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

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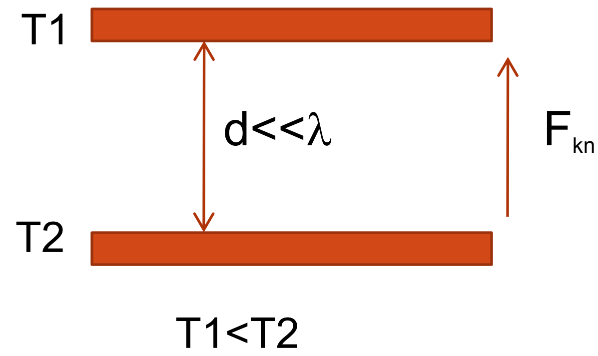
Outline

- Theory
- Design
- Goal of Simulation
- Results and Discussion
- Summary

Radiometric or Knudsen's Forces

- Gas kinetic forces generated in rarified gases when
  - Characteristic length is comparable to mean free path
  - Temperature gradients
- Origin of force explained using thermal transpiration
- Magnitude and direction of the force depend on
  - Temperature of surfaces
  - Separation of the surfaces
  - Ambient gas pressure and temperature

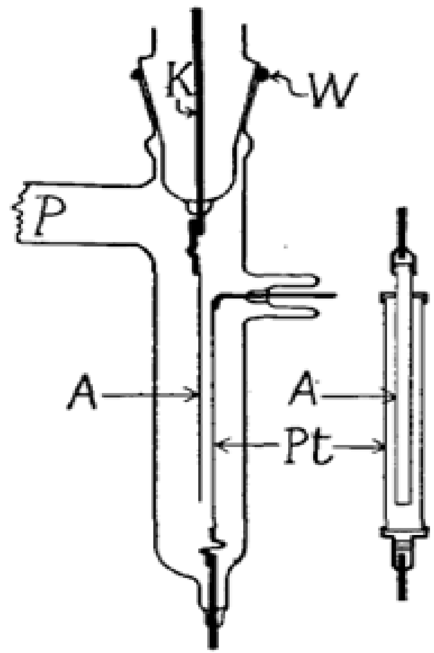


F_{kn} = Knudsen's Force

Direction of Knudsen's force between two surfaces held at different temperatures

Knudsen's Gauge

- Conventional Knudsen's gauges were shown to work from 10^{-6} mbar to 10^{-2} mbar*
- Despite the wide working ranges and good sensitivity they were never because mainstream because of
  - Extreme sensitivity to environmental shocks
  - The gauges could not be read remotely



Simplest form of a Knudsen's Gauge
A - Aluminum Foil
Pt - Platinum heater
W - Wax
P - To Pump Unit
K - Tungsten lead
Deflection of the aluminum foil is a measure of the pressure**

* W. Kreisel, *Vacuum*, **26**, 339 (1976)

** A.L.Huges, *Rev. Sci. Instrum.*, **8**, 409 (1937).

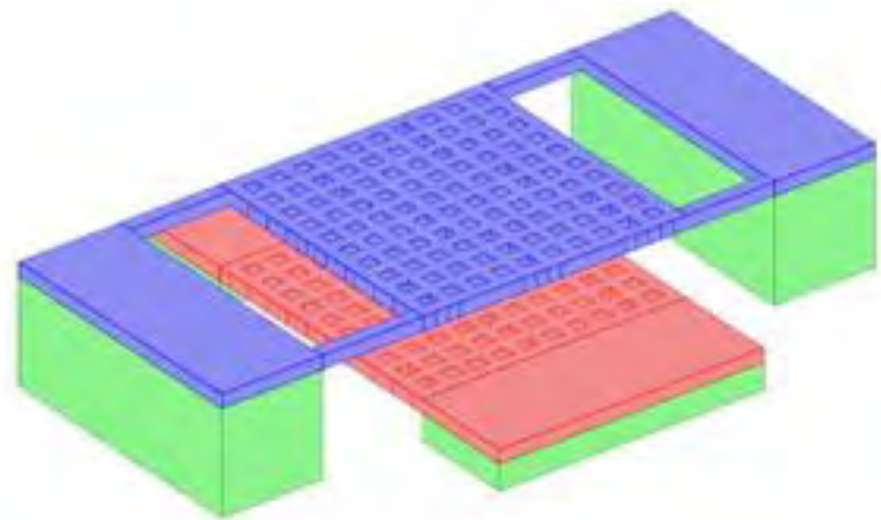
Why Miniaturize

- More immune to environmental shocks and noise because of higher resonant frequencies
- Remote reading possible by using the conventional capacitive readout in MEMS
- Wide operating range obtained in conventional gauges possible in miniaturized versions also
- Can be fabricated using surface micromachining techniques
- Has been shown that these forces are significant on heated microcantilevers*

* A.Passian et. al., *Ultramicroscopy*, **97**, 401 (2003).

