Flim Bulk Acoustic-Wave Resonator (FBAR)

Piezoelectric thin films convert electrical energy into mechanical energy and vice versa. Film Bulk Acoustic Resonator (FBAR) consists of a piezoelectric thin film sandwiched by two metal layers. A resonance condition occurs if the thickness of piezoelectric thin film (d) is equal to an integer multiple of a half of the wavelength (l_{res}). The fundamental resonant frequency ($F_{res}=1/l_{res}$) is then inversely proportional to the thickness of the piezoelectric material used, and is equal to $V_a/2d$ where V_a is an acoustic velocity at the resonant frequency (**Fig. 1**).

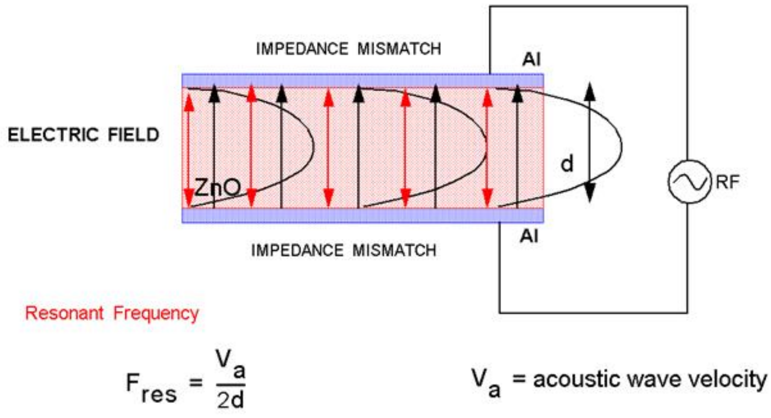


Fig. 1 *Schematic of longitudinal wave generation and propagation in an acoustic resonator by an electric field in the thickness direction*

A bulk-micromachined FBAR with Thickness Field Excitation uses a z-directed electric field to generate z-propagating longitudinal or compressive wave. In an LFE-FBAR, the applied electric field is in y-direction, and the shear acoustic wave (excited by the lateral electric field) propagates in z-direction**.**

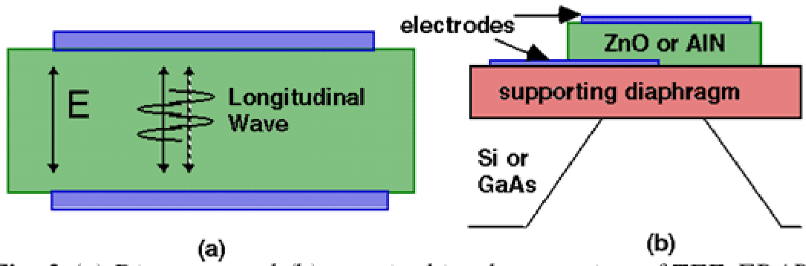


Fig. 2 *(a) Diagram and (b) a typical implementation of TFE-FBAR*

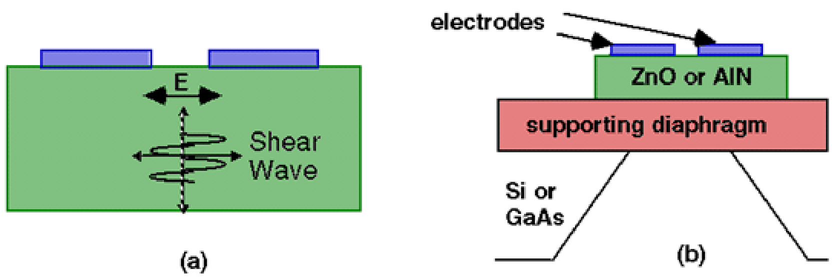
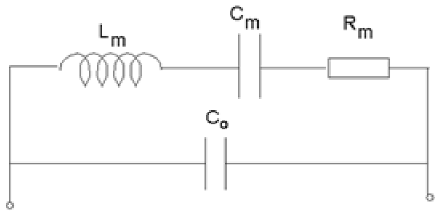


