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High Q, high frequency, high overtone bulk acoustic resonator with ZnO films*

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Abstract: Bulk acoustic wave resonators with piezoelectric films have been widely explored for the small size and high quality factor (Q) at GHz. This paper describes a high overtone bulk acoustic resonator (HBAR) based on Al/ZnO/Al sandwich layers and c-axis sapphire substrate. ZnO film with high quality c-axis orientation has been obtained using DC magnetron sputtering. The fabricated HBAR presents high Q at the multiple resonances from a 0.5–4.0 GHz wide band with a total size (including the contact pads) of 0.6 mm×0.3 mm×0.4 mm. The device exhibits the best acoustic coupling at around 2.4 GHz, which agrees with the simulation results based on the one-dimensional Mason equivalent circuit model. The HBAR also demonstrates Q values of 30 000, 25 000, and 6500 at 1.49, 2.43, and 3.40 GHz, respectively. It is indicated that the HBAR has potential applications for the low phase noise high frequency oscillator or microwave signal source.

Key words: Bulk acoustic wave resonator, Quality factor (Q), ZnO film, Mason's model
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1 Introduction

Bulk acoustic wave resonators with piezoelectric films including the film bulk acoustic resonator (FBAR) and high overtone bulk acoustic resonator (HBAR) have been widely explored for various applications such as frequency control (Driscoll *et al.*, 1992; Xu *et al.*, 1992; Yu *et al.*, 2007; Bi and Barber, 2008; Nam *et al.*, 2008; Ruby, 2010; Zou *et al.*, 2010) and sensors (Lin *et al.*, 2008; Katardjiev and Yantchev, 2012). They have a much higher operating frequency (usually at GHz) than the traditional quartz crystal resonator. Comparing the coaxial ceramic resonators and FBARs having quality factors (Q) of about 150 and 1000 at GHz respectively, HBARs demonstrate high Q greater than 10 000, which makes them good candidates for low phase noise reference oscillators, such as the local oscillator of chip scale atomic clock (CSAC) and the microwave oscillator for frequency agile radar applications (Driscoll *et al.*, 1992; Xu *et al.*, 1992; Yu *et al.*, 2007).

HBAR structure consists of piezoelectric transducers fabricated on a crystal substrate with low acoustic attenuation. Since the substrate thickness is much larger than that of the piezoelectric film, most energy is stored in the substrate, and Q is dominated by the acoustic property of the substrate. Usually ZnO, AlN, or lead zirconate titanate (PZT) film is used as the piezoelectric film of HBAR. PZT has the highest piezoelectric constant and electromechanical coupling coefficient. PZT film, however, has higher acoustic wave attenuation and lower sound velocities. Although AlN film has a much higher phase velocity and chemical stability, compared to ZnO film, it has lower piezoelectric coupling and more difficulty in deposition and texture control. The high electromechanical coupling factor and suitable acoustic velocity help ZnO film stand out from others.

Fig. 1 shows the cross-section schematic of the HBAR, including one-port and two-port devices. The

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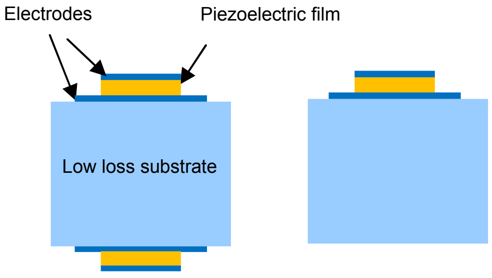
two-port HBAR at Westinghouse exhibited very high Q values from a 320 MHz to 1.5 GHz wide band with resonant responses occurring at 2.5 MHz spacing. The unloaded Q value of 125 000 was demonstrated at 640 MHz (Bailey *et al.*, 1992). The higher frequency range of 2 to 5 GHz, however, is demanded for wireless communication systems. The fabrication and assembly technology of the two-port device is complex compared to that of the one-port device. Another advantage of the one-port resonator is that the back side of the substrate can be trimmed to adjust the frequency space of the adjacent resonances. In recent years, most HBARs have been designed using one-port resonant configuration (Pang *et al.*, 2005; Masson *et al.*, 2006; Zhang *et al.*, 2006; Baumgartel and Kim, 2009). In this paper, the fabricated one-port HBAR presents high Q at the multiple resonances from a 0.5–4.0 GHz wide band with a total size (including the contact pads) of 0.6 mm×0.3 mm×0.4 mm.



