Excerpt from the Proceedings of the 2011 COMSOL Conference in Bangalore

A Wide Range MEMS Vacuum Gauge Based on Knudsen's Forces

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Abstract: In this paper, three dimensional finite element coupled electro-thermal and electro-mechanical analysis of a vacuum gauge based on Knudsen's forces is presented. Simulations have been performed using COMSOL 3.5a. Analytically derived expression for Knudsen's forces has been used as the starting point for designing the vacuum gauge and the effect of various parameters on the performance of the vacuum gauge has been studied carefully for optimization.

Keywords: MEMS, electro-thermal, electro-mechanical, vacuum measurement.

1. Introduction

Martin Knudsen [1] first demonstrated the 'absolute manometer' based on radiometric forces or thermal molecular pressure. Knudsen's manometer consisted of two parallel plates separated by a distance (***d***) much less than the ambient gas mean free path (λ). One of the plates can be heated and is fixed whereas the other is suspended by a sensitive support. According to the kinetic theory of rarified gases, heating one of the plates above the temperature of the surrounding walls causes a repulsive force to be exerted on the other plate and this force is proportional to the ambient pressure. The force on the suspended plate is then a measure of the gas pressure.

Ali et al. [2] showed that these forces can be measured using microcantilevers in the capacitive mode and also derived an analytical formula for these forces on microcantilevers [3].

In this paper, we design a miniaturized Knudsen type vacuum gauge using two suspended membranes, one designed as a heater with a very high spring constant and the other as a movable membrane with a serpentine spring support. The top view and the cross-section view of the basic structure are shown in fig 1 and fig 2.

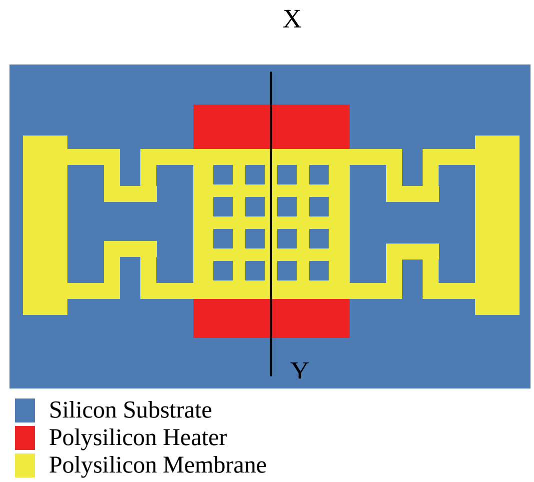


Figure 1. Top view of the designed Miniaturized Knudsen type vacuum gauge

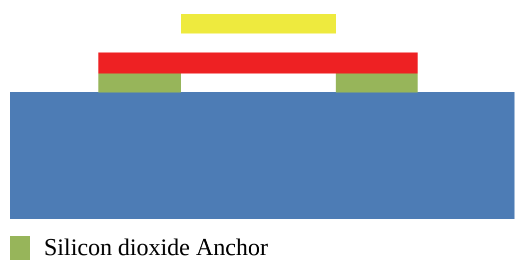


Figure 2. Cross-Section view along X-Y of the designed structure

The working of the designed structure is similar to the conventional Knudsen vacuum gauge. The heater in the designed structure is a polysilicon resistor and the membrane is also made of polysilicon. Passing current through the heater increases the temperature due to Joule heating. This creates a temperature gradient from the heater to the suspended membrane. The membrane then moves away from the heater changing the capacitance of the heater-membrane assembly. The capacitance can then be measured to estimate the pressure.

The analytical expression describing the Knudsen's force derived for a cantilever facing a substrate (fig 3.) is given by equation (1).

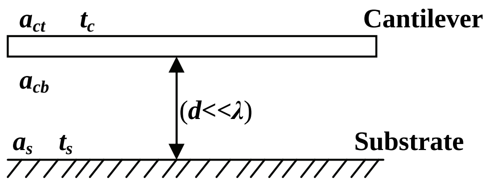


Figure 3. Cantilever-Substrate assembly for which the equation 1 is derived

$$F = \frac{p_r}{2}\left[\sqrt{\frac{(a_s t_s + a_{cb}(1-a_s)t_c)}{a_s + a_{cb} - a_s a_{cb}}} + \sqrt{\frac{(a_{cb} t_c + a_s(1-a_{cb})t_s)}{a_s + a_{cb} - a_s a_{cb}}} - \sqrt{(1 - a_{ct} + a_{ct} t_c)} - 1\right] \quad (1)$$

Where p_r is the ambient pressure, a_s a_{cb} and a_{ct} are the thermal accommodation coefficients of the substrate, cantilever surface facing the substrate, cantilever surface away from surface, t_s and t_c are the cantilever and substrate temperatures normalized to ambient temperature. Thermal accommodation coefficients are a measure of the fraction of the heat transferred between the surface and the molecule. A thermal accommodation coefficient of unity implies that the molecule temperature is equal to the surface temperature after a collision.

