Dependence of Resonance Characteristics on Thermal Annealing in ZnO-Based FBAR Devices

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Abstract— **In this paper, we present the film bulk acoustic resonator (FBAR) devices fabricated by considering the effects of annealing temperature on zinc oxide (ZnO) film growth characteristics. In order to determine the annealing temperature and annealing time at which the ZnO film can have good material properties, the several resonators containing ZnO layers were fabricated and annealed at various temperatures from 27°C to 300°C in Ar gas ambient. The effects of the annealing temperature and annealing time on the ZnO film properties were comprehensively studied in order to further improve the resonance characteristics of FBAR resonators.**

I. INTRODUCTION

Film bulk acoustic wave resonator (FBAR) or its technology plays an important role for the fabrication of the next generation radio-frequency (RF) filters. This is mainly because the FBAR technology can be integrated with the current silicon process technology, eventually enabling the current off-chip type of RF filters to be realized in the type of the microwave monolithic integrated circuits (MMICs) [1, 2]. The FBAR device operation is based on the resonance occurring in the piezoelectric film sandwiched between the two (top and bottom) metal electrodes [3]. Thus, the piezoelectric property may play a critical role in determining the resonance characteristic of the FBAR devices. It was also known that the piezoelectric property is largely determined by the c-axis preferred orientation of the piezoelectric film deposited on the bottom electrode [4].

In this paper, we present the dependence of the resonance characteristics on the thermal annealing conditions in ZnO-based FBAR devices. As a result, the resonant characteristics of the FBAR resonators were found to have a strong dependence on the post-annealing process conditions.

II. EXPERIMENTAL

In this work, the fabricated FBAR device consists of the piezoelectric ZnO film sandwiched between the top and bottom metal (cobalt) electrodes deposited on five layers of SiO_2/Mo Bragg reflector using RF magnetron sputtering technique, as shown in Fig. 1. The ZnO film was deposited at room temperature, in 10mTorr in Ar/O_2 high-purity mixture gas with the ratio of 3/1; and at RF power of 300 Watts. The five-layered SiO_2/Mo Bragg reflector was also fabricated by using a RF magnetron sputtering technique. The multilayered SiO_2 and Mo films were alternately deposited on Si wafer 4 inches. The 0.6μm thick Mo films were deposited at room temperature and under Ar gas pressure of 15 mTorr with DC power of 150 Watts while the 0.6μm thick SiO_2 films were deposited at room temperature under Ar gas pressure of 4 mTorr with RF power of 300 Watts. On top of the Bragg reflector, the ZnO film was deposited. Then for the top Co electrodes formation, the so-called lift-off process was used. The AZ1512 photoresist (PR) film patterns were defined first on the ZnO film by the conventional photolithography technique using pattern masks and then Co films were deposited on the PR film pattern, followed by the lift-off processing to strip off the remaining PR layers. The top Co electrodes patterning completed the fabrication of the FBAR devices.

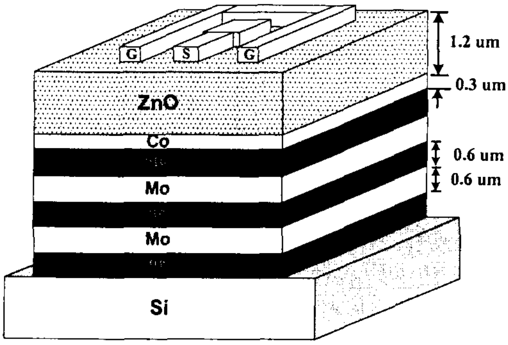

Fig. 1 Three-dimensional schematic structure of the FBAR device fabricated (five-layered SiO_2/Mo Bragg reflector) with the top Co electrode pattern.

Finally, in order to determine the annealing temperature and annealing time at which the ZnO film can have good material properties, the several resonators containing ZnO layers were treated with several thermal annealing conditions. Particularly for this work, the annealing temperature (from 27°C to 300°C in Ar gas ambient by Electric Dehydrate Furnace) and annealing time were mainly taken into account. The thermal annealing conditions are as follows: (a) non-annealing; (b) post-annealing at 100°C for 30 minutes; (c) post-annealing at 200°C for 30 minutes; (d) post-annealing at 200°C for 120 minutes; and (e) post-annealing at 300°C for 30 minutes.