(a) (b)

Fig. 1 Cross-section schematic of the high overtone bulk acoustic resonator (HBAR)
(a) Two-port HBAR; (b) One-port HBAR

2 Experiments

A 330±15 μm thick *c*-axis sapphire, polished on both sides, is used as the substrate. A metal thin film of Al of 120 nm thickness is deposited upon the substrate and then patterned to form the bottom electrode of the piezoelectric transducer. ZnO is deposited by a DC magnetron sputtering. A 0.96-μm thick high-quality *c*-axis orientation ZnO piezoelectric layer is deposited on the Al ground plane under the following sputtering conditions: 0.8 Pa of Ar/O_2 (1:2) gas mixture, 120 W power, and 200 °C substrate temperature. The ZnO film is patterned to reveal the contact pads on the bottom electrode. The top electrode of 200 nm thick Al is then deposited and patterned. The active area of the HBAR is 100 μm×100 μm (Fig. 2).

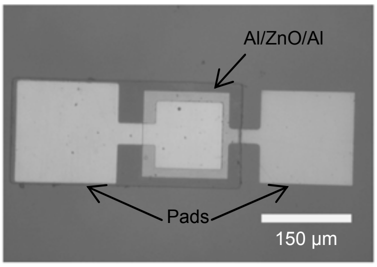


Fig. 2 Picture of a fabricated HBAR on sapphire

3 Simulation

The HBAR is simulated using a one-dimensional (1D) Mason equivalent circuit model (Fig. 3).

The reflection coefficients (e.g., S_{11}) are calculated from the circuit using Advanced Design System

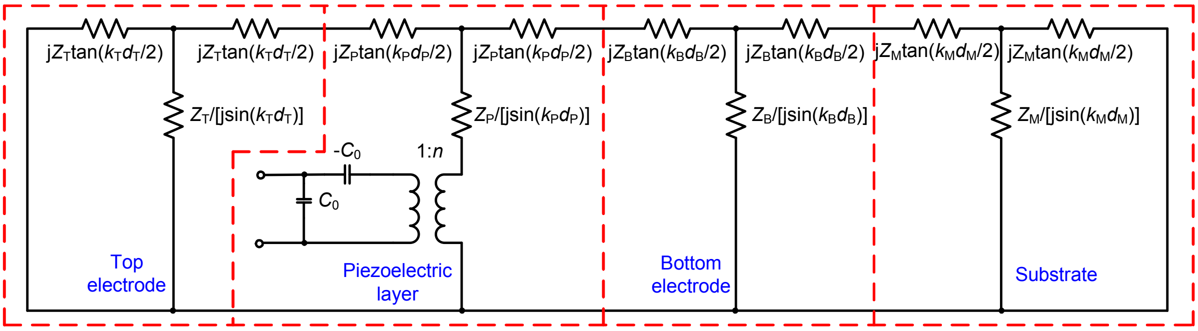


Fig. 3 The one-dimensional Mason equivalent circuit model
Z_T, Z_P, Z_B, and Z_M are the characteristic acoustic impedances of the top electrode, piezoelectric layer, bottom electrode, and substrate, respectively; k_T, k_P, k_B, and k_M are the wave numbers; d_T, d_P, d_B, d_M are the thicknesses

software. Fig. 4 shows the S_{11} of the HBAR device from 2.4 GHz to 2.5 GHz. The most strongly excited resonators are loaded near 2.4–2.5 GHz. The multiple resonant frequencies are separated by about 16 MHz from $\Delta f=V_s/(2d)$, where the longitudinal wave velocity is V_s=11 350 m/s and thickness of the sapphire substrate is d=350 μm.

