Deposition of ZnO thin films by magnetron sputtering for a film bulk acoustic resonator

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Abstract

To fabricate lateral-field excitation (LFE)-mode solid mounted resonator (SMR)-type film bulk acoustic resonators (FBARs), piezoelectric ZnO layers were deposited in an RF magnetron sputtering system. Control of the crystallinity, microstructure and electric properties of the piezoelectric layers was essential for fabricating high-quality LFE-mode SMR-type FBARs. In the appropriate deposition condition for FBAR devices, ZnO thin films with highly c-axis-preferred orientation (XRD rocking curve, 2θ = 2.17°), high resistivity of 10^6 Ω cm and surface roughness of 10.6 Å were deposited. Optimal substrate rotation was especially important for improvement of the c-axis-preferred orientation of ZnO films. Plasma properties such as the electron temperature, plasma density and saturated ion current were also analyzed for optimal ZnO deposition conditions using a Langmuir double-probe system. The resonator, for which the active piezoelectric area was 200×200 μm², consisted of 1.25-μm-thick ZnO film and a 110-nm Au electrode. Its series and parallel resonance frequencies appeared at 1.68 and 1.71 GHz, respectively, and the quality factor was 201.4 ± 7.4.

Keywords: ZnO; RF sputtering; Langmuir probe; Film bulk acoustic resonator

1. Introduction

The film bulk acoustic resonator (FBAR) is a prime candidate for the next-generation mobile communication devices to replace dielectric and surface acoustic wave (SAW) filters [1–3]. It is composed of a piezoelectric layer, top and bottom electrodes, and an isolation layer of a resonant region from a substrate. The isolation layers isolate the propagation of acoustic waves from the piezoelectric layer to the substrate with high acoustic loss. Therefore, the acoustic wave is confined within the piezoelectric layer and this enables a FBAR device to have high quality factor (Q). There are three types of construction for isolation layers: bulk micromachining, surface micromachining, and a Bragg reflector layer. At present, a combination of bulk micromachining and surface micromachining techniques is used to fabricate commercial FBAR devices. However, solidly mounted resonator (SMR)-type FBARs with a Bragg reflector are worth developing commercially as well as researching theoretically. ZnO thin films have been used as the piezoelectric layer, which must have the highly c-axis-preferred orientation [X-ray diffraction (XRD) rocking curve, 2θ < 6°] and high electrical resistivity (> 10^6 Ω cm) for the fabrication of high-Q FBAR devices. In this study, the preferred orientation of ZnO films and the plasma properties during sputtering were characterized using XRD rocking curves and Langmuir double probes, respectively. LFE-mode SMR-type FBAR devices were fabricated using ZnO piezoelectric film and their resonant properties were also measured.

2. Experimental

ZnO thin films were deposited by RF magnetron sputtering using a sintered ZnO target (4 inch, 99.99%, Cerac Co Ltd). The sputtering chamber was evacuated to 2×10⁻⁵ Torr using a turbomolecular pump prior to
the introduction of the Ar–O₂ gas mixture. The total working pressure, the oxygen content and the RF input power were varied in the ranges 5–35 Torr, 0–75% and 60–120 W, respectively. The distance between the ZnO target and the substrate and the substrate temperature were maintained at 7.6 cm and 25 °C, respectively.

Plasma properties such as the electron temperature, plasma density and saturated ion flux were analyzed with a Langmuir double-probe system (DLP2000, Plasmart Co Ltd). The tip Langmuir double-probe system was made of tungsten with a 0.5-mm radius and 10 mm in length. The voltage and time resolution of the DLP2000 system were 0.122 mV and 7.69 μs, respectively. The crystallographic texture was measured by XRD using a diffractometer (M18XHF-SRA, Mac-Science Co Ltd). XRD gave information concerning only those crystal planes for which the normal coincided with the substrate normal. The (00̅2) planes of grains in the ZnO films have an angular spread, which basically determines the electromechanical properties of the film. The angular spread of the (00̅2) plane of each grain around the maximum (00̅2) peak position was determined by X-ray rocking curve measurements. The full width at half-maximum (FWHM) of the rocking curve indicates the degree of dispersion of the basal planes of ZnO crystallites from the preferred c-axis orientation. The thickness of the films was measured from cross-sectional SEM micrographs. The height and root-mean square (RMS) roughness of films were measured by atomic force microscopy (AFM).