Fig. 3 *(a) Diagram and (b) a typical implementation of LFE-FBAR*

Both TFE-FBAR and LFE-FBAR can equivalent be represented with the equivalent circuit, shown in Error! Reference source not found., called Butterworth-Van Dyke (BVD) circuit. The resonator is modeled by a constant " clamped" capacitance C_o in parallel with an acoustic or " motional" arm that consists of motional capacitance C_m, motional inductance L_m, and motional resistance R_m. The C_o is the electrical capacitance between the two electrodes through which the electric field is applied. The motional components (C_m, L_m and R_m) model electromechanical response of a piezoelectric material.



$$f_s = \frac{1}{2\pi\sqrt{L_m C_m}} \qquad Q = \frac{2\pi f L_m}{R_m}$$

***Fig. 4** Butterworth-Van Dyke (BVD) equivalent circuit for a piezoelectric crystal.*

The resonant frequency of a TFE FBAR can be tuned by removing a portion of the resonator support layer as shown in Error! Reference source not found.. The removal of the support layer reduces the mass loading effect of the resonator, and increases the resonant frequency.

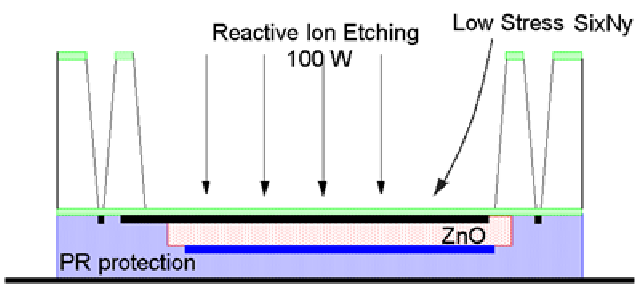


***Fig. 5** Schematic of the post-processing RIE tuning technique which removes the supporting nitride membrane from the backside of a completely processed and tested FBAR.*

Both of the resonant frequencies are measured to vary as the mass loading changes. When the 0.9µm thick Si_3N_4 support layer is removed by Reactive Ion Etching from the FBAR backside, the resonant frequency of the FBAR increases from 1.1 to 1.5 GHz, around 40% shift. In **Fig. 6**, we show the resonant frequency dependence on the Si_3N_4 support layer thickness measured on three FBARs. A similar experiment has been performed on an FBAR with parylene as its support layer, and the results are shown in **Fig. 7**. As can be seen by comparing **Figs. 6** and **7**, parylene has a much smaller mass loading effect on the frequency shift than Si_3N_4. This is due to the fact that Si_3N_4 has a larger mass density and much higher Young's Modulus than parylene, and affects the FBAR resonant frequency much more strongly.

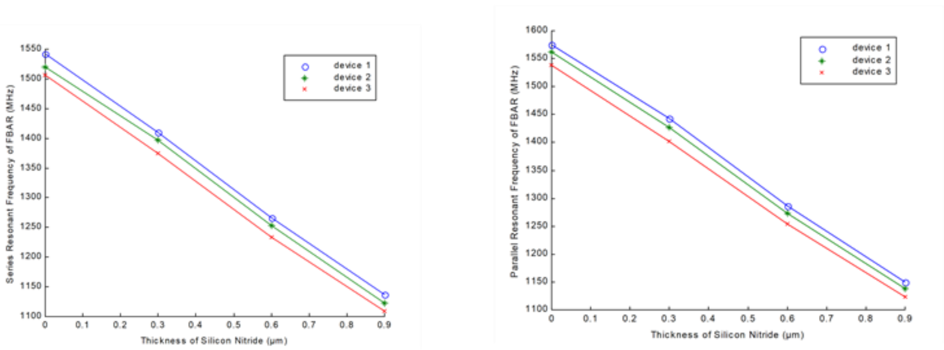


Fig. 6 *Dependence of series resonant frequency and parallel resonant frequency on the* Si_3N_4 *thickness.*

