Resonant MEMS microsensor
for the measurement of fluid density and viscosity

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Summary: A resonant MEMS microsensor was developed to measure fluid density and viscosity. It consists of a thin plate made of a SOI top layer vibrating at resonance in its first bending mode. Its working principle is based on the resonance frequency and quality factor affected by the surrounding fluid density and viscosity. Measurements have been done in a series of gases and liquids at different pressures and temperatures. The resonant MEMS is able to measure densities to ±1% in the range of 1 to 1100 kg/m³ and viscosities to ±5% in the range of 10 to 10⁵ μPa s.

Keywords: Density, viscosity, Resonant MEMS, vibrating plate, SOI
Category: 4 (Non-magnetic physical devices)

1 Introduction
In the petroleum industry, measurements of density and viscosity are required to determine the value of the produced fluid and production strategy. Density and viscosity measurements are also important in industrial process control, especially in chemical and food industries.

We took advantage of the fact that the vibration of a plate is affected by the surrounding fluid to design a resonant MEMS microsensor using SOI wafers and DRIE micromachining. In this paper, we will describe our sensor working principle and fabrication, and report the measurements obtained.

2 Principle of operation
The resonant MEMS microsensor, shown in Figure 1, consists of a thin vibrating plate made of the top silicon layer of a Fusion-Bonded SOI wafer. The use of SFB SOI wafers allows us to choose at will the thickness of the vibrating plate and simplifies the DRIE micro-machining steps by providing an etch stop with the buried oxide (BOX).

To drive into resonance the vibrating plate, magnetic forces are used as illustrated in Figure 2. The device is placed in a constant magnetic field B generated by an external electromagnet or a permanent magnet. With an alternating current I injected in a coil fabricated on the plate top surface, alternating Laplace forces F put the plate in forced oscillations. When the current is at the plate first natural frequency, the plate vibrates in resonance in its first bending or flexion mode with maximum amplitude. Piezoresistive gauges configured in Wheatstone bridges and placed close to the clamped edge are used to sense the varying strains in the plate as it oscillates. These bridges allows us to control and measure the resonance frequency f as well as the amplitude or equivalently the quality factor Q.

When the MEMS sensor is placed in a given fluid, its resonance characteristics, f and Q, will be affected by the surrounding fluid as follows. The fluid in proximity to the oscillating plate is moved by the body’s motion, adding effective mass or inertia to the intrinsic mass of the plate, hence decreasing f. The shearing associated with the fluid motion around the plate gives rise to viscous energy loss per cycle, and so makes Q < Q_vacuum. Thus, the density ρ and viscosity η of the fluid may be obtained by measuring f and Q of the vibrating plate in resonance.
3 MEMS fabrication

The starting wafer is a 4” SFB SOI wafer with a top Si layer 20 µm thick. A thermal oxide is first grown, then a 0.4 µm PolySi layer is deposited, implanted with boron and patterned to define an RTD for temperature in-situ measurement and the piezoresistive gauges for resonance control and f and Q measurements. After passivation and contact openings, a 1 µm thick aluminum layer is sputter deposited and patterned to define the coil and other interconnections.

DRIE is then used to etch from the front side the SOI layer around the plate and from the back side the Si substrate all underneath the plate. A final HF etch of the BOX layer releases the vibrating plate.

Figure 3 shows a completed resonant MEMS sensor in its package specifically designed to allow it to be dipped in various fluids, liquids or gases, at various pressures (up to 70 MPa or 10 kpsi) and temperatures (up to 150 °C).

4 Measurements

Table 1 shows f and Q measured in vacuum and in various fluids, namely inert gas (Ar), natural gas (CH₄), reservoir oil, formation water, and silicone oil. In vacuum and at 298 K, f₀ is 5.3 kHz, in good agreement with FEM simulations with ANSYS.

<table>
<thead>
<tr>
<th>Fluid</th>
<th>ρ (kg/m³)</th>
<th>η (mPa·s)</th>
<th>f (Hz)</th>
<th>Q</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ar → 0</td>
<td>5326</td>
<td>4556</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CH₄</td>
<td>7.23</td>
<td>0.011</td>
<td>4722</td>
<td>127</td>
</tr>
<tr>
<td>Ar</td>
<td>671</td>
<td>0.049</td>
<td>1429</td>
<td>60</td>
</tr>
<tr>
<td>Crude oil</td>
<td>774</td>
<td>1.02</td>
<td>1160</td>
<td>10</td>
</tr>
<tr>
<td>Brine</td>
<td>1060</td>
<td>0.99</td>
<td>1005</td>
<td>12</td>
</tr>
<tr>
<td>Si oil</td>
<td>1910</td>
<td>2200</td>
<td>527</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 1. f and Q in vacuum and various fluids.

With some approximations, simple relations can be derived to describe the dependency of f and Q on the fluid density ρ and viscosity η:

\[
f \approx f_0 \left(1 + \frac{\pi \frac{w}{h} \rho}{4 \rho_{Si}}\right)^{-1/2}
\]

and

\[
Q \approx \frac{3}{2} \sqrt{\eta} = \text{CST}
\]

where \( \rho_{Si} \) is the Si density, w and h are the plate width and thickness and CST is a constant [1, 2, 3].

However, a more elaborate model [3] was necessary to account for the f and Q variations over the whole range of densities and viscosities for both gases and liquids.

To calibrate the microsensor, three parameters defined in the model need to be adjusted by fitting the measures taken with argon. After this rather simple calibration, densities in the range of 1 to 1100 kg/m³ can be measured to ± 1%, and viscosities in the range of 10 to 10^5 µPa s to ± 5%.

These accuracies on ρ and η were obtained by comparing measured values with either accepted literature or experimental values.

Figures 4 and 5 show the error on measured densities and viscosities for Ar, N₂, CH₄, heptane, crude oil, formation water and reference standards.

References