The LFE-mode SMR-type FBAR device was composed of Au film for the electrode, ZnO film for the piezoelectric layer, SiO₂/W film for the Bragg reflecting layer and Si for the substrate, as shown in Fig. 1. Au films were deposited with the electron-beam evaporation method and deposition of the other layers was carried by RF magnetron sputtering. It is important to control the thickness of each Bragg reflecting layer and the piezoelectric layer to a quarter and a half wavelength, respectively, of the acoustic wave. Patterns on the electrodes and piezoelectric layers were made using basic semiconductor processes. Finally, the resonant properties of the LTE-mode SMR-type FBAR devices were measured using a Cascade RF-1 probing station, Cascade GSG-150 probes, and a Hewlett-Packard 8753E network analyzer.

3. Results and discussion

Fig. 2 shows the growth rate of ZnO films deposited at various chamber pressures as a function of RF input power and O₂ concentration. The growth rate with the O₂ concentration was measured under the optimal condition of 10 mTorr of chamber pressure and 120 W of RF power. The growth rate increased with increasing chamber pressure. It is known that an increase in RF power allows a linear increase in the growth rate during RF magnetron sputtering. A high growth rate, 25 nm/min, was achieved at RF power of 120 W. The high growth rate does not provide enough time for atoms to move to equilibrium sites on the surface of the growing film. As a result, the c-axis orientation of ZnO thin films deposited at higher growth rates is likely to be inferior. The higher O₂ content in the working gas resulted in lower growth rates for ZnO films, as shown in Fig. 2. The growth rate of ZnO films was dramatically decreased with increasing oxygen content from 0 to 25%, but appeared to be saturated beyond 25% O₂ content. Without consideration of the bonding energy of the target material, energy transfer from the argon ions in the plasma to the target atoms having similar atomic weight occurs easily. In particular, the sputtering rate of the ZnO target should be high without O₂ because of the high growth rate. However, an increase in O₂ concentration in the working gas reduces the number of incident Ar atoms, which can transfer their high energy to the target. Therefore, the growth rate for ZnO films decreased with increasing oxygen content [4,5].

The final I–V curve for the plasma was acquired by averaging 101 I–V measurements. Fig. 3 shows I–V plots for plasma at various oxygen contents. Because oxygen gas in plasma has lower plasma density than argon gas, the I–V curves had notable fluctuations with increasing oxygen content. Fig. 4 shows the plasma density, electron temperature and saturated ion current density for plasma as a function of RF input power and oxygen content. As the RF power was increased, the plasma density and saturated ion current density increased, resulting in a decrease in electron temperature. On the other hand, as the oxygen content was increased, plasma density and saturated ion current density decreased, and the electron temperature increased.

XRD patterns of ZnO films deposited under various conditions, especially without substrate rotation, are shown in Fig. 5. When ZnO films were deposited without substrate rotation, the crystallinity and c-axis-preferred orientation of ZnO films were dramatically changed with varying deposition parameters, such as the working pressure, oxygen content and RF input power. The crystallinity of ZnO thin films deposited at 5 mTorr was inferior, i.e. was nearly amorphous. However, the crystallinity and c-axis-preferred orientation of ZnO film were improved at 10 mTorr. The crystallinity and c-
Fig. 2. Variation of growth rate of the ZnO films deposited under various deposition conditions.

Fig. 3. $I-V$ plots for plasma at various oxygen contents.
Fig. 4. (a) Plasma density and (b) electron temperature and saturated ion current density of plasma for various RF input powers and oxygen contents.
ZnO films deposited under no oxygen content showed a high growth rate and poor c-axis-preferred orientation, as shown in Fig. 7.