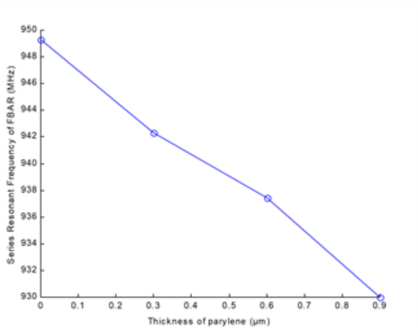


Fig. 7 *Series resonant frequency vs. parylene thickness.*

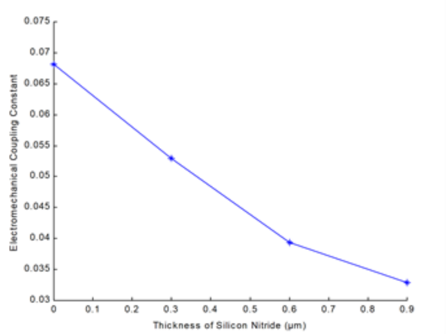


Fig. 8 *Electromechanical coupling constant vs.* Si_3N_4 *thickness (i.e., mass loading).*

Electromechanical coupling constant k_t^2 is related to the difference of the two resonant frequencies as

$$k_t^2 = \frac{\pi^2 (f_p - f_s)}{4 f_s}$$

k_t^2 increases as the Si_3N_4 is removed from the FBAR backside. The change of k_t^2 as a function of the mass loading by the Si_3N_4 support layer are plotted in **Fig. 8**, respectively.

An air-backed, Al/ZnO/Al film-bulk-acoustic resonator (FBAR) that is free-standing by itself has been fabricated. Unlike a conventional FBAR structure, the newly fabricated resonator doesn' t employ any supporting layer below or above it, but the whole resonator body (consisting of ZnO piezoelectric layer sandwiched by two aluminum layers) suspends by itself in the air. Some SEM pictures of the fabricated FBAR devices with various shapes are shown in **Fig. 9**. **Figure 10** shows SEM picture of the Al bridges that act as leading electrodes and also to hold the FBAR (which free stands in air). Picture of an FBAR viewed from its backside is shown in **Fig. 11**.

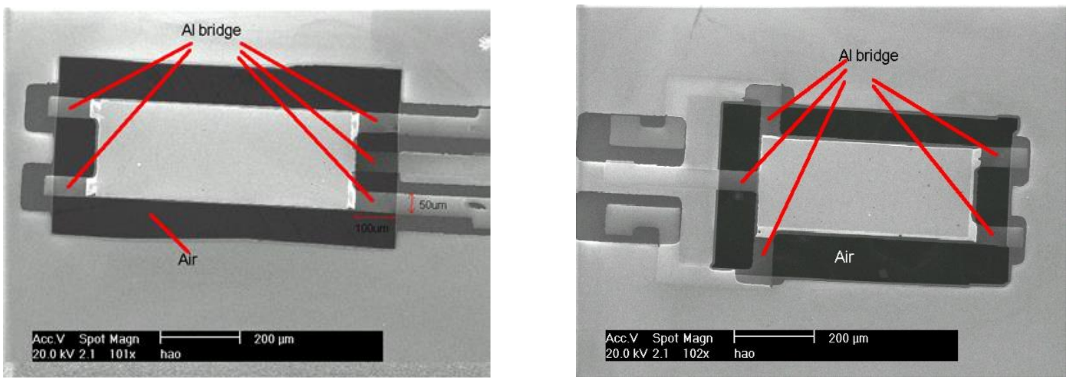


Fig. 9 *SEM pictures of the fabricated free-standing air-backed FBARs held by Al bridges.*