Equation (1) can be used for calculating Knudsen's forces on our designed membrane by replacing the substrate temperature with the heater temperature and the cantilever temperature with the membrane temperature.

2. Simulation in COMSOL

2.1 Simulation procedure and complete structure

The simulation of the designed structure was done using two different models. The first model was used to obtain the temperature profile and average temperature of the designed structure using coupled electro-thermal simulations. The model calculates the temperature profile of the heater and the membrane for different ambient pressures and applied heater voltages.

The second model was used to obtain the deflection of the membrane using electro-mechanical simulations. The forces acting on the membrane are electrostatic force, Knudsen's force and the membrane spring restoring force. All the forces are taken into account to obtain the deflection of the membrane at different pressures. The model returns the surface charge concentration on the heater and the membrane for different applied voltages. Integrating the surface charge concentration divided by the potential difference between the heater and the membrane over the entire heater surface gives the capacitance between the heater and the membrane.

The designed structure has four heaters connected together in parallel and four suspended membranes, one over each of them. The membranes are also connected to each other to increase the change in capacitance of the gauge for a given pressure. The heater area is 525 µm x 525 µm with 100 symmetrically spaced etch holes. Different spring constant structures are tested.

The top view of the complete structure is shown below

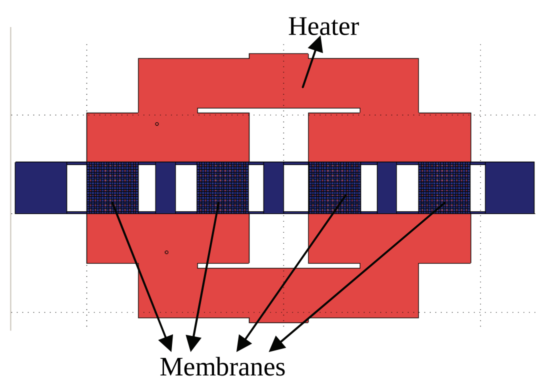


Figure 4. Top view of the complete structure

2.2 Electro-Thermal model

The top view of the designed heater is shown in fig 5. The heater is made of doped polysilicon deposited over silicon dioxide which forms the anchor for the suspended heater.

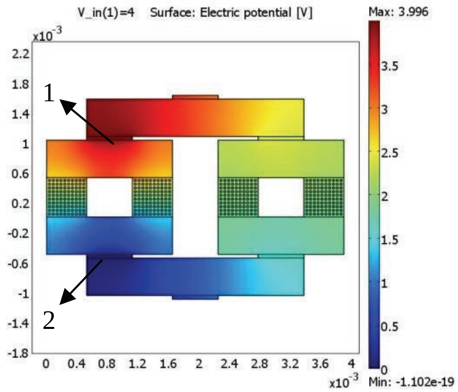


Figure 5. Top view of the polysilicon heater and the voltage at different points on it for 4V applied across points 1 and 2.

The polysilicon with etch holes in the center forms the suspended heater which can be released by sacrificial oxide etching. The rest of the polysilicon is designed to provide equal voltage drop across the heaters to have uniform surface temperature.

The schematic of the model used for three dimensional simulations is shown in fig 6.

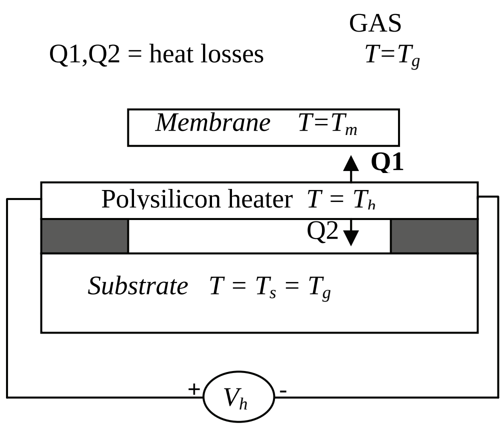


Figure 6. Schematic of simulated heater model used for simulation

Since the structure is placed in vacuum, all surfaces can be assumed to be thermally insulating except where the oxide anchors contact the substrate and the air gaps between the membrane and the heater and the membrane and the substrate. The heat loss through the air gaps is a function of pressure because thermal conductivity of air depends on the pressure as given by the relation [5]

$$k_{air} = k_{air,o} \times \frac{1}{1 + \frac{7.6 \times 10^{-5}}{p.\frac{d}{T}}} \qquad (2)$$

Where $k_{air,o}$ is the thermal conductivity of air at room temperature (298K), T is the average temperature of the two surfaces between which the air gap is present.

