

In-Liquid Quality Factor Improvement for Film Bulk Acoustic Resonators by Integration of Microfluidic Channels

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Abstract—We demonstrate a significant improvement in the quality factor (Q) of film bulk acoustic resonators (FBARs) in liquid environments via the integration of microfluidic channels. Our device consists of a longitudinal-mode excited zinc oxide (ZnO) FBAR and parylene-encapsulated microfluidic channels. Considerable enhancement in the Q of the resonant system is obtained by confining the liquid in the microfluidic channels of thickness comparable to the acoustic wavelength. The improved FBAR achieves Q values of up to 120, which represents an improvement of a factor of eight over those of current state-of-the-art devices.

Index Terms—Acoustic resonators, microelectromechanical devices, piezoelectric resonators, Q factor.

I. INTRODUCTION

LABEL-FREE biomolecular sensors in liquid media (in contrast to fluorescent and radioactive labeling methods) have attracted much interest for a variety of applications ranging from pharmaceutical research to medical diagnostics. This is mainly due to the fact that label-free detection eliminates the labeling processes, which may introduce chemical modifications of the target molecules [1]. However, commonly used label-free protein detection techniques, such as surface plasmon resonance [2], [3] and quartz crystal microbalance (QCM) [4], [5], are significantly less sensitive than labeling methods [1]. Film bulk acoustic resonator (FBAR)-based sensing devices are sensitive to small mass loading and are therefore excellent candidates for implementing high-sensitivity sensors.

FBARs consist of a thin piezoelectric layer, such as AlN or ZnO, sandwiched between two metal electrodes. The piezoelectric composite has a fundamental frequency above 1 GHz due to its small thickness ($\sim 1 \mu\text{m}$) and thus produces a large frequency shift with a small mass loading. State-of-the-art FBAR biosensors exhibit a mass sensitivity of more than $1000 \text{ Hz} \cdot \text{cm}^2/\text{ng}$ —over 1000 times higher than that of QCMs [6]–[10].

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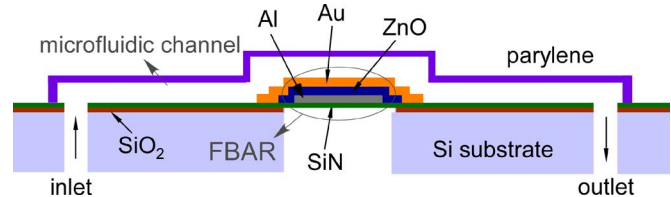


Fig. 1. Schematic structure of an FBAR integrated with a parylene microfluidic channel.

In a gaseous environment, the acoustic energy is contained inside the FBAR body due to the very low acoustic impedance of the air. This fact allows for a high-quality factor (Q) of the resonator and, consequently, a high resolution of the sensor. In liquid environments, however, damping and viscous drag result in acoustic energy leakage, and the Q falls by a factor of approximately 10–100. A Q of 15 is typically observed in pure water compared with 200–1000 in air [8], [10]. The substantial loss of Q increases the minimum detectable shift in frequency and reduces the mass resolution.

Shear-mode (rather than longitudinal mode) vibration can be used to suppress the loss of Q , but it results in a loss of sensitivity. A Q of 100–150 has been observed in water for shear-mode FBARs, but their sensitivity is approximately merely a third of that in longitudinal FBARs (800 versus $2500 \text{ Hz} \cdot \text{cm}^2/\text{ng}$) [11], [12].

II. DEVICE DESIGN, FABRICATION, AND EXPERIMENTAL SETUP

A. Device Design

We designed an FBAR device in which the liquid is confined in an integrated microfluidic channel. This structure allows a significant improvement in Q over typical longitudinal FBARs operating in liquid environments without compromising the sensitivity to mass loading, as is commonly found in shear FBARs. The approach is to form a thin liquid layer on the solid resonator, which shortens the distance that the acoustic wave has to travel in the liquid and thus minimizes the energy dissipation. A three-layer FBAR (Al/ZnO/Au) was fabricated on a suspended silicon nitride (SiN) membrane, and a parylene enclosure on top of the FBAR formed the microfluidic channel, as shown in Fig. 1. The channel thickness was defined by the thickness of a sacrificial layer, and inlet/outlet ports were accessed from the back side of the die.

