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Longitudinal bulk acoustic mass sensor

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A polycrystalline silicon longitudinal bulk acoustic cantilever is fabricated and operated in air at 51 MHz. A mass sensitivity of 100 Hz/fg (1 fg = 10^{-15} g) is obtained from the preliminary experiments where a minute mass is deposited on the device by means of focused ion beam. The total noise in the currently applied measurement system allows for a minimum detectable mass of 0.5 fg in air.

The presented research aims at developing high-Q silicon based devices for ultrasensitive mass detection in viscous fluids—initially in air and ultimately in liquids. Especially the latter is a paramount property to achieve the final goal of fulfilling the demand for robust real time portable diagnostic applications. We will present a mass sensor based on a longitudinal bulk acoustic cantilever with a Q factor of 3100 in air. Preliminary results yield a mass sensitivity of 100 Hz/fg (1 fg = 10^{-15} g) and a minimum detectable mass of 0.5 fg, which makes this a promising technology especially since these measurements have been performed in air at ambient conditions. This initial mass sensitivity characterization has been conducted by depositing a platinum compound by means of focused ion beam (FIB) equipment. The novelty of this research is comprised by the achieved high mass sensitivity and Q factor augmented by the simple microelectromechanical system fabrication, which is complementary metal-oxide-semiconductor compatible.

So far the highest mass sensitivity, regarding mechanical resonators, has been obtained by flexural type. However when turning to bio/chemical detection in higher viscous regime than vacuum, these flexural devices experience severe challenges caused by the increased hydrodynamic damping. Thus bulk acoustic technology becomes interesting especially when turning to bio/chemical detection in higher viscous regimes. The longitudinal extensional case, it can be estimated as one-half of the actual mass of the resonator. The latter depends on the mode shape but, in this longitudinal extensional case, it can be estimated as one-half of the actual mass of the resonator. The analytical expression for the resonance frequency of an ideal clamped-free beam operated in bulk acoustic mode is given by:

\[ \Delta f = \frac{2m_{\text{eff}}}{f_0} \]

where \( f_0 \) is the initial resonance frequency, \( \Delta f \) is the change in frequency, and \( m_{\text{eff}} \) is the effective mass of the resonator. The latter depends on the mode shape

The device is operated in a longitudinal extensional mode, as shown in Fig. 1(a), where the two cantilevers constituting the resonator are moving along the length in antiphase motion. This mode is actuated electrostatically and the resulting resonance frequency is detected by capacitive readout between the two electrodes and the resonator, as shown in Fig. 1(b). The time varying motional output current \( i_{\text{out}} \) measured at the sense electrode is given by

\[ i_{\text{out}} = V_{\text{dc}} \frac{dC_0}{dL} \frac{dl}{dt} \]

where \( V_{\text{dc}} \) is the applied dc voltage, \( C_0 \) is the static capacitance between the resonator, and the electrodes and \( dl \) is the longitudinal displacement.

The mass sensitivity of the sensor is given by the linear relation in Eq. (2) for \( \Delta m \leq m_{\text{eff}} \):

\[ \frac{\Delta m}{\Delta f} = \frac{2m_{\text{eff}}}{f_0} \]

where \( f_0 \) is the initial resonance frequency, \( \Delta m \) is the added mass, \( \Delta f \) is the change in frequency, and \( m_{\text{eff}} \) is the effective mass of the resonator. The latter depends on the mode shape.

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From finite element method analysis this frequency corresponds to a Young’s modulus of 160 GPa, which is in good agreement with similar polycrystalline silicon films previously reported. From the resonance response a Q factor of 3100 is found, which is considered good for the specific device, but indicates that there is still room for improvement compared to similar (monocrystalline Si) devices operated in vacuum.

To evaluate the mass sensitivity, the device is first measured in air, then a small mass of a platinum compound is deposited on the resonator structure, as seen in Fig. 4. This is achieved through ion beam assisted deposition from an organometallic precursor being C₅H₅Pt(CH₃)₃ for the case of Pt deposition. The resulting compound consists of C, O, Pt, and Ga (45%–55%, 5%, 40%–50%, and 5%–7%, respectively), where composition variation depends on the purity of the source and vacuum environment of the FIB system. Finally, after FIB deposition the device is again measured in air.

From SEM inspection, the dimension of the Pt deposition is obtained, resulting in an estimation of the added mass to be around 484 ± 91 fg, where the error is based on the above shown composition variation. Inevitably further characterization of the actual composition is needed to precisely determine the added mass.

The resonance signal before and after the mass deposition is shown in Fig. 5. Rewriting the sensitivity expression in Eq. (2) and using that the decrease in frequency is 47 kHz from the initial resonance frequency. A mass change of 554 fg is attained. This mass change is found to be in good agreement with the estimated added mass of 484 ± 91 fg.

From the expression in Eq. (2) the previous stated sensitivity of 100 Hz/fg is obtained from an effective mass calculated based on SEM images and a density of polycrystalline Si.
line silicon of 2300 kg/m³ along with the resonance frequency \( f_0 = 51 \) MHz. By looking at the phase noise of the entire system \( d\varphi_n \), which amounts to 0.01° and the slope of the phase signal at the resonance frequency \( d\varphi_n / df_n \) (\(-2 \times 10^{-4}\) degrees/Hz) the resulting experimental minimum detectable mass is found from Eqs. (5) and (2) to be 0.5 fg,

\[
df_{\text{min}} = \frac{d\varphi_n}{df_n} \cdot \frac{1}{\varphi_n}. \tag{5}
\]

This value shows that there is room for improvement since the ultimate mass detection, based purely on thermomechanical noise is 3 ag.\(^{15}\)

The long term frequency stability will have to be further investigated, as this will directly impact the sensitivity. Results from similar devices from the same batch have shown a frequency stability, on the time scales corresponding to the described characterization experiment, indicating an up to factor 10 increase in minimum detectable mass.

In conclusion, a longitudinal bulk acoustic mass sensor with a sensitivity of 100 Hz/fg in air have been presented. To our knowledge this constitutes an unprecedented demonstration of point mass sensitivity in air, for bulk acoustic resonators. Through the simple characterization by means for FIB assisted Pt deposition, it has been shown that these type of resonators have great potential as mass sensors in air due to the high \( Q \) factor and in-plane motion.