The substrate temperature is taken as equal to the ambient gas temperature. Thermal isolation boundary condition is applied for all the boundaries except where the oxide anchors meet the substrate where constant temperature boundary condition is applied (equal to substrate temperature). The complete meshed structure is shown in fig 7 and the generated temperature profile is shown in fig 8.

Thermal conductivities of the materials silicon, silicon dioxide, and polysilicon were taken as 150 W/(m.K), 1.4 W/(m.K) and 40 W/(m.K). The electrical resistivity of the polysilicon heater is taken as 3×10^{-5} Ω.m and the thermal coefficient of resistance is 5×10^{-3} /K. The values were taken from [4] and COMSOL material library.

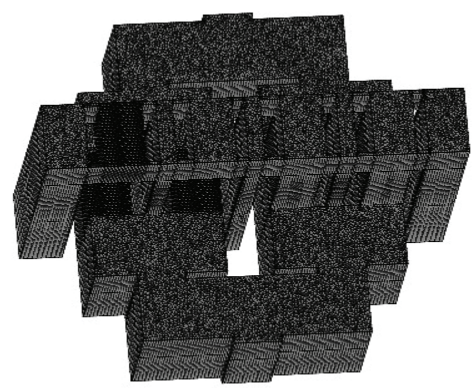


Figure 6. Meshed complete sensor structure for electro thermal simulation

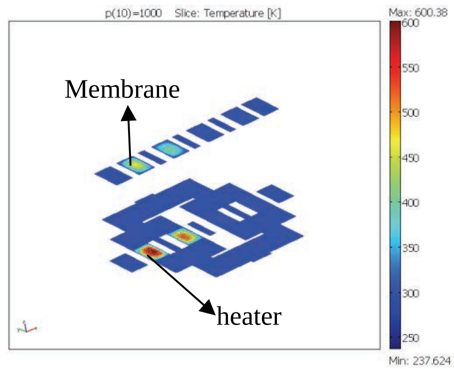


Figure 8. A slice plot showing the temperature profile of the top of the heater surface and bottom of the membrane

2.3 Electro-Mechanical model

The schematic used for electro-mechanical simulation is shown in fig 9. The electric potential distribution of the heater and the potential of the membrane are given directly as inputs to the model. The average heater temperature and the average temperature of the top and bottom surface of the membrane obtained from the simulation in the previous model are used for calculating Knudsen's force and this force is applied as a uniform force on the bottom surface of the membrane. Once the deflection of the membrane is obtained, the capacitance is found by integrating the surface charge density divided by the electric potential over the heater surface.

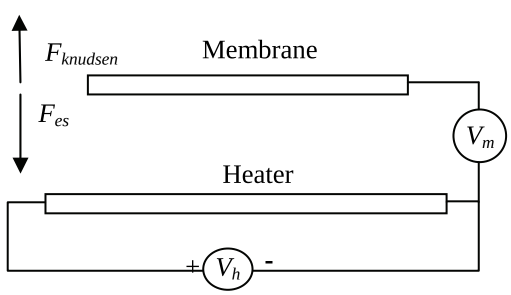


Figure 9. Schematic of simulated membrane model used for simulation

The complete meshed structure is shown in fig 10 and the generated deflection is shown in fig 11.

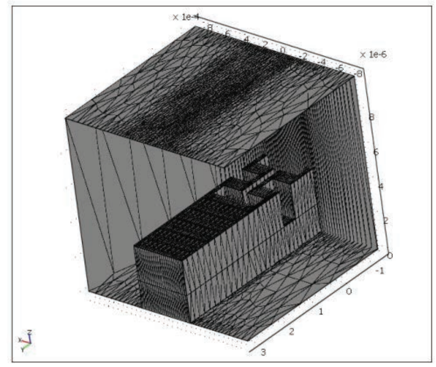


Figure 10. Meshed structure used for electro thermal simulation

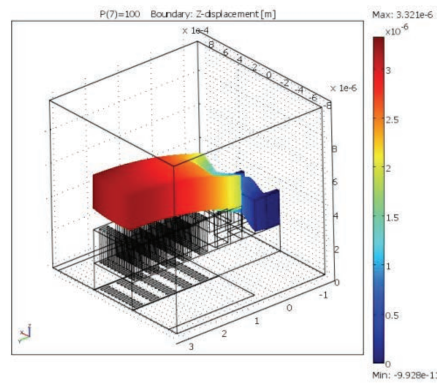


Figure 11. A boundary plot showing the z-deflection of the membrane for a pressure of 100Pa and a heater voltage (*Vh)*=0.6V

