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Hales, Jan Harry; Teva, Jordi; Boisen, Anja; Davis, Zachary James

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Longitudinal bulk acoustic mass sensor

J. H. Hales, a) J. Teva, A. Boisen, and Z. J. Davis
Department of Micro and Nanotechnology–DTU Nanotech, Technical University of Denmark, DTU Bldg. 345 East, DK-2800 Kongens Lyngby, Denmark

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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 regime—initially in air and ultimately in liquids. Especially since these measurements have been performed in air.

FIG. 1. (Color online) Picture (a) shows a SEM image of the resonator where the mode of vibration is indicated along with the length L = 30 μm, width w = 2.5 μm, and a thickness of t = 2.3 μm. (b) shows a schematic of the applied one-port actuation and readout scheme, where the output electrodes (I_{out}) are combined and connected to the network analyzer input.

a)Electronic mail: jan.hales@gmail.com.

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contacts are created and the resonator is released in HF. The latter is patterned to form the electrodes. Finally the metal contacts are created and the resonator is released in HF.

\[ f_0 = \frac{1}{4L} \sqrt{\frac{E}{\rho}}, \]

where \( E \) and \( \rho \) are the Young’s modulus and density, respectively, of the resonator material and \( L \) is the length of a single cantilever measured from the middle anchoring, as shown in Fig. 1(a). As also seen from Fig. 1(a), an alteration of the end part of the cantilever from the ideal beam case is implemented. This ensures good electrode-resonator overlap despite a decrease in line width during fabrication. The altered geometry results in the following analytical expression for the resonance frequency:

\[ f_0 = \frac{1}{4L} \sqrt{\frac{1}{1 + \frac{2}{w_cL_c}}} \cdot \frac{E}{\rho}, \]

where \( w_c \) and \( L_c \) are the width and length of the end part exceeding the width of the beam, respectively.

A three mask fabrication scheme with five major steps, outlined in Fig. 2, is applied to realize the resonator. The scanning electron microscope (SEM) image in Fig. 1(a) shows the resulting device where the resonator and the electrodes are defined by standard UV lithography using in situ boron doped polycrystalline silicon as resonator structural material. The underlying 5 \( \mu \)m thick plasma enhanced chemical vapor deposited (PECVD) oxide serves both to minimize the contact capacitance to the substrate and as a sacrificial layer. The thick oxide increases the yield of the subsequent device release in hydrofluoric acid (HF) by minimizing the possibility of stiction between the substrate and the suspended device.

Initial characterization of the device is shown in Fig. 3 where the effect of electrostatic spring softening, as expected, is seen to decrease the resonance frequency linearly with the applied dc voltage squared. The unperturbed inherent resonance frequency is found to be 51.0032 MHz by extrapolating the linear fit to zero applied dc bias voltage.

From finite element method analysis this frequency corresponds to a Young’s modulus of 160 GPa, which is good agreement with similar polycrystalline silicon films previously reported.\( ^{11} \) 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.\( ^{12} \)

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 consist 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.\( ^{13} \) 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.\( ^{13,14} \)

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 polycrystal-
line silicon of 2300 kg/m³ along with the resonance frequency \( f_0 = 51 \text{ MHz} \). By looking at the phase noise of the entire system \( d\theta_{\text{noise}} \), which amounts to 0.01° and the slope of the phase signal at the resonance frequency \( d\theta_n / df_n \left( -2 \times 10^{-4} \text{ degrees/Hz} \right) \) the resulting experimental minimum detectable mass is found from Eqs. (5) and (2) to be 0.5 fg,

\[
d_f = \frac{d\theta_{\text{noise}}}{d\theta_n / df_n}
\]

(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.