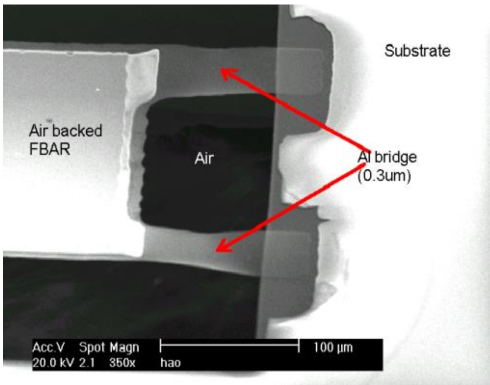


Fig. 10 *SEM picture of the 0.3 μm thick Al bridge.*

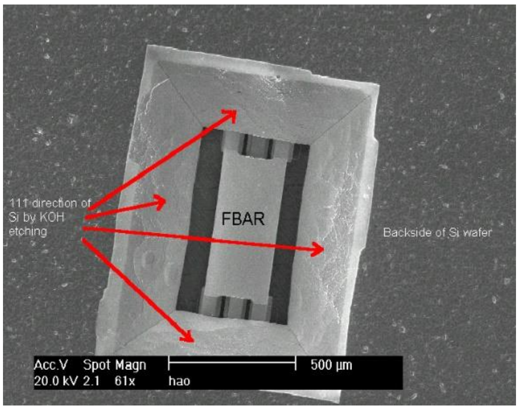


Fig. 11 *Backside view of an air-backed FBAR.*

S_{11} measurements of an FBAR with its underneath Si_3N_4 layer at 0.9μm, 0.6μm, 0.3μm, 0μm and in the case of the ZnO being patterned from the wafer backside are shown in **Fig. 12**.

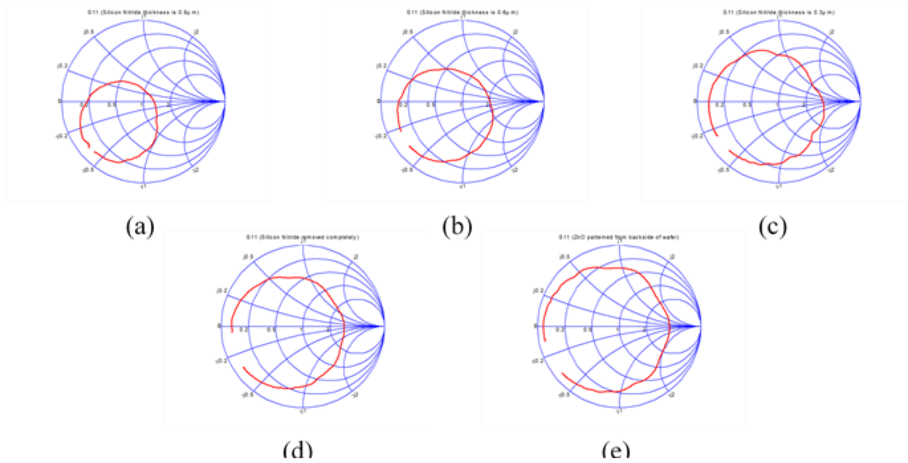


Fig. 12 *S_{11} of an FBAR when (a) Si_3N_4 thickness is 0.9μm (1100MHz~1250MHz) (b) Si_3N_4 thickness is 0.6μm (1200MHz~1350MHz) (c) Si_3N_4 thickness is 0.3μm (1300MHz~1450MHz) (d) Si_3N_4 is completely removed (1500MHz~1650MHz) (e) ZnO is patterned from backside (1500MHz~1600MHz)*

The quality factor Q_s at the series resonant frequency in the free-standing air-backed FBAR is calculated to be 1,322. It is about six times larger than that in the FBAR with 0.9μm thick Si_3N_4 as a support diaphragm. The quality factor Q_p at the parallel resonant frequency in the case (e) is calculated to be 513, three times that in the case (a). Figure of Merit (FOM) of an FBAR is defined as the product of Q and k_t^2. Insertion loss in an FBAR-based filter is inversely proportional to the FOM of the FBARs. In the free-standing air-backed FBAR, we have increased k_t^2 twice and the quality factor six times, and filters made out of this kind of resonator are expected to have larger bandwidth and much lower insertion loss compared to that made by an FBAR built on a support diaphragm.