3. Results and Discussion

Our main objective for the simulations was to find the optimized values of the heater voltage, membrane voltage and spring constant of the membrane for which the structure gives best performance for a given separation of the heater and the membrane. Ideal characteristics would be a low heater and membrane voltage, high heater and membrane temperature and a low spring constant. With a little analysis it can be seen that the spring constant of the beam is the dominant parameter and, once specified, it determines all the other parameters.

The spring constant defines the pull-in voltage of the heater membrane assembly (since gap is already fixed). Since the heater voltage cannot exceed the pull-in voltage, it is limited which again limits the maximum temperature that can be obtained.

It has to be noted that the pull-in voltage here is slightly different from the usual case as there is a voltage gradient in one of the plates (the heater). Also for maximum sensitivity, we want low electrostatic forces. It can be shown mathematically that for an applied heater voltage V_h (fig 9), minimum electrostatic force exists between the membrane and the heater for a membrane voltage of $V_h/2$.

3.1 Pull in voltages for different spring constants

The spring constant of the structure was varied by varying the thickness of the polysilicon membrane from 0.2µm to 2µm for a given spring structure. Details of the spring structure and membrane are given in fig 12.

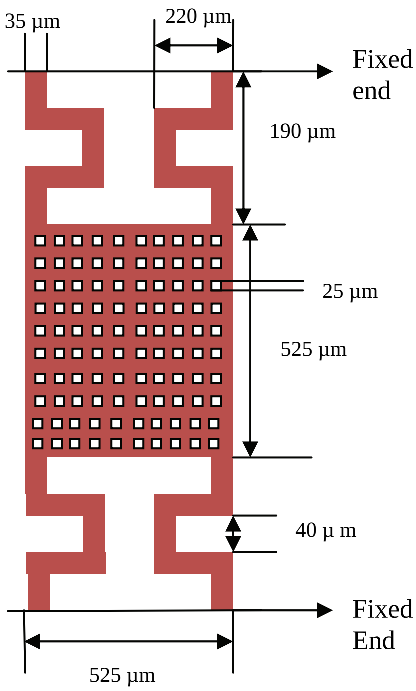


Figure 12. The membrane and serpentine spring constant structure used for pull-in voltage calculations

The pull in voltages obtained for different thicknesses of the membrane with serpentine springs is shown in figure 13.

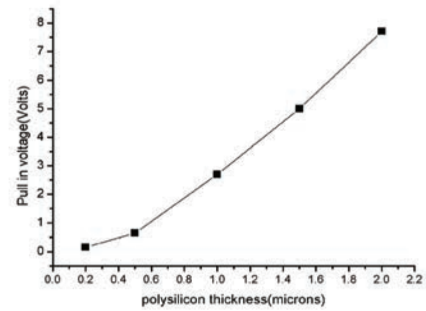
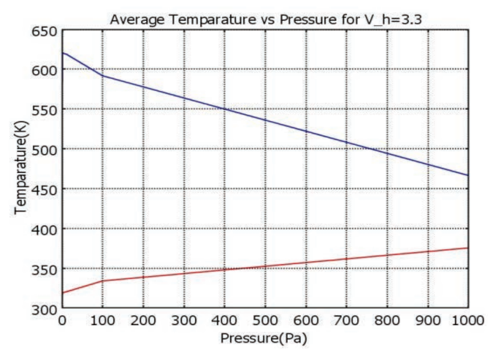


Figure 13. Pull in voltage variation for a given spring structure for varying thickness

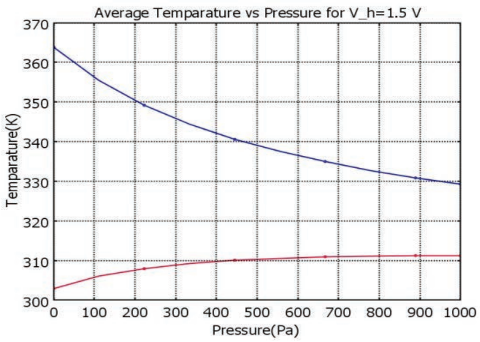
For stable operation, the voltage applied to the heater has to be less than the pull-in voltage. Nominally, two thirds the pull-in voltage was chosen for finding temperature profiles.