Miniature Knudsen pressure gauge: Structure

- Designed structure contains
  - Heater to induce thermal gradients
  - Membrane that deflects due to Knudsen's forces
- Heater-Suspended polysilicon plate with etch holes fixed rigidly to its anchors
- Membrane-Polysilicon plate with etch holes connected to its anchor with springs



Polysilicon Heater

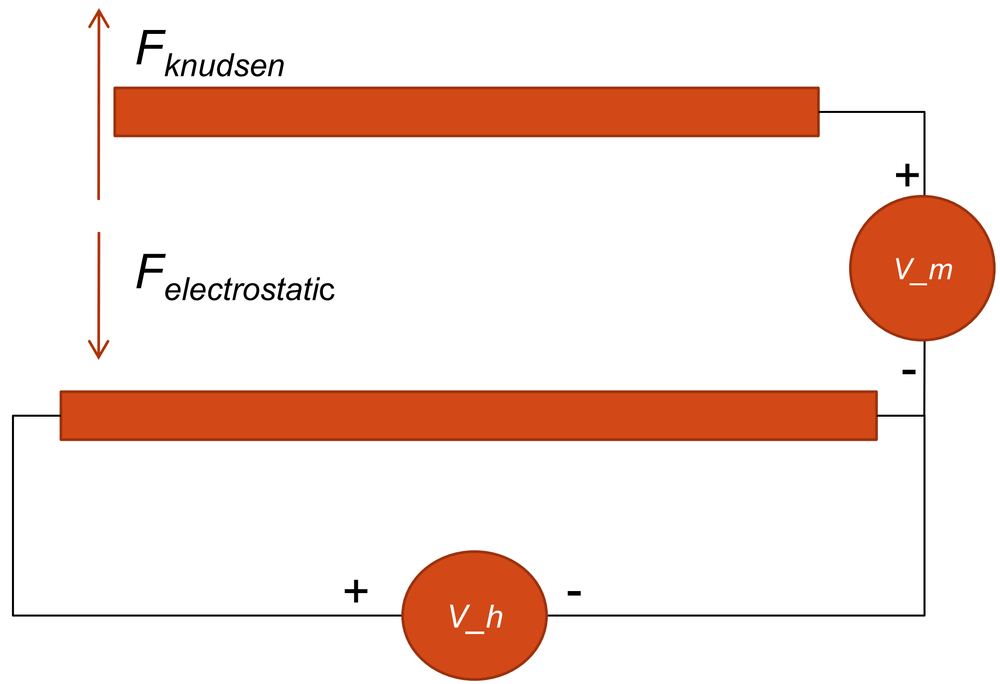
Oxide Anchors

Polysilicon Membrane

Simple form of the Miniaturized Knudsen gauge

Miniature Knudsen pressure gauge: Operation

- Current passed through the polysilicon heater, raising its temperature due to Joule heating
- Knudsen's forces due to the temperature gradient between heater and the membrane displace the membrane
- Capacitance between the heater and the membrane changes
- The capacitance is a measure of the ambient pressure



V_h - Heater Voltage
V_m – Membrane *voltage*

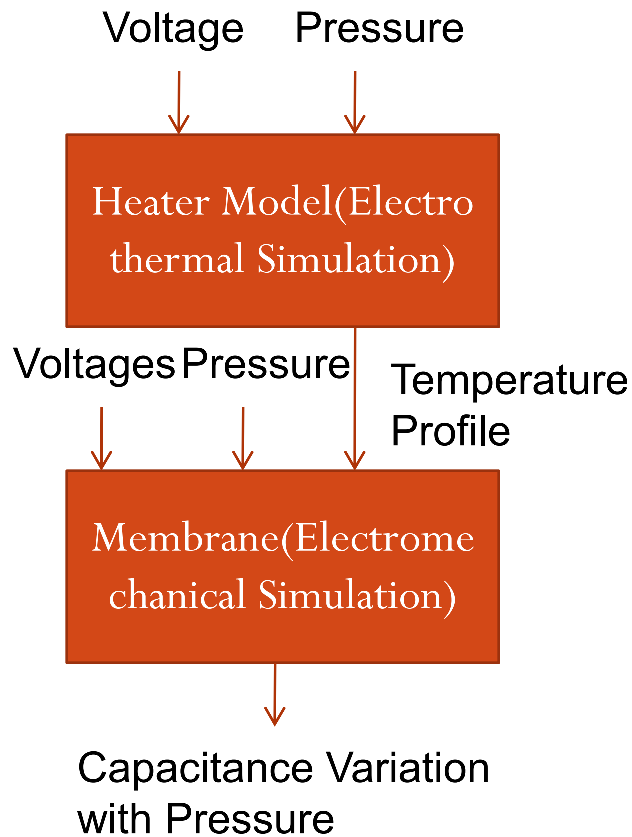
Schematic showing the various forces acting on the membrane