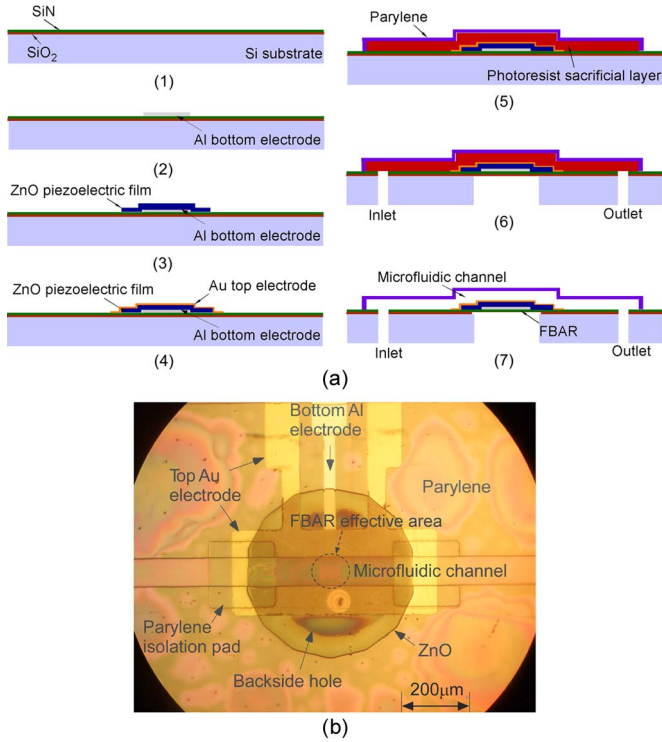


Fig. 2. (a) Fabrication process of the microfluidics integrated FBAR and (b) a top view of the resulting device.

B. Fabrication

As shown in Fig. 2(a), the resonator was fabricated using the standard silicon micromachining technology. A 2000-Å-thick thermal oxide layer and a 4000-Å-thick low-stress SiN layer were deposited on a silicon wafer to form the supporting membrane. This was followed by a 1500-Å Al film, which formed the bottom electrode. The bottom electrode was circular (with a diameter of 100 μm) and determined the effective area of the FBAR. A ZnO film (0.55-, 2-, or 4- μm thickness) was sputtered in a reactive chamber, and a 1500-Å Cr/Au layer was deposited to form the top electrode. A 3- μm -thick photoresist was spun and patterned on the FBAR as a sacrificial layer that defined the fluidic channel, which was 80 μm \times 12 mm \times 3 μm , corresponding to width, length, and thickness, respectively. A 3.5- μm -thick parylene-C film was deposited on top of the sacrificial photoresist pattern to form the channel enclosure. Then, the wafer was etched from the back side by deep reactive ion etching to form the channel inlets/outlets and to release the SiN/SiO₂ membrane. The membrane size was determined by the diameter of these back-side holes, which were typically 400 μm . This is substantially larger than the effective area of FBARs so that the anchor loss could be minimized. Finally, the sacrificial layer was removed with acetone, and the microfluidic channels were dried in a supercritical CO₂ chamber. The resulting device is shown in Fig. 2(b).

C. Experimental Setup

The Q values for the three fabricated devices were examined separately in three different environments: 1) in air; 2) in contact with water of large depth; and 3) in water confined to the

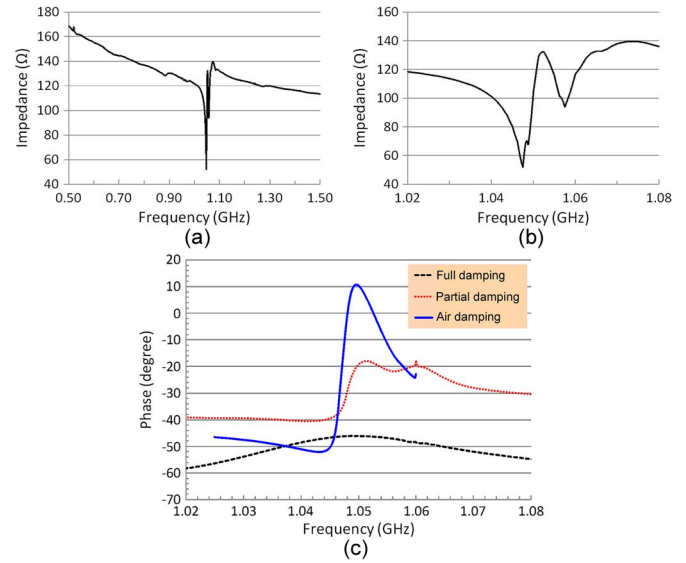


Fig. 3. (a) Impedance spectra of a 2- μm -thick ZnO FBAR from 500 MHz to 1.50 GHz, (b) zoom-in view over the frequency range of 1.02–1.08 GHz, and (c) the phase spectra of the FBAR in the air (air damping), in the water (full damping), and with the microfluidic channel (partial damping) near the resonant frequency.

integrated microfluidic channel. These situations corresponded to the “air damping,” “full damping,” and “partial damping” of the mechanical vibrations of the resonator, respectively. The devices were characterized using the S -parameter S_{11} measured by an HP 8510C network analyzer. The Q of the series resonance was calculated from $Q_s = (f_s/2)(d\phi_z/df)|_{f=f_s}$, where ϕ_z is the phase of the impedance Z , which was extracted from the recorded S_{11} data.

