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Vacuum Pressure and Gas Detection with a Silicon Based Micromechanical Squeeze Film Sensor

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Abstract

In this work a new concept for the fabrication of a silicon based micromechanical squeeze-film sensor has been developed. A thin film of a gas is trapped between the resonator structure and its fixed substrate and builds up a squeeze-film arrangement. Characteristic parameters, such as resonance frequency, quality-factor and phase-shift depend on pressure and viscosity of the trapped gas and thus can be used for sensing these gas properties. First samples with different geometries have been fabricated by using a combination of dry and wet etching of the silicon substrate. Measurement results of the squeeze effect of this micro sensor are shown and compared with theoretical simulations.

Keywords: squeeze film; vacuum; resonance frequency; quality-factor; pressure; viscosity

1. Introduction

In this study we designed, fabricated and characterized a micro sensor employing the squeeze film effect to measure important fluidic parameters such as pressure and viscosity of the gas under reduced pressure conditions. The squeeze film theory is a lubrication theory model for the case of two parallel surfaces with a motion normal to each other while squeezing an embedded compressible fluid in the gap. The isothermal squeezed film effect has been modelled by W. S. Griffin [1] and J. J. Blech [2]. The solution of the linearised Reynolds equation has two components, leading to a squeeze spring and a squeeze damping coefficient. F. Pan [3] presented analytical solutions for torsional motion of the plates.

The motion of the resonator system can be described by the standard second-order differential equation of a harmonic oscillator. Pressure induced changes in the squeeze spring coefficient lead to a change in the global system spring coefficient, inducing a shift in resonance frequency.

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2. Sensor Setup and Packaging

The sensors were designed with different geometries for the resonating cantilever structures and were fabricated by using standard microsystem technology (Fig. 1, 2). After initial deposition of a silicon nitride masking layer, a membrane with a thickness in the desired range of 20-40 μm is manufactured into the silicon wafer by time controlled anisotropic wet etching with KOH. As a next step, the resonating cantilevers are etched out of the membrane by means of dry etching (DRIE). A backside contact to the substrate is provided by a sputtered gold layer. The counter structure defining the squeeze-film gap is fabricated on a glass substrate. First a cavity with defined depth in the range from 2-20 μm is etched with HF. Then an aluminium layer is sputter-deposited and structured forming counter electrodes both for excitation and for capacitive detection inside the gap with contact pads on the unrecessed glass substrate.

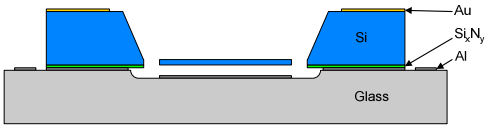

Fig. 1. Schematic cross section view of the sensor

The resonators are excited electrostatically by applying a combined AC/DC voltage in the range of 0.01-15 V. The resonant behaviour of the device is detected capacitively by a second electrode pair connected to an electronic amplification unit. As an alternative way, some measurements were done by optical means, using a laser vibrometer from Polytec.

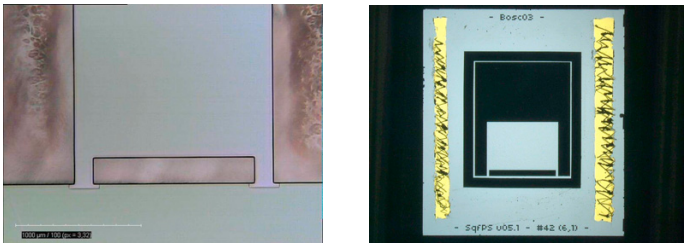

Fig. 2. Micrographs showing the geometry of a resonator with single side suspension; (a) front view (b) back view

In order to allow maximum flexibility for combining different cantilever structures with varying squeeze film gaps, a special mounting technology was used. It consists of mechanically clamping the silicon-cap onto the glass-die (Fig. 3).

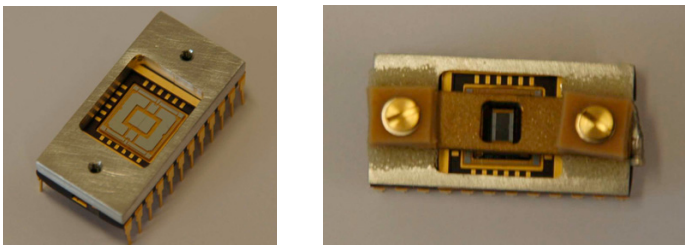

Fig. 3. Sensor packaging: (a) Socket with glass-cap and electrodes, (b) Complete packaging with silicon-die and mounting bridge

3. Experimental Setup and Results

The shift in resonance frequency and the quality factor of the micro resonator are measured by using a custom-built vacuum measurement set up, providing a defined gas atmosphere with adjustable pressure from 10^{-6} mbar up to atmospheric pressure. Four different gases were used: N_2, Ar, CO_2 and Ne. The main properties of these gases are listed in Table 1.