Goals of simulation

- Study the effect of variation in following parameters on the Knudsen gauge performance
  - heater current
  - membrane voltage
  - membrane spring constant
- Find the optimum values for these parameters
- Obtain the operation of high spring constant and high temperature combination and low spring constant and low temperature combination
- Comparison of the two approaches
- Estimate the capacitance variation of the membrane-heater assembly with pressure for membranes with different thicknesses

Miniature Knudsen pressure gauge: Simulation Procedure

- Two 3-D Models used
- The first model calculates the temperature profile of the heater and the membrane
- The second model calculates the deflection of the membrane due to Knudsen's forces and electrostatic forces
- Knudsen's forces are calculated using analytical formula from*
- The second model also calculates the capacitance between heater and membrane

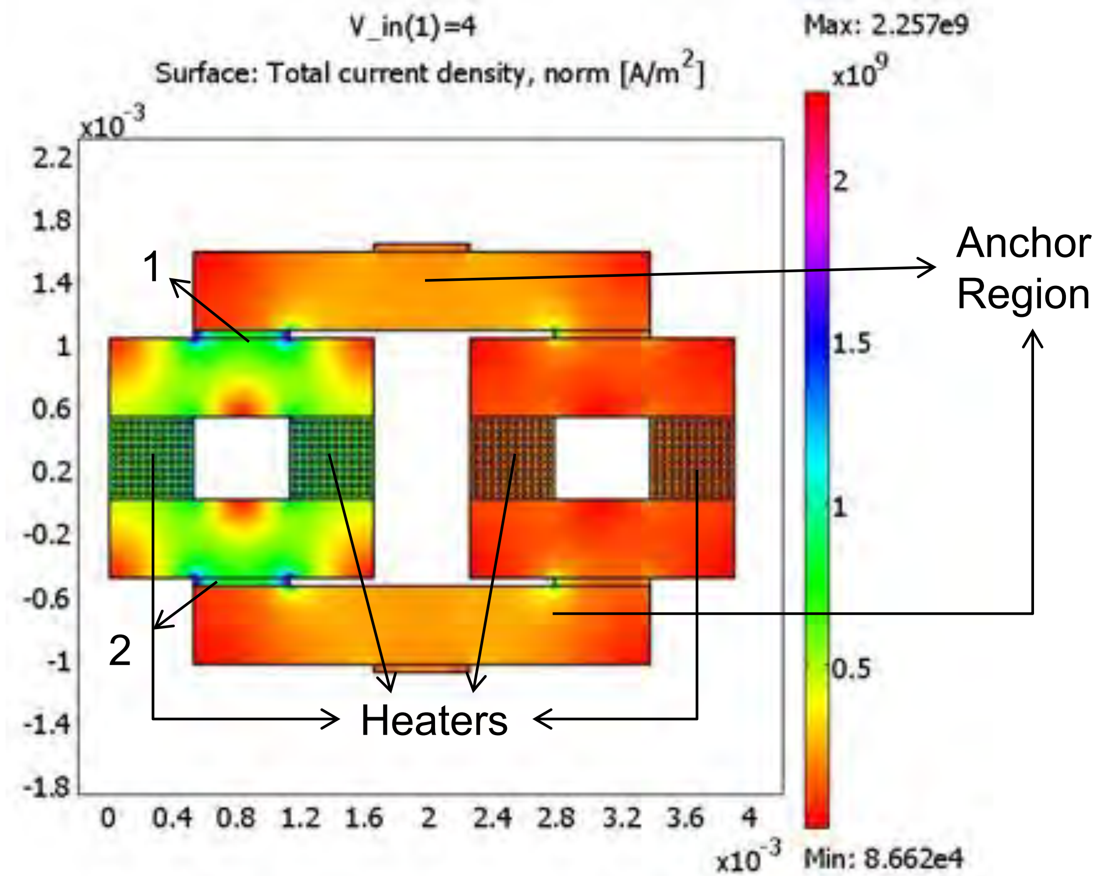


Schematic showing the various forces acting on the membrane

* A.Passian et.al. ,*J. Appl. Phys.*, **92,** 6326 (2002).

