Bulk Acoustic Resonator Devices using ZnO-Based Film and Back Cavity

Xin Li, Mengwei Liu, and Yanlu Feng

Abstract—The purpose of this study was to investigate bulk acoustic resonator (FBAR) devices using ZnO-based film and back cavity. A Mason equivalent circuit model was adopted to simulate the impedance characteristics of FBAR devices. The influence of piezoelectric material thickness, electrode thickness, and resonance area on the impedance characteristics of FBAR devices was analyzed. Structural parameters of the FBAR devices were designed, and bulk silicon micromachining was applied to fabricate Al/ZnO/Al-based FBAR devices with a back cavity. X-ray diffraction analysis shows that ZnO piezoelectric films have a highly preferred c-axis orientation. The frequency response of longitudinal wave FBAR devices has been measured by an RF network analyzer, and the results indicate the series resonant frequency and parallel resonant frequency of the fabricated FBAR devices determined to be 1.546 GHz and 1.590 GHz, respectively, which are close to the simulated results. According to the measured results, the effective electromechanical coupling coefficient and the quality factor have been calculated to be 6.83% and 350, respectively. The findings of this study may serve as reference for the development of FBAR devices.

Keywords—back cavity, bulk silicon micromachining, film bulk acoustic resonator, ZnO piezoelectric film

I. INTRODUCTION

The wireless communication technology has developed rapidly in recent years. Frequencies have increased from 500 MHz to 6 GHz, and the device circuitry has become progressively miniaturized and integrated. As important elements in RF circuits, filters have also had to shrink and integrate. Common surface acoustic wave filters and dielectric elements in RF circuits, filters have also had to shrink and integrate. As important

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shown in Fig. 2. The devices have a series resonant frequency \( f_s \)
and a parallel resonant frequency \( f_p \). When a given AC voltage is applied,
the series resonant frequency \( f_s \) of the device is obtained under the following conditions:
the polarization vector \( P \) and the electrical field \( E \) are in phase within the
piezoelectric film, the generated current is at maximum, and the electrical
impedance of the FBAR is at minimum. The parallel resonant frequency \( f_p \) is obtained when the polarization vector \( P \) and the
electrical field \( E \) are completely out of phase, the generated current is at minimum, and the electrical impedance of the FBAR is at maximum.

![Fig. 1 the structure diagram of an ideal FBAR](image)

**B. The device parameters**

In addition to \( f_s \) and \( f_p \), the effective electromechanical
coupling coefficient and the quality factor \( Q \) are two important
parameters in evaluating the performance of the FBAR devices.
These parameters are defined according to the equations [11]

\[
K_{\text{eff}}^2 = \left( \frac{\pi}{2} \right) f_p - f_s \quad \text{and} \quad f_p = \frac{dZ_m}{df},
\]

where \( dZ_m \) represents the conversion degree between the mechanical and
electrical energy in the device. The bandwidth of an FBAR filter increases with increasing \( K_{\text{eff}}^2 \). \( K_{\text{eff}}^2 \) depends primarily
on the piezoelectric material with a secondary dependency on the
thickness of the upper and the lower electrode layers.

The quality factor \( Q \) indicates the bulk acoustic wave loss
in the FBAR and the insertion loss of the FBAR filter. The in-band insertion loss decreases with increasing \( Q \). \( Q \) depends
not only on the acoustic wave loss in the electrode and
piezoelectric materials but also on the degree of confinement of
the bulk acoustic waves within the sandwich structure. The loss
of bulk acoustic waves in the material and the degree of leakage
in the FBAR decreases with increasing \( Q \). In actual production,
the \( Q \) value is enhanced primarily by the high-quality manufacture
and orientation of the piezoelectric film.

![Fig. 2 electrical impedance characteristics of an FBAR](image)

![Fig. 3 an FBAR with back cavity](image)

**C. Structure of the FBAR**

According to transmission line theory, the incident wave is
reflected back when the load is infinite or zero. Thus, the acoustic
impedance of the upper and lower boundary in the
sandwich structure must be infinite or zero. Since the acoustic
impedance of the air is approximately zero, it serves as the
better acoustic limiting interface. Another acoustic limiting
interface is a Bragg reflection layer composed of 1/4
wavelength deposition layers with alternating high and low
acoustic impedances. The surface of the upper electrode in an
FBAR device is usually in contact with the air. However, the
lower surface of the FBAR device is usually in contact with a
substrate material such as silicon making it necessary to form a
better acoustic limited interface via the etching process.

MEMS micromachining etches away most of silicon on
the back of the device, forming a back cavity and creating the
interface between the air and the metal on the surface of the
lower electrode. With air at both electrodes, the generated
acoustic waves are confined in the sandwich structure. For
silicon substrates, the etching process typically uses wet
etching or Inductively Coupled Plasma. Either method removes
most of the substrate when forming the FBAR device, yielding
a device with poor mechanical strength. The devices are easily
broken during production, decreasing the yield. To address this
problem, low stress silicon nitride or silicon dioxide is
deposited as a support layer below the lower electrode to
improve mechanical rigidity at the expense of a reduced \( Q \)
value [12]. Fig. 3 shows an FBAR device with a back cavity.

