Developing a New Pressure Measurement Mechanism Based On Squeeze Film Damping Effect

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***Abstract*—This paper introduces a novel approach for measuring low pressures based on MEMS technology. In this technique the mechanism of squeeze film damping is used. A voltage is applied to a fixed-fixed MEMS beam and its step response is obtained; for each pressure there is a different response. Then the settling time is measured and we can relate each settling time with a defined pressure. Here, first we use some equations to relate pressure with the squeeze film damping effect; after that we use a micro beam model and relate its parameters with pressure. Then we use numerical analysis and simulation to show the procedure of pressure measuring. All simulation results are shown and discussed.**

Keywords: MEMS, Pressure, Squeeze Film Damping, Step response

I. INTRODUCTION

A pressure sensor typically measures the pressure of gases or liquids. It usually acts as a transducer and generates a signal as a function of the imposed pressure [1].
Examples of MEMS pressure sensor applications in the industry includes: design of air-bag systems, interior climate control, air intake, diagnostic system for braking, tire pressure and engine performance monitoring and optimization through controlling the ignition and the composition of the petrol mixture, in audio systems to compensate for loudspeaker or microphone resonances and in medical applications for dialysis and middle ear diagnosis [2][3].

Pressure can be measured in three ways: absolute pressure, differential pressure and gauge pressure. There are also different mechanisms for sensing pressure, like: piezoresistive, capacitive, optical and resonance based mechanisms.

In a Piezoresistive mechanism, a piezoresistive sensing element is used to detect the stress in a thin silicon diaphragm in response to a pressing load. The basic structure of a piezoresistive pressure sensor consists of four sensing elements in a Wheatstone bridge configuration that measure the stress within a thin crystalline silicon membrane. The stress is a direct consequence of the membrane deflection in response to an applied pressure differential across the front and back sides of the sensor. There are some disadvantages to the piezoresistive mechanism:

- The relatively small gage factor at high temperatures
- Temperature sensitivity of the piezoresistive read out
- Junction leakage current at high temperatures [4].

In the Capacitive mechanism a capacitive methods is used to sense the displacement of a thin diaphragm. Silicon micro machined capacitive types of pressure sensors have some advantages such as:

- High pressure resolution
- Versatility
- Low temperature sensitivity
- Low power consumption [6, 5].

The fundamental problem in these sensors is the poor dynamic range [6]. Also there are two major limiting factors for high density production. These limiting factors are:

- Hermetic vacuum sealing of capacitive cavity
- Electrical lead transfer between the vacuum-sealed cavity and the outside world [5].

In the Optical mechanism, silicon diaphragm and the cavity–fiber interface, act as reflectors, forming a Fabry–Pérot interferometer. A diaphragm moves due to the applied pressure, thus changing the Fabry–Pérot reflectivity and then allowing the measurement of pressure. In harsh environments (high temperature, vibration, EM interference, dust, etc.), in which electronic devices cannot operate, optical interrogation of these sensors gives us a valuable chance [7].

In the resonance based mechanism, changes in the resonant frequency or the alteration in gas density that are caused by pressure are used to measure stress. The micro-beam resonant pressure sensor is a device with an embedded doubly clamped bridge vibrating at the resonance frequency, which is changed as a function of the applied pressure. There is a special advantage to this type of sensors: it can provide the highest precision until now. Other advantages consist of its very small size, high accuracy, digital output signals, connection to computer and the ability to use in figure

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displaying devices. Generally, mechanical characteristics of the structure may be able to affect the precision of sensor. This kind of pressure sensor is used in Aeronautics and Astronautics field such as the experiments performed on engines.

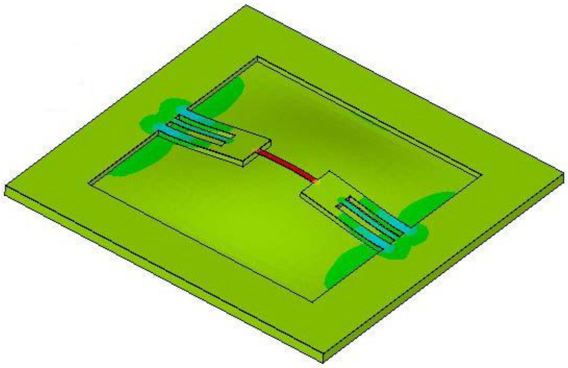

Fig. 1. Schematic of a resonant pressure sensor with silicon nitride resonant

Another mechanism that is presented here is the one in which the ambient pressure directly affects the damping coefficient of an excited capacitive shunt switch that is usually used in communication circuits. This mechanism is very similar to the resonance based mechanism. This mechanism exploits the squeeze film damping phenomena and its effects on dynamic characteristics of an electro statically excited fixed-fixed beam.