Polysilicon Heater

- Four heaters connected in parallel
- Anchor region is designed such that the membranes have a uniform temperature across them
- The heaters are 525 μm x 525 μm x 0.5 μm n-doped polysilicon plates with 100 symmetrically placed etch holes of dimensions 25 μm x 25 μm

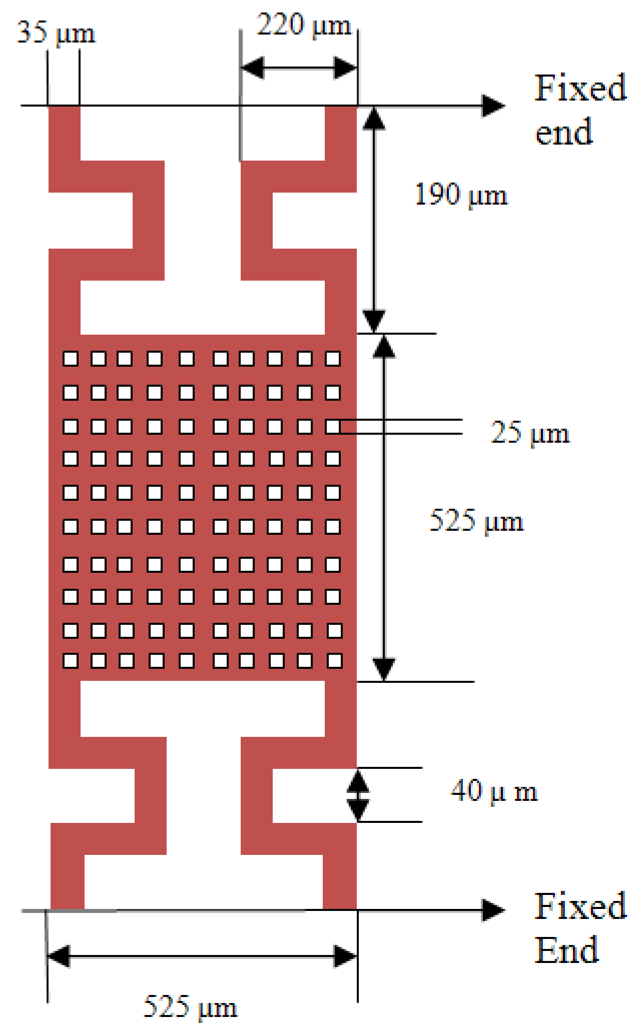


Top view of the polysilicon heater and the current density on it for 4V applied across points 1 and 2 passing a current of 500mA through the heater.