**III. DEVICE SIMULATION AND ANALYSIS**

**A. Mason equivalent circuit model**

The general analytic expression for the impedance of the
piezoelectric layer in an FBAR device is derived from acoustic
theory and given in Formula 3[13].

\[
Z = \frac{1}{j\omega C_0} \left[ 1 - k_1^2 \tan \theta \left( z_1 + z_b \right) \cos^2 \theta + j \sin 2\theta \right]
\]

The above formula is properly mathematically processed. The transformed formula is expressed as

\[
Z = \frac{1}{j\omega C_0} \left[ 1 - \frac{1}{jZ \tan \theta + Z_0} \left( z_1 + z_b \right) \tan 2\theta \right]
\]

where \( C_0 \) is the static capacitance; \( \theta \) is the phase displacement;
\( k_1^2 \) is the electromechanical coupling coefficient; and \( z_1 \) and \( z_b \)
are the normalized acoustic impedances at the upper and lower surfaces of the piezoelectric material, respectively. (Regarding the normalized acoustic impedances, \( z_t = Z_t / Z_p \) and \( z_b = Z_b / Z_p \), where \( Z_p \) is the characteristic acoustic impedance of the piezoelectric materials and \( Z_t \) and \( Z_b \) are the acoustic impedances at the upper and lower surfaces of the piezoelectric material, respectively.) Additionally, \( n^2 = 2\theta/k^2 \omega C_0 Z_p \) represents the transformer in AC circuits. The usual symbols represent the inductance and the impedance. Therefore, Formula 4 can be represented with a Mason equivalent circuit for the piezoelectric material as shown in Fig. 4, with \( Z_d = jZ_p \tan \theta \) and \( Z_e = jZ_p \csc 2\theta \). For an ideal FBAR device, \( Z_t = Z_b = 0 \).

In the circuit, \( C_0 = \varepsilon_S A/2d \) and \( \theta = \omega d / \nu_a \), where \( A \) represents the effective area of FBAR, \( \varepsilon_S \) represents the clamped dielectric constant, \( 2d \) represents the thickness of the piezoelectric layer, and \( \nu_a \) represents the longitudinal wave velocity. From these values along with the characteristic acoustic impedance \( Z_p \) and the acoustic impedances \( Z_t \) and \( Z_b \), we obtain the Mason equivalent circuit of the corresponding piezoelectric layer.

In an FBAR device with a composite structure, the bulk acoustic waves propagate not only along the c-axis in the piezoelectric layer but also in the ordinary acoustic layer, the upper and lower electrode layers, the Bragg reflection layer, and the supporting layer. Therefore, electromagnetic transmission line theory can be adopted to express the transmission of acoustic waves in the ordinary acoustic layer. The transformer in Figure 4 represents the conversion between mechanical energy and electrical energy. Therefore, the Mason equivalent circuit of the ordinary acoustic layer assumes the form shown in Figure 5, where \( Z_d \) and \( Z_e \) represent the acoustic impedances, \( Z_{im} \) represents the input impedance, and \( Z_L \) represents the load acoustic impedance.

![Fig. 4](image)

**Fig. 4** the Mason equivalent circuit of the piezoelectric layer

![Fig. 5](image)

**Fig. 5** the Mason equivalent circuit of the ordinary acoustic layer

The expression for \( Z_{im} \) obtained from Figure 5 is

\[
Z_{im} = Z_f + \frac{(Z_f + Z_g)Z_e}{Z_f + Z_g + Z_e}.
\]

and from transmission line theory, the expression for \( Z_{im} \) is

\[
Z_{im} = Z_0 + jZ_0 \tan(kd),
\]

Where \( Z_0 \) is the characteristic acoustic impedance, \( k \) is the acoustic transmission constant, and \( d \) is the thickness of the acoustic layer. Comparing Formulas (5) and formula (6), we obtain the formulas (7) and (8)

\[
\frac{Z_f + 2Z_g Z_e}{Z_f + Z_g} = jZ_0 \tan(kd)
\]

\[
\frac{Z_0}{Z_f + Z_g} = j\tan(kd).
\]

Applying trigonometric transformations to Formulas (7) and (8), we obtain

\[
Z_f = jZ_0 \tan\left(\frac{kd}{2}\right)
\]

\[
Z_g = \frac{Z_0}{j \sin(kd)}
\]
Fig. 6 shows the Mason equivalent circuit diagram of an FBAR device where $f_s$ and $f_p$ are the series resonant frequency and the parallel resonant frequency of the FBAR devices, respectively; $f_x$ represents either the series resonant frequency or the parallel resonant frequency; and $\angle Z_{in}$ is the impedance phase in radians. The upper and lower electrode, piezoelectric, and supporting layers are cascaded together to obtain the Mason equivalent circuits. We can analyze different cascading forms depending on the requirements in actual simulation.

B. FBAR simulation

We used the ADS (Advanced Design System) software from Agilent for our tests [14]. Fig. 7 shows the ADS simulation scheme. The fabricated FBAR has an upper Al electrode layer, a ZnO piezoelectric layer, and an Al lower electrode layer. All layers are 0.1μm thick.

