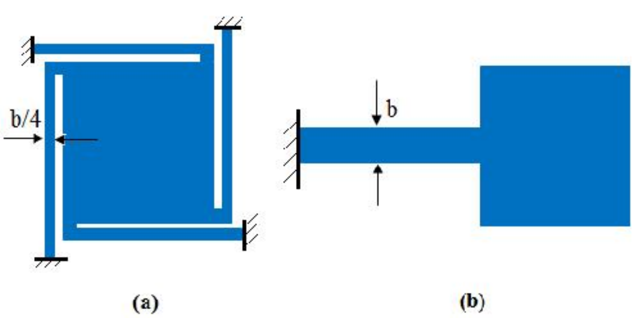

Figure 2. Modeling the supporting beams by springs

The force and pressure which is produced by fluid flow could be obtained as follows:

$$P = \frac{1}{2}\rho V^2 \quad (1)$$

$$W = PA \quad (2)$$

Where P is pressure, W is total force, A is area that is exposed to the flow, ρ is the fluid density and V is the flow velocity. Applied force to flowmeter can be divided into two parts:

1- The force is due to the fluid flow impacts on membrane, which is imposed to free end of the supporting beam fig3.a.

2- Uniform force, which is caused by airflow pressure on surface of supporting beam itself (fig 3-b).

The total stress which is induced to piezoresistors is obtained from two mentioned forces.

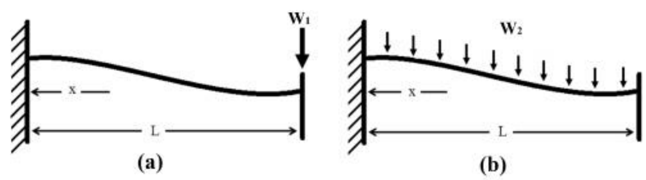

Figure 3. (a) Applied force to supporting beam due to membrane displacement, (b) uniform air flow force on supporting beam.

The stress in each point of the beam in fig3 could be determined in accordance with:

$$\sigma_1 = \frac{W_1 C}{I}\left(\frac{L}{2} - X\right) \quad (3)$$

$$\sigma_2 = \frac{W_2 L C}{I}\left(\frac{1}{3} - \frac{X}{L} + \frac{X^2}{2L}\right) \quad (4)$$

$$\sigma = \sigma_1 + \sigma_2 \quad (5)$$

In equations (3-5), w_1 and w_2 are imposed force to free end, and surface of the supporting beam respectively. σ_1 and σ_2 are stresses which are caused by w_1 and w_2. L is length of supporting beam, C is distance between the diffusion depth of piezoresistors and neutral axis, and I is moment of inertia, which is defined as:

$$I = \frac{bh^3}{12} \quad (6)$$

Where b and h are width and thickness of supporting beams respectively. It is obvious that maximum amount of stress is produced at fixed end of beam(x=0). Considering the length piezoresistores which is negligible compared to the length of supporting beams in equations 3 and 4 piezoresistors is assumed to be placed at the fixed end of the beam. According to equation 1-6 total stress is calculate through equation 7:

$$\sigma = \sigma_1 + \sigma_2 = \frac{6\rho V^2 LC}{bh^3}\left(\frac{A_1}{2} + \frac{A_2}{3}\right) \quad (7)$$

Where σ is total stress, A_1 and A_2 are area of membrane and supporting beam respectively, so the total stress at fixed end of supporting beam can be formulated as follows:

$$\sigma = \sigma_1 + \sigma_2 = \frac{6\rho V^2 LC}{bh^3}\left(\frac{y^2}{2} + \frac{bL}{3}\right) \tag{8}$$

Where y is the size of membrane's square. Variation of pizoresistors due to applied stress is obtained by:

$$\frac{\Delta R}{R} = \frac{\pi_{44}}{2}(\sigma_l - \sigma_t) \tag{9}$$

Where π_{44} is piezoresistance coefficient, σ_l and σ_t are longitudinal and transverse stress components respectively. Considering force direction which is applied longitudinally to supporting beams, longitudinal stress would be the dominant and transverse stresses can be ignored [18], By combining the Eqs. 8 and 9, the final equation is given by:

$$\frac{\Delta R}{R} = \frac{\pi_{44}}{2}\left(\frac{6\rho V^2 LC}{bh^3}\left(\frac{y^2}{2} + \frac{bL}{3}\right)\right) \tag{10}$$

According to [19] π_{44} is chosen to be 70 which is constant in wide range of temperature. The following values in table1 were used for flowmeter design.

TABLE I. FLOWMETER DIMENSIONS AND FLUID DENSITY

Parameter	***Size***	***Unit***
Length of beam	600	µm
Thickness of beams and membrane	1	µm
Width of each beam	25	µm
Membrane area (y^2)	500×500	μm^2
distance between the diffusion depth of piezoresistors and neutral axis[1]	0.45	µm
Air density	1.29	Kg/m^3
Supporting beams and membrane material	Bulk(100) silicon	

By replacing the table1 values in equation 10, the sensitivity is related to the air velocity via the following expression:

$$\frac{\Delta R}{R} = 0.106V^2\% \tag{11}$$

According to expression (11), 0.5m/s flow results in 0.025% resistor changes. To detect piezoresistor variation, a simple readout circuit is proposed. As shown in fig4 0.025% variation of piezoresistor leads to 300µV changes in analog output voltage that 12 bit ADC is sufficient for resistors variation.