Table 1. Main properties of the gases used in the experiments

Gas species	Number of atoms	Dynamic viscosity [kg/m/s] [4]	Product of mean free path and pressure [m mbar] [5]	Molecular weight [g/mol] [4]
N_2	2	$17.9 \cdot 10^{-6}$	$5.9 \cdot 10^{-5}$	28.014
Ar	1	$22.8 \cdot 10^{-6}$	$6.4 \cdot 10^{-5}$	39.948
CO_2	3	$14.83 \cdot 10^{-6}$	$4.0 \cdot 10^{-5}$	44.010
Ne	1	$31.6 \cdot 10^{-6}$	$12.7 \cdot 10^{-5}$	20.180

The measurements shown in the following were done with a resonator comparable to the one shown in Fig. 2. The quadratic plate with a size of 2400×2400 μm² is suspended to the sensor frame by a double cantilever on one side of the mass. The length and width of the beams are 200 μm and 80 μm, respectively, the thickness of the whole structure is 36 μm while the squeeze-film gap is 5 μm.

The resonance frequency shift (Fig. 4), and the quality factor (Fig. 5) of this sensor were measured under different pressure levels ranging from $2 \cdot 10^{-6}$ to 300 mbar and for different gas species.

The pressure dependent shift of the resonance frequency is nearly independent of the gas species. In vacuum pressure below 0.03 mbar the resonance frequency barely changes at all (Fig. 4a) and for pressures higher than 10 mbar a linear correlation between the square of the resonance frequency and the ambient pressure can be seen (Fig. 4b). For intermediate pressures a nearly linear behaviour can be observed [6].

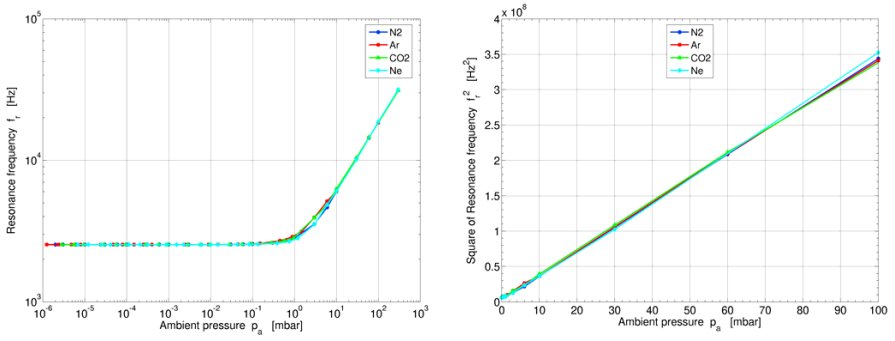

Fig. 4. (a) Resonance frequency vs. ambient pressure for different gases; (b) Square of resonance frequency vs. ambient pressure for different gases

The results of measuring the quality-factor are shown in Fig. 5. The left hand diagram shows the Q-factor as a function of pressure, varying over nearly seven orders of magnitude between $2 \cdot 10^{-6}$ and 10 mbar. For pressures below 10^{-4} mbar, a maximum Q-value of about 45000 is reached, limited by material damping inside the silicon structure. Gas damping becomes negligible in this region and therefore the Q-value becomes independent of pressure.

For low pressures in the molecular flow regime with Knudsen numbers well below 1 (corresponding to pressures below 1 mbar), the quality factor is independent of gas species and the corresponding viscosity. This can be attributed to the large mean free path of the gas molecules in comparison to the squeeze film gap. As a consequence,

the atoms only interact with the vibrating surfaces of the sensor but they do not interact with each other. Viscosity, however, is a property arising from the interaction of gas molecules with each other.

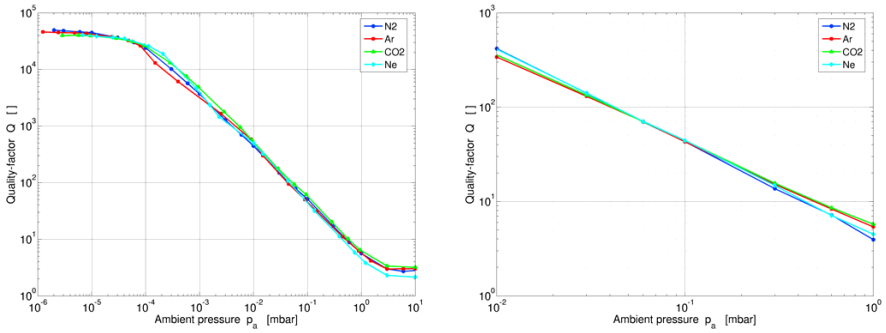

Fig. 5. Quality-factor versus ambient pressure for different gases: (a) Cold cathode sensor and Pirani sensor (b) Membrane based sensor

The apparent deviation of the different gases being visible in the range between 10^{-4} and 10^{-3} mbar can be attributed to the uncertainty of the pressure measurement which was carried out with both a cold cathode sensor and with a Pirani sensor. Their dependence on the kind of gas could not be compensated completely. Fig. 5b shows a magnified view of the section between 0.01 and 1 mbar. For pressures above 10^{-1} mbar an increasing dependence of the Q-value on the viscosity of the gas can be seen. The deviations near 10^{-2} mbar can be attributed to uncertainties of the membrane based sensor operating near its resolution limit.

4. Conclusion

In this work we designed, developed and measured a micro sensor using the squeeze effect to measure important fluidic parameters such as gas pressure and viscosity under reduced pressure conditions. First prototypes with different geometries have been developed using a combination of dry and wet etching. The measurements of the squeeze effect of this micro sensor show gas species independent linear changes in resonance frequency over a wide pressure range. This could be used very favourably for a gas species independent vacuum pressure sensor. In the molecular flow regime the quality-factor is independent of the gas species.

Acknowledgements

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