III. CHARACTERIZATION AND DISCUSSION

When operating in air, the fundamental resonant frequencies of the 0.55-, 2.0-, and 4.0- μm -thick ZnO FBARs were approximately 2.0 GHz, 1.05 GHz, and 600 MHz, respectively. The impedance spectrum of the FBAR with the 2.0- μm ZnO layer is shown in Fig. 3(a) and (b). The sharp resonance peak had a Q of approximately 250 in air, and the 0.55- and 4.0- μm -thick ZnO FBARs also possessed high Q values. The high Q obtained in air implies a small energy loss per resonance cycle. The back-side hole was then filled with a water droplet to measure the Q at full damping. The depth of the water was more than 450 μm , which is much larger than the acoustic wavelength in water ($\sim 1.42 \mu\text{m}$ at 1.05 GHz), and therefore, it could be considered practically infinite. This mode of operation corresponded to full damping. A significant drop in Q to approximately 10 was observed immediately for all of the three FBAR devices. The low values of Q are resulted from the loss due to the smaller acoustic impedance mismatch at the FBAR/water interface than that at the FBAR/air interface. The viscous damping in liquid scales with the square of the frequency and is considerably high in the gigahertz frequency range.

In order to measure the Q at partial damping, water was pumped through the microfluidic channel integrated on top of the FBAR, driven by an external syringe pump. The flow rate of 25 $\mu\text{L}/\text{h}$ was controlled by an infusion syringe pump in

TABLE I
MEASURED Q FOR DIFFERENT DAMPING CONDITIONS

ZnO thickness (μm)		0.55	2.0	4.0
Resonant freq. (GHz)		2.20	1.05	0.60
Q at air damping		220	240	430
Q at full damping		12	7	15
Q at partial damping	Average value	38	89	100
	Standard deviation	3.5	25	13

order to maintain a constant pressure. This pressure caused a deflection of $0.3 \mu\text{m}$ of the parylene enclosure at the position of the FBAR. The device is suitable for detecting a minute amount of analyte for lab-on-a-chip systems, since $25 \mu\text{L}/\text{h}$ is a low sampling rate for biosensors. In this experiment, Q dropped from 250 to 120 when the water reached the active FBAR surface. This Q value is nearly 12 times our measured Q for the full damping case (see Table I) and at least eight to ten times greater than the reported values for longitudinal FBARs immersed in water [12], [13]. Note that Q at partial damping showed large device-to-device variation; this is believed to be due to the process variations of the channel thickness and the thickness of parylene films. The contact liquid damping also influenced the resonant frequency of the FBAR. The resonant frequency shifted from 1.0472 GHz in air to 1.0286 GHz in deep water (i.e., at full damping) due to the mechanical loading by the liquid layer. The phase spectra of a resonator with a $2\text{-}\mu\text{m}$ ZnO layer at different damping conditions are shown in Fig. 3(c). The series resonance was defined as the frequency at which the impedance was at a minimum. The largest phase slope at resonance indicated $Q \sim 240$ in air, the smallest phase slope indicated $Q \sim 7$ at full damping, and the relatively sharp slope corresponded to $Q \sim 120$ at partial damping. The Q improvement at partial damping is attributed to the integrated microfluidic channel since the acoustic wave is confined in the thin water layer. The confinement of the liquid in a microfluidic channel dramatically shortens the distance that the acoustic wave travels in the lossy liquid and therefore allows a larger proportion of the acoustic energy to be reflected back from the water/enclosure interface.

IV. CONCLUSION

The Q of an FBAR in liquid environments was improved significantly by confining the liquid inside a microfluidic channel. This integration minimized the acoustic energy loss due to the viscous damping and radiation into the liquid. FBAR

devices with Q values of up to 120 in liquid environments were demonstrated using this technique. These values were at least eight to ten times higher than previously reported values in liquid environments. This improvement enhanced the mass resolution of longitudinal mode FBARs and provided the scope for a new range of high-resolution sensors for biomolecules in liquid media.

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