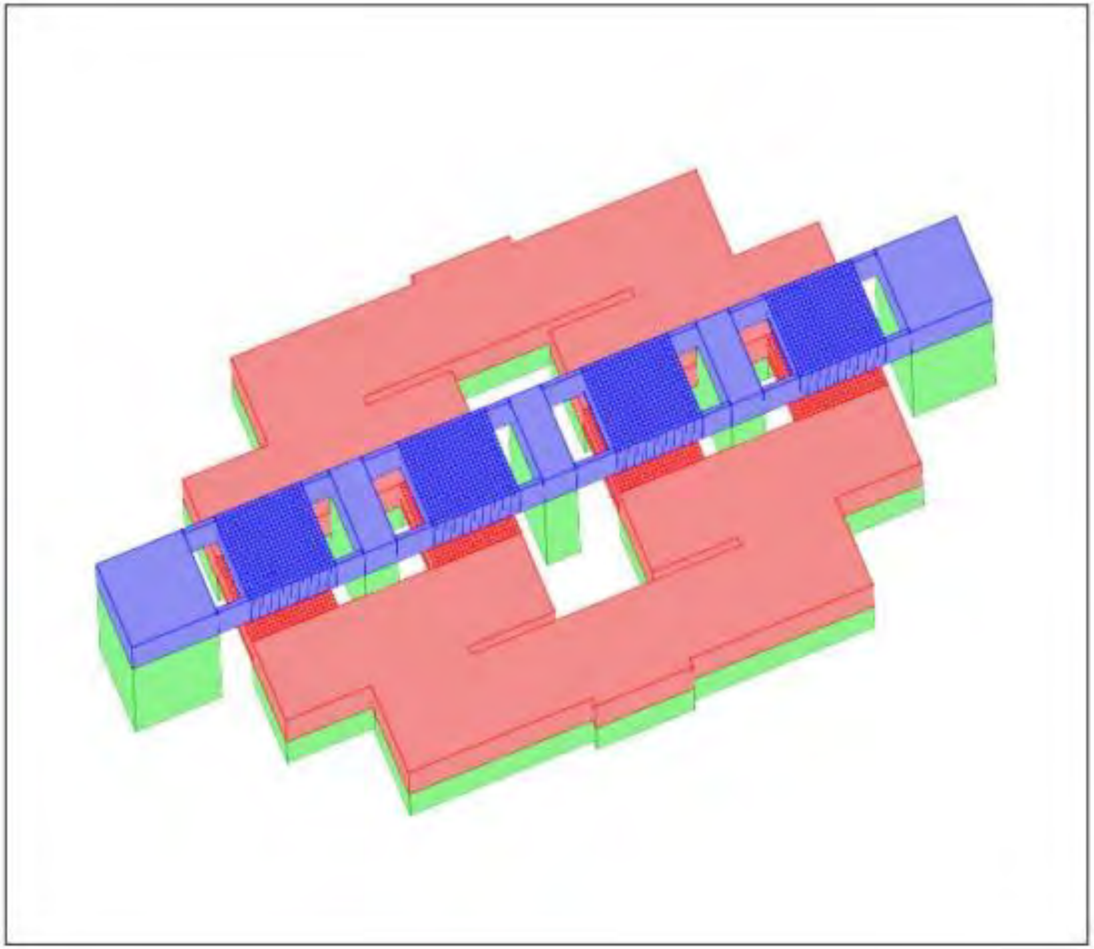
Polysilicon Membrane

- The four heaters have a suspended membrane over each of them
- The membrane is made of n-doped polysilicon
- Thickness of the polysilicon layer is varied to obtain different spring constants

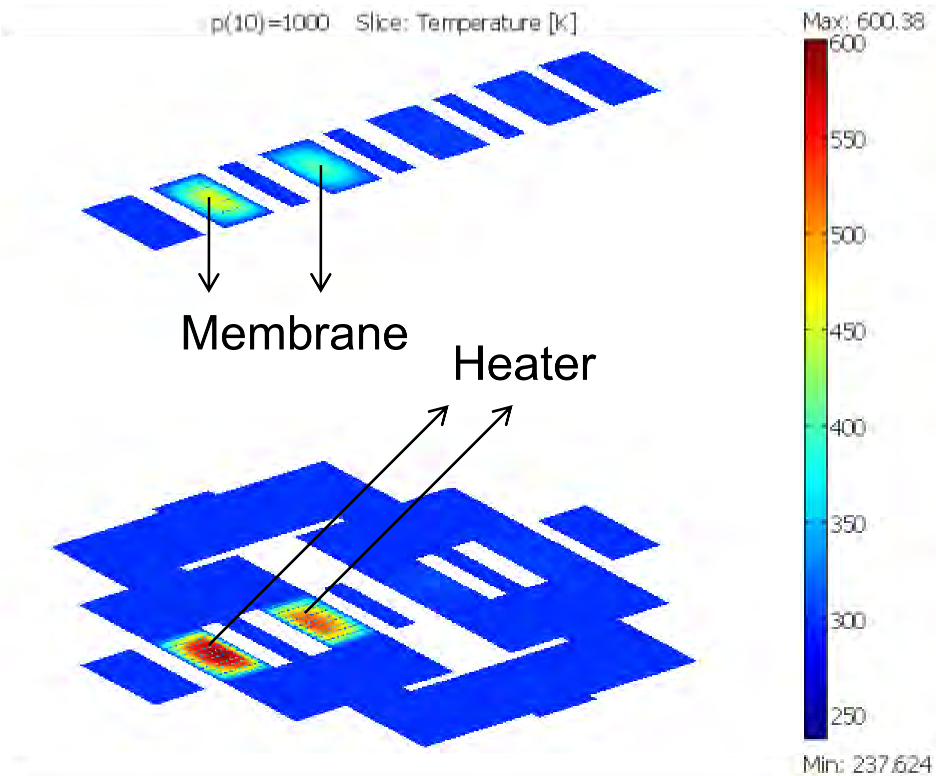
Polysilicon Thickness	Effective Spring Constant
0.5 µm	0.5 N/m
1 µm	18 N/m
2 µm	128 N/m