III. RESULTS AND DISCUSSION

First, the effects of annealing temperature in Ar gas ambient on the resonance characteristics in FBAR devices were investigated by measuring the return loss (S_{11}) using Network Analyzer - System Agilent/HP 8510C and a probe station. In Fig. 2, the return loss S_{11} measurements were plotted together for comparison where (a) non-annealing; (b) post-annealing at 100°C for 30 minutes; (c) post-annealing at 200°C for 30 minutes; and (e) post-annealing at 300°C for 30 minutes.

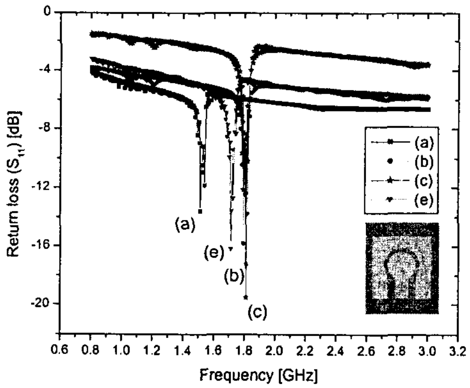

Fig. 2 the return loss S_{11} measurements were plotted together for comparison where (a) non-annealing; (b) post-annealing at 100°C for 30 minutes; (c) post-annealing at 200°C for 30 minutes; and (e) post-annealing at 300°C for 30 minutes.

As shown in Fig. 2, in non-annealing case (a), the return loss, S_{11} is about -13dB while in post-annealing cases, the values of S_{11} are considerably improved where the post-annealing case (b), $S_{11} \approx -17.3$dB; case (c), $S_{11} \approx -19.5$dB; and case (e), $S_{11} \approx -16.2$dB. The improvement of the return loss by the post-annealing process appears to be mainly due to the higher quality of ZnO film as the temperature increased from 100°C to 300°C. On the other hand, ZnO film is reactive material and very sensitive to temperature [5]. It seems that the quality of ZnO film seems to have been degraded because the annealing temperature was relatively too high (300°C). Therefore, in order to get the higher quality of ZnO film, the best temperature for the post-annealing seems to be 200°C, as shown in case (c). Second, based on the above experimental results, the effects of the post-annealing duration in Ar gas ambient on the resonance characteristics of the FBAR devices were also investigated. Fig. 3 illustrates the comparison of the return loss S_{11} factors measured. The resonators were post-annealed at 200°C for 30min, case (c) and 200°C for 120min, case (d), respectively.

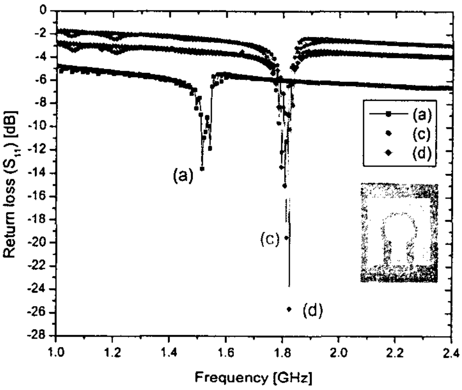

Fig. 3 Comparison of return loss values for various annealing cases: (a) non-annealing; (c) post-annealing at 200°C for 30min.; and (d) post-annealing at 200°C for 120min.

In Fig. 3, a significant improvement of the return loss S_{11} was observed. Increasing the annealing time from 30 minutes to 120 minutes, the value of S_{11} increased ~6 dB in the same top-pattern electrode as shown in the figure. In the case (c), the S_{11} value is ~19.5dB and in the case (d), S_{11} is ~25.6dB. Fig. 4 illustrates the results of the return loss, S_{11} of the FBAR devices with somewhat different top-electrode patterns. All these patterns were also post-annealed at 200°C for 30 minutes. As a result, the Co electrode FBAR devices, fabricated on five-layered reflector, show reasonably good return loss ranged from 22 to 31dB at resonant frequency of ~1.55GHz. The resonator performance could be estimated through using the following two figures of merit (FOM), K^2_{eff} and $Q_{s,p}$ [6] where K^2_{eff} and $Q_{s,p}$ represent the maximum attainable bandwidth of filter and resonator loss, respectively [7].

$$Q_{s,p} = \frac{f_{s,p}}{2}\left|\frac{d\angle Z_{in}}{df_{s,p}}\right| \qquad (1)$$

where the $\angle Z_{in}$ is the slope of the input impedance phase; $f_{s,,p}$ are the series and parallel resonance frequencies [8].