3.2 Temperature gradients for different pressure and voltages

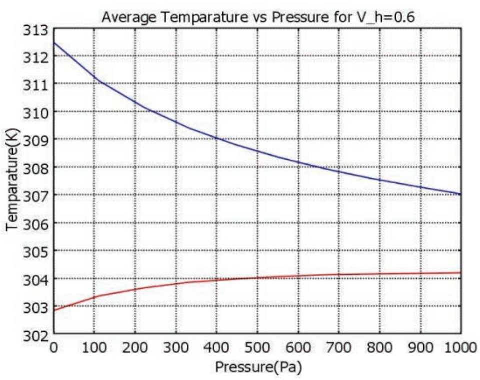
The average temperatures of the heater surface and membrane for different applied heater voltages and for various values of pressure are shown in fig 14. Note the fall in heater temperature as pressure increases. This is due to effective cooling of the heater by air between the substrate and the heater. The increase in the temperature of the membrane is also due to increased heat conduction of the air gap between the heater and the membrane.



(a)



(b)



(c)

Figure 14. Average temperature of heater (shown in blue) and membrane (shown in red) for (a) *Vh*=3.3V (b) *Vh*=1.5V (c) *Vh*=0.6V

The average temperatures dependence on the input voltage is shown in fig 15.

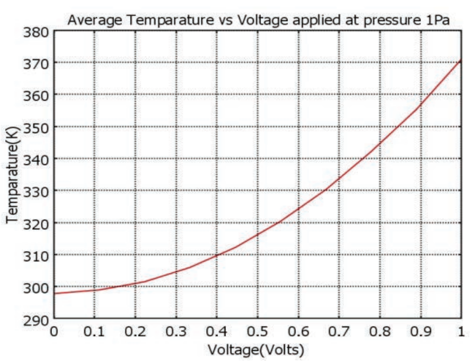
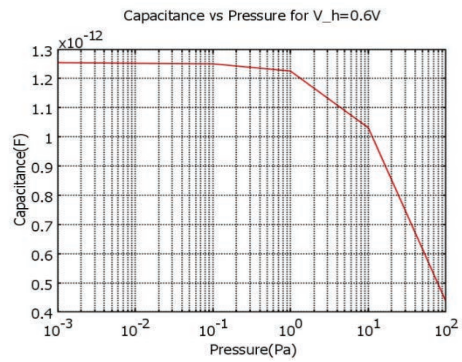


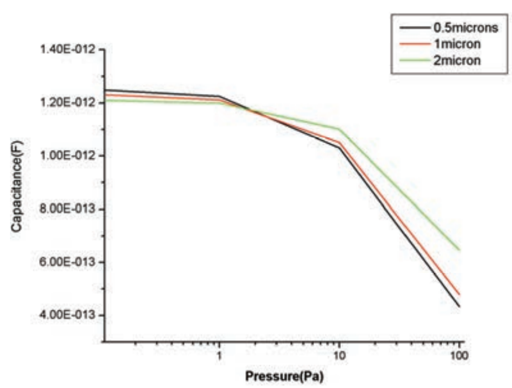
Figure 15. Average temperature of heater as a function of applied voltage

3.3 Capacitance variation with pressure

The capacitance variation with pressure for different beam thickness is shown in fig 16. From the curves it can be easily seen that a membrane with lower spring constant and lower voltage applied to the heater offers better performance as it has the same capacitance variation as the membranes with a higher spring constant consuming less power in doing so and is slightly more sensitive in the given range compared to the higher thickness membranes in spite of the higher temperatures.



(a)



(b)

Figure 16. (a)Capacitance variation with pressure for the designed structure with V_h=0.6V. (b)Comparision for 3 different thicknesses for a single membrane and heater assembly

4. Conclusions

A three dimensional finite element model has been developed for modeling a miniaturized Knudsen type pressure gauge. The net change in capacitance is about 0.7 pF. A parallel combination of four such sensors makes the change 2.8 pF. Commercial capacitance to digital converters like Analog Devices AD7745 CDC have a resolution of 4 aF. At a pressure of 10^{-3} Pa (10^{-5} mbar) the capacitance changes by 24 aF from the capacitance value at zero pressure for a 1 µm thick polysilicon membrane. The minimum detectable pressure should then be in this range.

From the results it is seen that the inherent nonlinearity of the system is responsible for the wide operating range of the sensor. The structure can be fabricated using surface micromachining techniques.

This work was carried out at the NPMASS design center, Microelectronics and MEMS Laboratory, Department of Electrical Engineering, IIT Madras, Chennai.

5. References

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