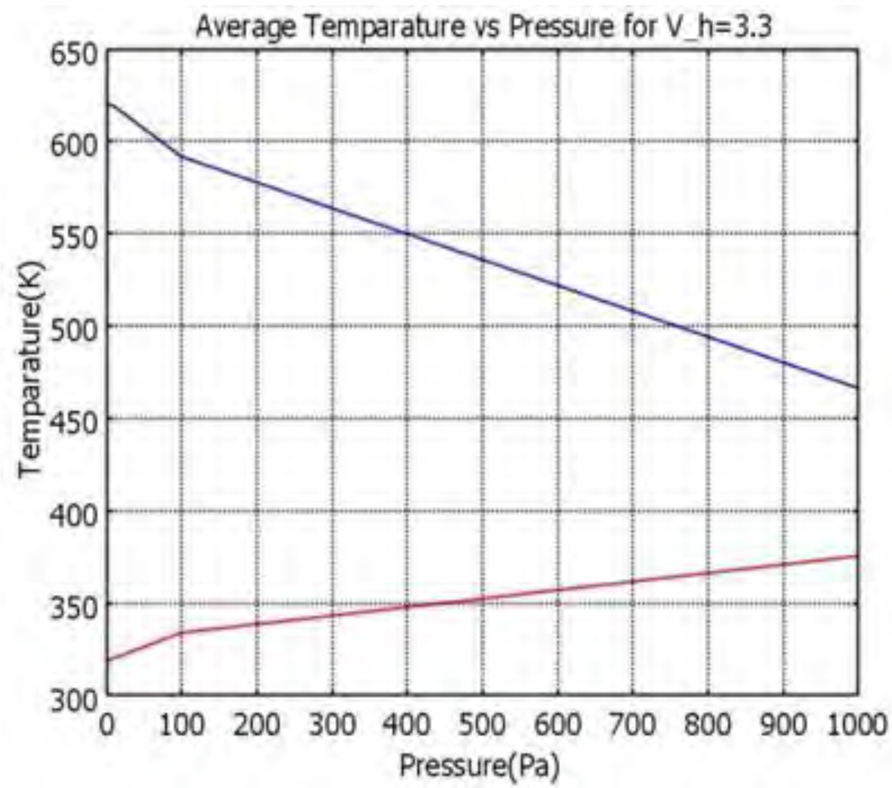
Complete Designed Structure



Simulation Results : Heater

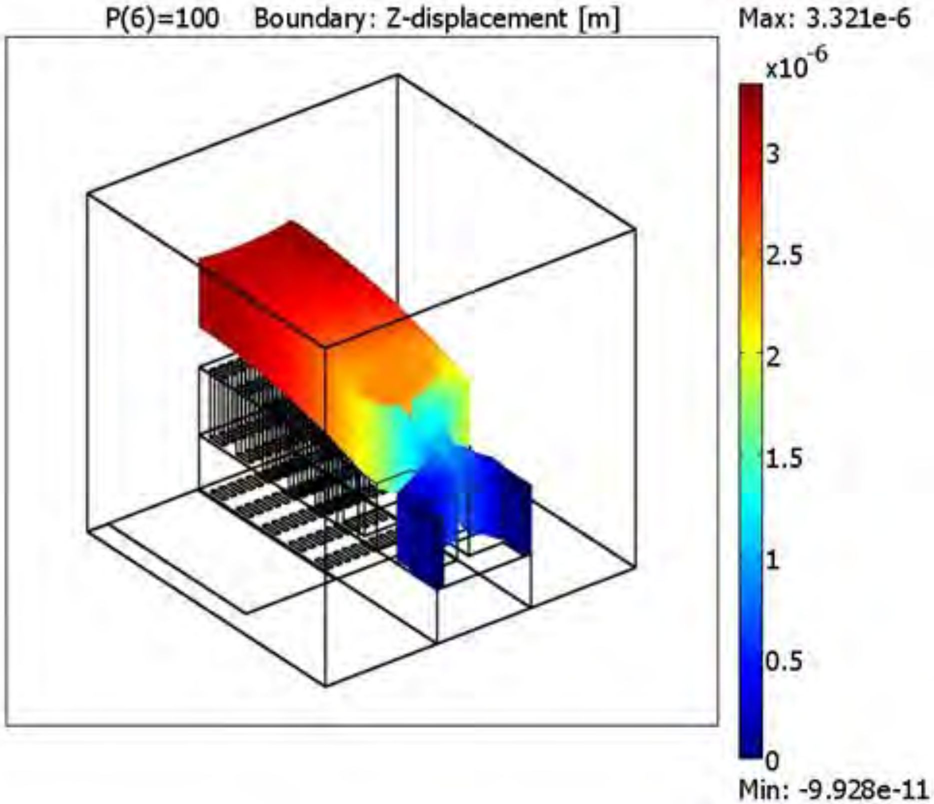


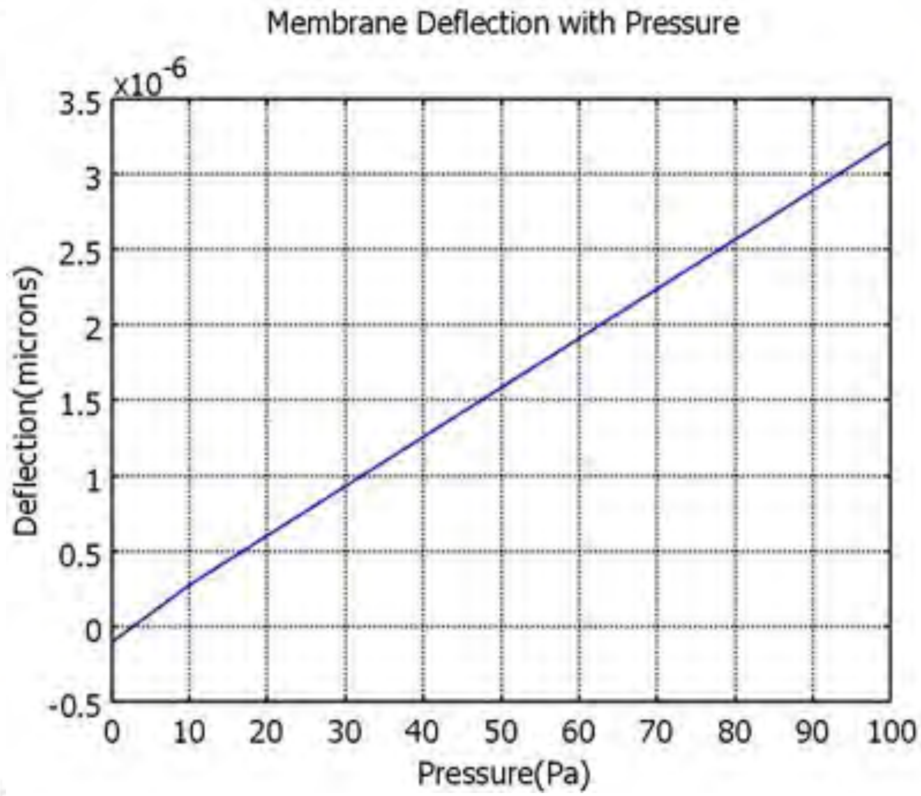
A slice plot showing the temperature profile of the top of the heater surface and bottom of the membrane at 1000 Pa with a heater current of 900mA



Average temperature of heater (shown in blue) and membrane (shown in red) at a heater current of 900mA