II. SQUEEZE FILM DAMPING

In sensors and actuators that use capacitive measurement principles or electro static driving forces, there is usually a very small gap between their moving surfaces. Subsequently, if one surface moves against the other, the air in between behaves as a squeezed gas film. This behavior affects dynamic behavior of movable parts in these electrostatic sensors. The interaction of the air with the moving structure is known as the squeezed film damping effect **[**8].

This phenomenon has an interesting frequency response: below the cut-off frequency, the gas has enough time to flow away from the gap, thus causing dissipation, whereas above the cut-off frequency, the gas film is trapped and squeezed between the moving plates and behaves like a spring, at the cut-off frequency the viscous and spring-like forces acting on the surfaces are equal. When designing micromechanical devices, the gas-film behavior is of great importance [9].

Squeeze-film damping can be modeled by the Reynolds equation which is derived from the Navier-Stokes and continuity equations. In the past, the squeeze-film damping effect on the dynamics of microstructures had been studied extensively. There are various approaches which are proposed to get the approximate solution of the coupled equation of elasticity and the Reynolds equation using numerical or semi numerical techniques [10].

For the particular case of squeeze film damping, flow of an isothermal and compressible fluid, Navier-Stokes equations will lead to the nonlinear Reynolds equation, which governs the pressure field associated with the 2D flow (*y-z* plane) generated by the movement of one plate in the *x*-direction. If the motion of the plates is small, the two plates are substantially parallel and the motion is perpendicular to the surfaces of the plates. This second-order non-linear partial differential equation can be linearized. Assuming that the gas undergoes an isothermal process, the linearized equation can be written as [9]:

$$\frac{P_a d^2}{12\eta_{eff}}\nabla^2\left(\frac{P}{P_a}\right)-\frac{\partial}{\partial t}\left(\frac{P}{P_a}\right)=\frac{\partial}{\partial t}\left(\frac{z}{d}\right) \quad (1)$$

Where P is the small changes of the static pressure, P_a , and the variation of the plate spacing, z, is also assumed to be small compared with the static gap width, d. ∇^2 is the Laplace operator and η_{eff} is the effective gas viscosity. At small pressures, the gas flow can be modeled by a modified Reynolds equation because the molecular mean free path λ is not negligible compared with the gap width. In the case of the linearized Eq. (1), the modification can be expressed using the effective viscosity [9]:

$$\eta_{eff}=\frac{\eta}{1+f\,(K_n)} \quad (2)$$

Where $K_n=\frac{\lambda}{d}$ is the Knudsen number and η is the viscosity coefficient. The effective viscosity η_{eff} depends on static pressure, P_a ,because the mean free path λ is inversely proportional to pressure [9]:

$$\lambda=\frac{P_0}{P_a}\lambda_0 \quad (3)$$

Where λ_0 is the mean free path at pressure P_0. A good approximation proposed by T. Veijola for the effective viscosity is [9]:

$$\eta_{eff}=\frac{\eta}{1+9.638K_n^{1.159}} \quad (4)$$

III. MICRO BEAM MODEL

To demonstrate the physics of the problem, the vibrating microbeam is considered as an equivalent spring-mass-damper system, Figure (2) shows this structure. The transverse deflection *z* (*x*, *y*, *and t*) of a point on the plate is given by equation below:

$$m\frac{\partial^2 z}{\partial t^2}+C_S\frac{\partial z}{\partial t}+K_S z=f_{drive}+f_{fluid} \quad (5)$$

Where m is the equivalent mass of the oscillating structure, c_s the structural damping coefficient of the beam which accounts for internal energy losses and k_s is the structural spring constant. In equation (5), f_{drive} is the external force that excites the beam and f_{fluid} is the damping force exerted by the gas present in the space between the micro plate and the substrate of structure.