The simulation results of the impedance characteristics are shown in Fig. 8. The thick line represents the amplitude frequency characteristic of the FBAR, and the fine line represents the phase frequency characteristic. The figure shows that the theoretical values of the series and parallel resonant frequencies of the FBAR device are 1.579GHz and 1.592GHz, respectively.

C. Analysis of FBAR performance

1) Influence of the piezoelectric material thickness on the impedance characteristics of an FBAR

The impedance characteristic curves of the FBAR with ZnO thicknesses of 0.7μm, 1μm, 1.3μm and 1.6μm are shown in Figure 9. The upper Al electrode layer thickness, lower Al electrode layer thickness and resonance area are 0.1μm, 1μm, 200μm×200μm, respectively. The resonant frequency of the FBAR gradually decreases with the increase of the ZnO layer thickness.

2) Influence of the upper electrode thickness on the impedance characteristics of an FBAR

The impedance characteristic curves of an FBAR with upper Al electrode thicknesses of 0.1μm, 0.13μm, 0.16μm and 0.19μm are shown in Figure 10. The ZnO layer thickness, lower Al electrode layer thickness, and resonance area are 1μm, 1μm, and 200μm×200μm, respectively. Fig.10 shows that the resonant frequency of the FBAR decreases as the thickness of the upper Al electrode increases. The propagation path of the bulk acoustic waves increases with the increase of the electrode thickness, resulting in a decrease in the resonant frequency.

3) Influence of the resonant area on the impedance characteristics of an FBAR

Fig. 11 shows the impedance characteristic curves of FBAR devices with resonance areas of 200μm×200μm, 300μm×300μm and 400μm×400μm. The thicknesses of the upper Al electrode, ZnO piezoelectric layer, and lower Al electrode layers are all 0.1μm. From Fig. 11, one sees that the resonant frequency is independent of the resonance area. As the
resonance area increases, the impedance of the non-resonance region decreases.

The structure of the filter can be optimized using these FBAR performance characteristics.

D. Optimal design of FBAR structure

According to the simulation analysis, the series and parallel resonance frequencies of the FBAR are related to the thickness of the piezoelectric material and electrodes. The ADS software determined the optimal thickness of the piezoelectric material, enabling calculation of the required series and parallel resonant frequencies of the FBAR.

The resonant frequency of our fabricated FBAR device is about 1.5GHz using a ZnO piezoelectric layer thickness of 2μm and upper and lower Al electrode thicknesses of 0.1μm and 1μm, respectively. We left the electrode thickness unchanged and optimized other parameters by changing the thickness of the ZnO piezoelectric layer. Fig. 12 shows the impedance characteristic of an optimized FBAR device. The thickness of ZnO piezoelectric layer after optimization was 1.171μm with a series resonance frequency of 1.5 GHz. The thickness of the upper Al electrode layer, ZnO piezoelectric layer and lower Al electrode layer in the final design of the FBAR device are 0.1μm, 1μm and 1μm, respectively.

Aluminum and zinc oxide are used for the electrodes and piezoelectric layer, respectively. The use of Inductively Coupled Plasma etching for the back of the device solves the silicon fragility problem. The front and back of an FBAR with a circular electrode is shown in Fig. 14. The small circle in the Fig. 14a is the upper electrode of the FBAR, and the big circle is the lower electrode of the FBAR. The zinc oxide film is sandwiched between them.

Fig. 14 a fabricated FBAR device

V. RESULTS AND ANALYSIS

The ZnO piezoelectric film in the FBAR devices vibrates along the thickness direction to form resonance, ZnO
piezoelectric to be oriented along the c-axis. Fig. 15 shows the X-ray Diffraction curve of ZnO film. When $2\theta=34.6^\circ$, there is an obvious diffraction peak in the film indicating that ZnO piezoelectric films produced by sputtering have a high preference for orientation along the c-axis direction.

The electrode of our FBAR was welded to the PCB board, and we used an Agilent E5071C RF network analyzer for measurement. The S22 test diagram of the amplitude frequency characteristic is shown in Fig. 16. The resonance characteristics of our fabricated FBAR device are obvious.

The fabricated devices have two resonant frequencies: the series resonant frequency of 1.546 GHz and the parallel resonant frequency of 1.590 GHz, which are similar to the previous theoretical simulation results of 1.579 GHz and 1.592 GHz. According to Formulas (1) and (2) and the experimental data, $K_{eff}^2$ and Q for our fabricated FBAR devices were calculated to be 6.83% and 350, respectively.

VI. CONCLUSION

We analyzed the influence of the thickness of the ZnO thin film, the thickness of the electrodes, and the effective resonance area of the FBAR device on the impedance characteristics of the device. We also developed a suitable fabrication process for an FBAR device with a back cavity and used an Agilent E5071C RF network analyzer to measure a fabricated FBAR. The series and parallel resonant frequencies were both similar to the theoretical results obtained with software simulation. The good $K_{eff}$ and Q values of the fabricated FBAR devices were expected. The RF filters and duplexer devices will be used widely in wireless mobile communication systems.

REFERENCES


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