When the substrate was not rotated but fixed, ZnO films deposited were apt to show large stress and poor thickness uniformity. As expected, ZnO films deposited at a substrate rotation speed of 20 rev./min showed lower stress and better thickness uniformity, even though they had an approximately six-fold lower growth rate. Fig. 8 shows XRD patterns of ZnO films deposited at substrate rotation speed of 20 rev./min and constant pressure of 10 mTorr with various Ar/O2 ratios, indicating that samples with substrate rotation had better c-axis preferred orientation than those without substrate rotation. When the substrate was rotated, the properties of ZnO films were not dramatically affected by the RF input power, working pressure and oxygen content (up to 10% content). During rotation, incident atoms seem to have sufficient time to arrive at thermodynamically stable sites, so that in ZnO films deposited with substrate rotation were less affected by the deposition parameters.

The LFE-mode SMR-type FBAR device consists of Si substrate, a SiO2/W Bragg reflector, a bottom floating Au layer, a ZnO piezoelectric layer, a top signal Au electrode and a top ground electrode. The bottom floating Au layer plays a role in improving coupling between the applied electric field and acoustic excitation. The bottom and top Au electrodes on a 10-nm Ni–Cr adhesion layer were deposited by electron-beam evaporation to a thickness of 110 nm. The area of the square-shaped bottom electrode and the top signal electrode was 430×430 and 200×200 μm2, respectively. The gap between top signal and top ground electrodes was 30 μm, and the width of the top ground electrode was 200 μm. The ZnO film was 1.25 μm thick, which corresponded to the 2.5-GHz resonant frequency of the FBAR device when the mass loading effect of the Au electrode was not taken into account.

The S11 parameter of the LFE-mode SMR-type FBAR device is shown in Fig. 9. The series resonance appeared at 1.68 GHz, while the parallel resonance appeared at 1.71 GHz. The reason for the lowering of the resonant frequencies was the mass loading effect due to the 120-nm-thick Au electrode. The effective coupling coefficient of the LFE-mode SMR-type FBAR device was 0.0432, which corresponds to 54% of theoretical value for an ideal ZnO FBAR device. The Q factor of the resonator measured using the QZERO program was as high as 201.4±7.4.

4. Conclusion

Piezoelectric ZnO film was deposited using RF magnetron sputtering to fabricate an LFE-mode SMR-type FBAR device. The optimal conditions for ZnO deposition were 120 W of RF power, 10 mTorr of chamber...
Fig. 6. FWHM values of X-ray rocking curves for ZnO films deposited without substrate rotation under various deposition conditions.

Fig. 7. Dependence of FWHM values of X-ray rocking curves on the thickness of ZnO films.
pressure and 50% \( \text{O}_2 \) concentration. In addition, suitable substrate rotation was very important for improvement of the \( c \)-axis-preferred orientation of \( \text{ZnO} \) films. The electron temperature, plasma density and saturated ion current were approximately 5.5–5.8 eV, 1.0–1.3 \( \times 10^{11} \) \( \text{cm}^{-3} \) and 3.5–4.3 mA/cm\(^2\), respectively. The piezoelectric-active area was 200\( \times \)200 \( \mu \text{m}^2 \), and the thickness of \( \text{ZnO} \) film and Au electrode was 1.25 \( \mu \text{m} \) and 110 nm, respectively. The series and parallel resonance frequencies of the FBAR device appeared at 1.68 and 1.71 GHz, respectively, which represent 68.4% of the values for a \( \text{ZnO} \) FBAR of the same thickness without a mass loading effect. The effective coupling coefficient was 0.0432, which corresponds to 54% of the theoretical value for an ideal \( \text{ZnO} \) FBAR device. The \( Q \) factor of the resonator was as high as 201.4 \( \pm 7.4 \).

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References