Simulation Results : Membrane

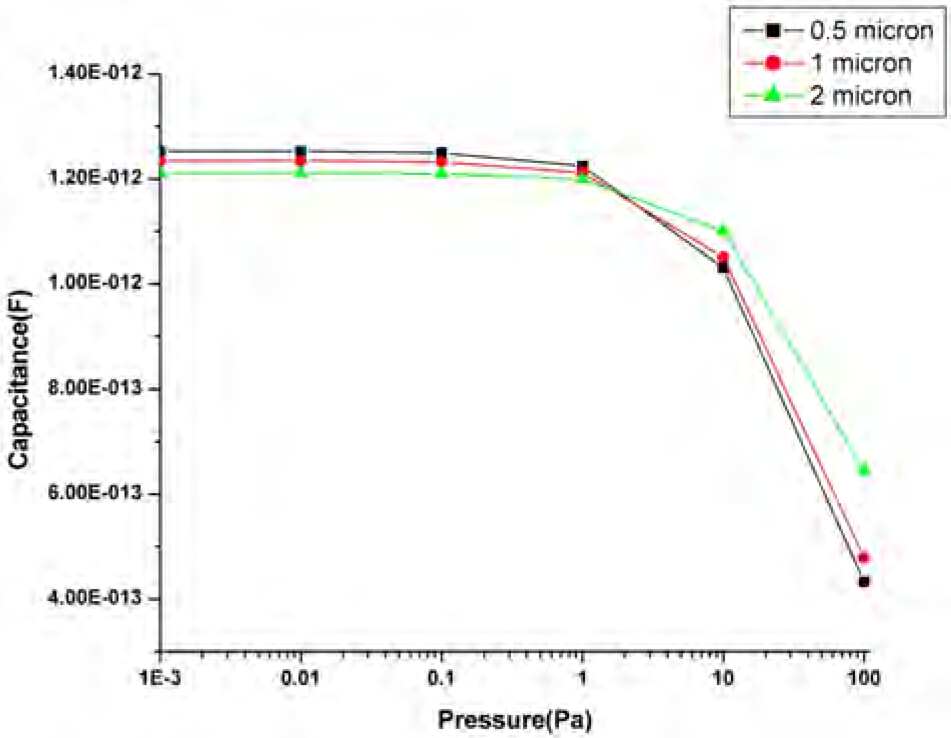




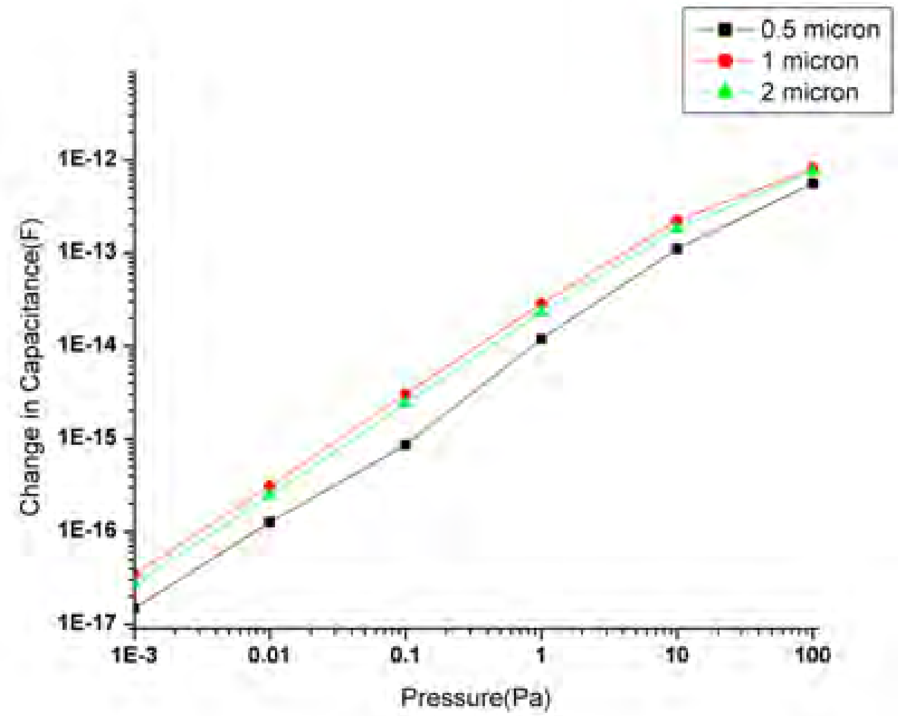
A boundary plot showing the deflection of the membrane for a pressure of 100Pa and a heater voltage of 0.6V

Deflection of the membrane as a function of pressure for an applied heater voltage of 0.6V

Simulation Results : Capacitance variation with pressure



Capacitance variation with pressure for membranes with different thicknesses



Absolute change in capacitance at different membranes with different thicknesses

Summary

- A 3D finite element model has been developed for modeling a miniaturized Knudsen type pressure gauge
- The working of the concept has been validated using simulation
- It is seen that the spring constant is the critical parameter of the sensor
- The system is inherently non linear and this fact can be exploited to obtain very large operating ranges
- With capacitance detection in atto Farads range(Analog Devices AD7745 CDC)* should be possible to measure minimum detectable pressure in 10^{-5} mbar range

* http://www.analog.com/static/imported-files/data_sheets/AD7745_7746.pdf

Thank You