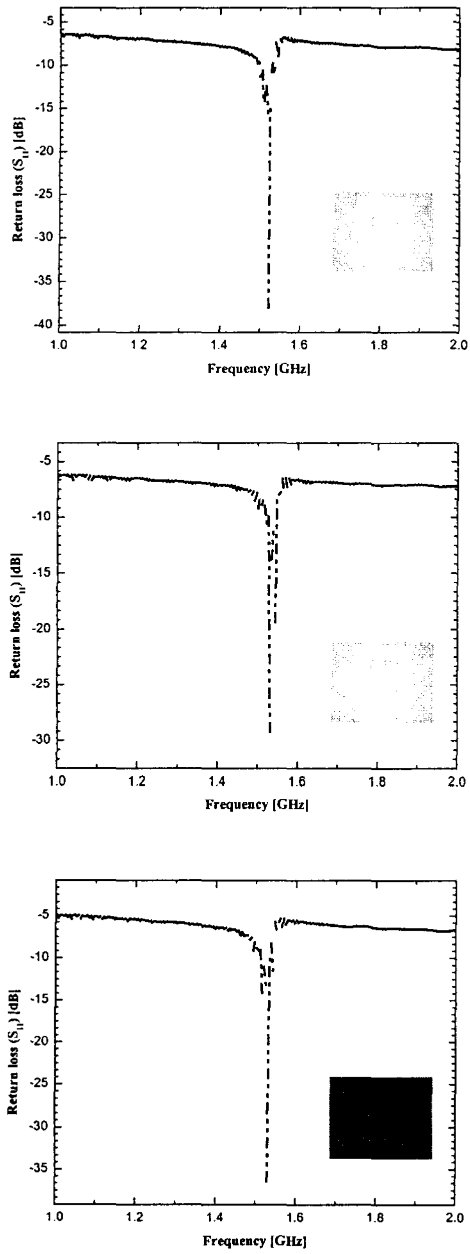

Fig. 4 Top-view patterns and return losses S_{11} of one-port FBAR devices with different patterns.

Fig. 5 shows the slope of $\angle Z_{in}$ as a function of the frequency with the first top-electrode pattern in Fig. 4. The calculated series and parallel Q-factor values (Q_s and Q_p) and K^2_{eff} for one typical resonator are tabulated in Table 1.

[Table 1] Summary of the calculated series and parallel Q-factor values (Q_s and Q_p), and K^2_{eff} for a typical resonator pattern.

f_s (GHz)	f_p (GHz)	K^2_{eff} (%)	Q_s	Q_p
1.532	1.548	2.55	2262	2948.2

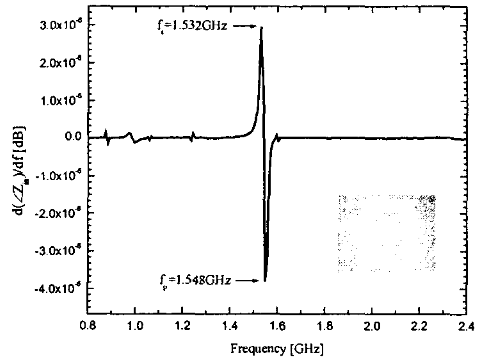

Fig. 5 Slope of $\angle Z_{in}$ as a function of the frequency for the specific resonator.

IV. CONCLUSIONS

In this paper, the resonance characteristics of the FBAR devices are presented along with post-annealing process conditions in an inert gas ambient. The post-annealing process conditions for the FBAR device fabrication are shown to have a strong influence on the return loss characteristics. In this work, the post-annealing of the 200°C and two hours seems reasonably good, resulting in the high quality ZnO film. The cobalt electrode FBAR devices, fabricated on five-layered Bragg reflectors with post-annealing process, significantly improve the return loss value (from 22 to 34dB) at the resonant frequency of ~1.55GHz as compared to the non-annealing cases.

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