[1] The thickness of moveable part is 1µm, diffusion depth for piezoresistors is 0.1µm that results in 0.45µm distance between the diffusion depth of piezoresistors and neutral axis in supporting beam

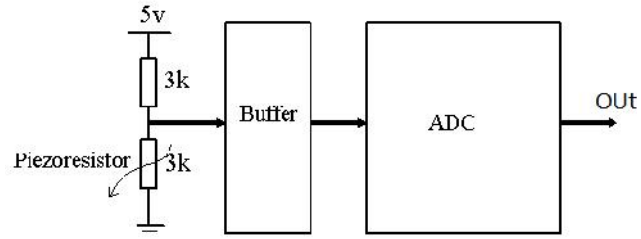

Figure 4. Proposed readout circuit

According to fabrication process which uses anisotropic backside etching with KOH solution [17] total size of the structure would exceed table1 values and will be equal to1.5×1.5 mm^2.

III. SIMULATION RESULTS

The simulation of the proposed structure is performed by fluent and IntelliSuite softwares, which are appropriate for flow and solids analysis respectively.

Fig.5 shows the simulation result for pressure distribution at flow channel which a membrane located vertically in the middle of the channel, then outcome pressure is applied to survey mechanical simulations and resistor variation. Stress distribution in maximum air flow(6m/s) is shown in fig6, maximum stress is at the fixed end of the supporting beams which is in elastic region of silicon, so there would be no cracking in silicon structure.

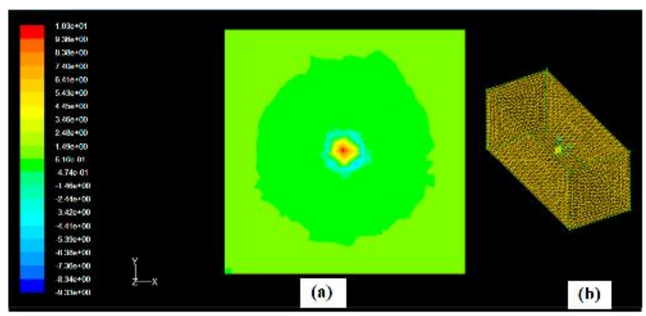

Figure 5. Fluidic simulation result (a) pressure distribution in channel that membrane is located in the center of it (b) channel and membrane simulation environment

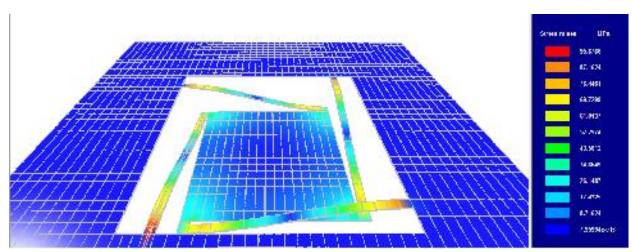

Figure 6. Simulation result for stress distribution at 6m/s air velocity

Fig.7 shows simulation and calculation result for pizoresistor variation to its absolute value for full range air velocity. As shown in fig7 calculation and simulation are in good agreement. However, they are not exactly coincided each other, which can be due to ignoring piezoresistors length compared to beams and also negligible deflection of membrane.

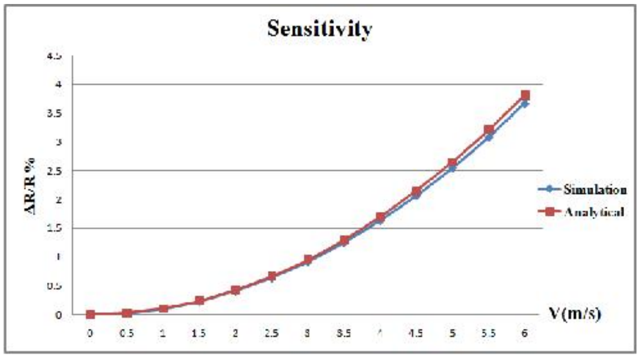

Figure 7. piezoresistors variation in full range of applied air flow

IV. FABRICATION PROCESS

Proposed fabrication process consists of following steps:

1. Oxidation of a SOI wafer
2. Lithography and oxide pattern
3. Diffusion
4. Lithography and front side pattern
5. Back side pattern
6. Releasing the structure

Final structure's cross section is shown in fig8.

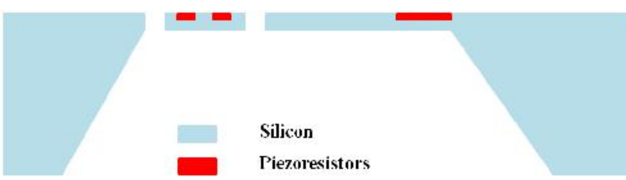

Figure 8. Cross section of proposed fabrication process

V. CONCLUSION

In this paper a MEMS-based micro flow-rate sensor comprising of silicon membrane which is supported by four beams with diffused piezoresistor is proposed. P-type piezoresistor is used to achieve high sensitivity and simple electrical readout is presented. Designed structure is mechanically more stable compared to previous cantilever beam sensors. The suspended part bending in unwanted torsional and lateral direction is eliminated by new proposed structure. Simulation results and calculation results are in good agreement. Proposed fabrication process is in bulk micromachining technology by using SOI wafer, further work can be done for the fabrication of flowmeter by ordinary silicon wafers and surface micromachining.

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