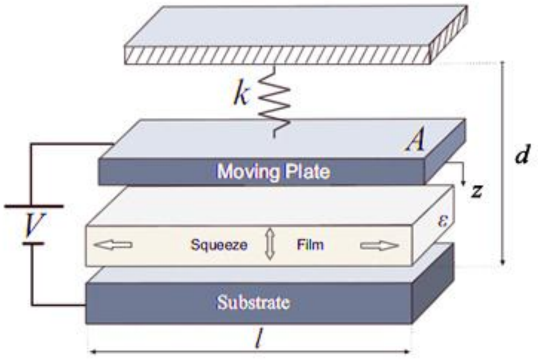

Fig. 2. Microbeam structure

The electrical field resulted from the voltage potential difference between the moving mass and the fixed electrode, with area *A*, causes an electrical attractive force on the mass. Assuming vertical motion of the surfaces, the electrostatic force is [11]:

$$f_{drive} = f_{El} = \frac{\varepsilon A V^2}{2d^2} \quad (6)$$

Where ε is the dielectric constant of the gas and *d* is the gap width.

Solving set of equations (1), (5) and (6) results in the dynamic model of electro statically actuated micro beam under squeeze film damping effect.

IV. NUMERICAL SIMULATION AND ANALYSIS OF MICRO BEAM

The dynamic model of micro beam developed in earlier section is numerically solved using FEM and the transient step response of this model is obtained for different ambient pressures. Figure (3) shows step response of the micro beam for the ambient pressure of 600 Pa. As indicated earlier, damping characteristic of squeeze film damping is a function of the ambient pressure, so for different pressures, transient step response characteristics of the system are different. Figure (4) Shows settling time versus ambient pressure, as it shows, settling time decrease from 0.015s to 0.0017s as pressure increase from 50 Pa to 600 Pa. therefore by measuring the settling time of an actuated microbeam it is possible to measure ambient pressure. Figure (4) also shows that settling time exponentially decreases as ambient pressure increases and measuring the settling time in very low pressures is easier.

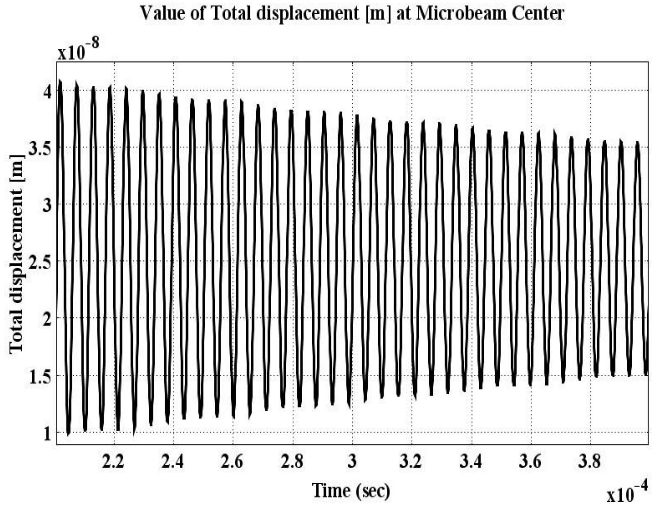

Fig. 3. Step response of the microbeam to 1 volt excitation voltage.

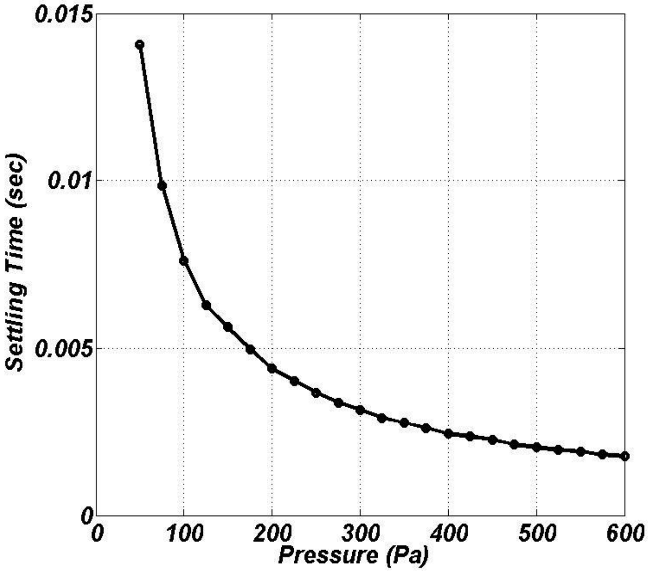

Fig. 4. Setlling time versus pressure.

V. CONCLUSION

This paper presented a brief survey of different mechanisms for measuring ambient pressure and proposed a new mechanism for measuring very low pressures, this mechanism is based on "**squeeze-film damping effect**". A dynamic model for an electrostatically actuated microbeam under squeeze film damping effect is derived and it is solved using FEM. Results show the possibility of measuring ambient pressure through processing the time response of the structure. Very low pressures from 1 Pa to hundreds of Pa can be measured using this novel mechanism.

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