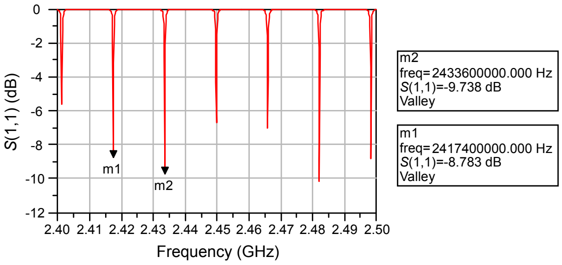


Fig. 4 Calculated S_{11} from 2.4 to 2.5 GHz

4 Results and discussion

The crystalline and micromorphology of the ZnO film is examined by X-ray diffraction (XRD) and scanning electron microscope (SEM) (Fig. 5). The ZnO film grows with a high degree of (002) orientation, which indicates that the deposited ZnO film is a highly c-axis oriented piezoelectric film. SEM surface and cross-section views of the film reveal that the average grain size of the ZnO film is about 150 nm, and the film has well-aligned columnar grains.

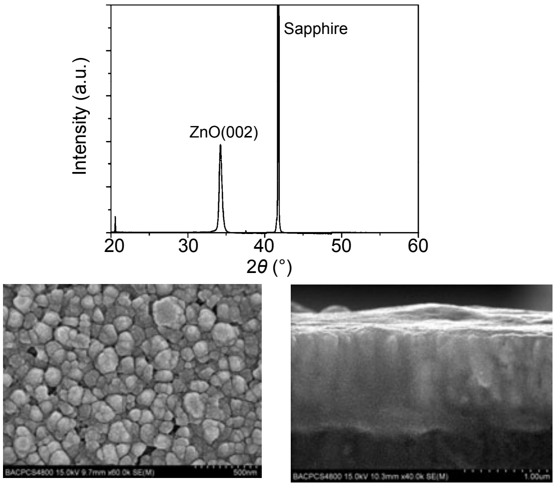


Fig. 5 X-ray diffraction (XRD) pattern and SEM surface and cross-section views of the ZnO film

The reflection coefficients (e.g., S_{11}) of the fabricated HBARs are measured with an Agilent E5071C network analyzer. Multiple resonances occur in a very wide band from 0.5 to 4.0 GHz. The most strongly excited resonators are loaded near 2.4 GHz, corresponding to a half wave length of ZnO film. Fig. 6 is the measured S_{11} from 2.4 GHz to 2.5 GHz, corresponding to the simulation results. The measured spacing of the resonator modes agrees with the theoretical results. The measured return loss of the non-resonance range is larger by 2−4 dB than the calculated results, which is because the calculation of the loss of leads and pads is so difficult that it is not considered in the simulation.

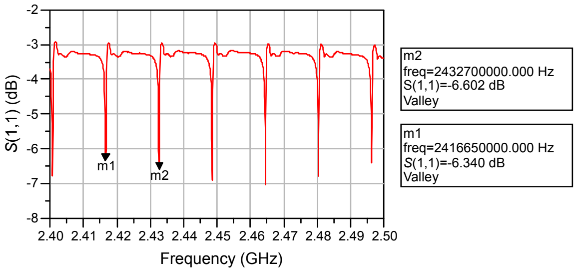


Fig. 6 Measured S_{11} from 2.4 to 2.5 GHz

The important parameters of the HBAR device at 1.49, 2.43, and 3.40 GHz are calculated (Table 1). Q and K_{eff}^2 are defined as follows:

$$Q_{f_{\text{s/p}}}=\frac{f_{\text{s/p}}}{2}\left|\frac{\mathrm{d}\angle Z_{\text{in}}}{\mathrm{d}f}\right|_{f_{\text{s/p}}},\quad K_{\text{eff}}^2=(\pi/2)^2\frac{f_{\text{p}}-f_{\text{s}}}{f_{\text{p}}},\qquad(1)$$

where f_s and f_p are the series and parallel resonance frequencies, respectively. The resonators exhibit an unloaded f_Q product in excess of 1×10^{13} Hz, which has a larger magnitude than that of surface acoustic wave (SAW) resonators and the same order of magnitude as bulk acoustic wave (BAW) quartz crystal resonators. The oscillator using the HBAR device can be implemented directly at S and C microwave bands without a frequency multiplier. Therefore, the HBAR low phase noise microwave signal sources or oscillators are more desirable compared to the signal sources or oscillators based on BAW or SAW resonators.

Table 1 Important parameters of the HBAR device at three different frequencies

Frequency (GHz)	K_{eff}^2 (%)	Q_{f_s}	Q_{f_p}	$f\cdot Q_{f_s}$ ($\times10^{13}$ Hz)	$f\cdot Q_{f_p}$ ($\times10^{13}$ Hz)	FOM ($Q_{f_s}\cdot K_{\text{eff}}^2$)
1.49	0.0385	16000	30000	2.384	4.470	6.16
2.43	0.0953	4000	25000	0.972	6.075	3.81
3.40	0.0479	6500	3000	2.210	1.020	3.11

FOM: figure of merit

Fig. 7 shows the measured magnitude and phase of impedance and the Smith charts near the resonance in a narrow frequency range for 1.49, 2.43, and 3.40 GHz. The mechanical loss of the piezoelectric ZnO films and the electrical loss of the electrodes (including leads and pads) should be further decreased to make the resonance trace closer to the perimeter of the Smith chart, to obtain higher Q values.

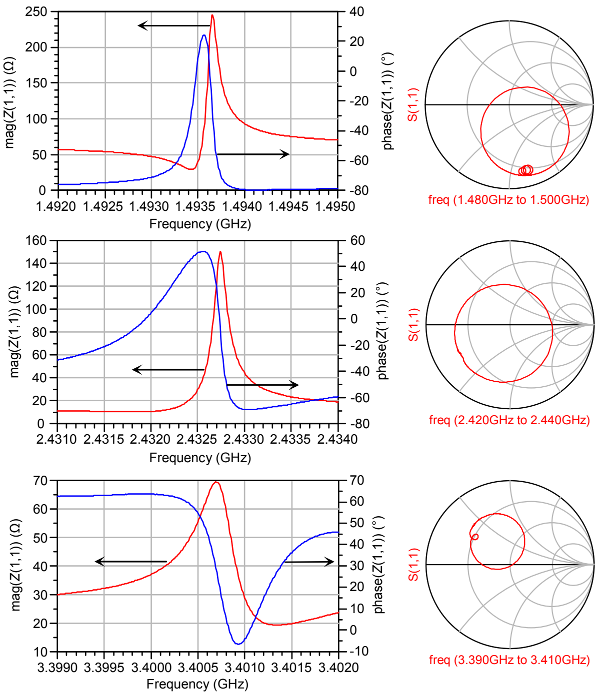


Fig. 7 Measured magnitude and phase of impedance (left) and the Smith chart (right) near the resonance in a narrow frequency range for 1.49, 2.43, and 3.40 GHz from top to bottom

5 Summary

This paper describes the ZnO film deposited by a DC magnetron sputtering and HBAR based on sapphire substrate. HBAR presents high Q at the multiple resonances from a 0.5–4.0 GHz wide band with a total size of 0.6 mm×0.3 mm×0.4 mm. The best acoustic coupling occurs at around 2.4 GHz, which agrees with the simulation result. The HBAR has potential application for the low phase noise high frequency oscillator or microwave signal source.

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