Comparison of Resonance Characteristics of ZnO-Based FBAR Devices for Various Thermal-Annealing Conditions

Hae-il Song, Linh Mai, and **Giwan Yoon,** *Members, KIMICS*

Abstract—In this paper, the effects of various annealing conditions on the resonance characteristics of ZnO-based FBAR devices are compared. Several FBAR device samples were fabricated by using three different annealing methods while one sample remained non-annealed as a reference for comparison. Return loss (S_{11}) could be significantly improved by both Bragg reflector-annealing and/or post-annealing. Especially, the use of the combined annealings resulted in most desirable resonance improvement compared with the Bragg reflector-annealing or post-annealing method alone.

Index Terms—Film bulk acoustic resonator (FBAR), Bragg reflector, Thermal annealing, Return loss (S_{11}), and Q-factor

I. INTRODUCTION

The rapid growth of wireless communication area has demanded more advanced new filters with higher performance to protect receivers from adjacent channel interferences and noises. Currently, the existing communication components need to be further minimized and also integrated on one small chip. Recently, film bulk acoustic resonator (FBAR) filter has attracted much attention as a possible next-generation novel filter technology mainly because it has small size as well as high performance and also it can be integrated fully with other CMOS/RFIC circuitry, eventually being able to potentially realize a single-chip radio or a transceiver in the future. The FBAR is largely grouped into three types. First group is a back-etched type supported by the edge of the substrate. Second one is a surface-micromachined type with an air-gap under the resonator part. Last one is solidly mounted-type having a Bragg reflector part which is used to acoustically isolate piezoelectric material from the substrate. [1-3]

Several studies for resonance characteristic improvements have been done by thermal annealing on Bragg reflectors just before the deposition of bottom electrodes [4, 5] and also on the resonator immediately after the deposition of top electrodes [6]. In this paper, the first method, annealing only on Bragg reflector, is named "Bragg reflector-annealing" method and the second one, annealing after the completion of the top electrode deposition, is named "post-annealing" method. Finally, the combination of the first and second processes is named "combined-annealing" method. Up to now, no investigation has been reported on the effects of the combined use of both Bragg reflector-annealing and post-annealing methods. In this paper, we for the first time presented a feasibility study of the combined annealing and its effects on the resonance characteristics particularly for ZnO-based FBAR devices with 7-layered Bragg reflectors.

II. EXPERIMENTAL

In this experiment, the ZnO-based FBAR devices are composed of the piezoelectric ZnO film sandwiched between the top and bottom electrode (Cobalt) deposited on 7-layered SiO_2/W Bragg reflector. Each part of the FBAR device with Bragg reflector was fabricated using a RF/DC magnetron sputtering technique. A 7-layered SiO_2/W Bragg reflector was fabricated by alternately depositing SiO_2 and W films on a 4-inch Si wafer. Each layer has one quarter wave-length ($\lambda/4$) thickness of the resonance frequency in order to acoustically isolate the piezoelectric layer part from the substrate part. The 0.6μm-thick SiO_2 films were deposited at room temperature and under the Ar gas pressure of 15 mTorr in 32sccm and RF power of 300 Watts for 55 minutes. The 0.6μm-thick W films were also fabricated at room temperature and under Ar gas pressure of 15 mTorr in 32sccm and DC power of 200 Watts for 24 minutes. The substrate wafer with Bragg reflector was then segmented into four small samples for the further fabrication of four different FBAR devices, which were annealed by different annealing methods while keeping one sample non-annealed. Immediately before the bottom electrode deposition, the Bragg reflector annealing was made, meaning that Bragg reflectors of only two samples were thermally annealed in a sintering furnace at 400°C for 30 minutes while the other two samples remained non-annealed. Then, the 0.3μm-thick bottom electrode (Cobalt) was deposited on four samples at the same time at room temperature and under Ar gas pressure of 20 mTorr in 32sccm and DC power of 130 Watts for 30 minutes. Then, 1.2μm-thick ZnO piezoelectric film was deposited on the bottom electrode at room

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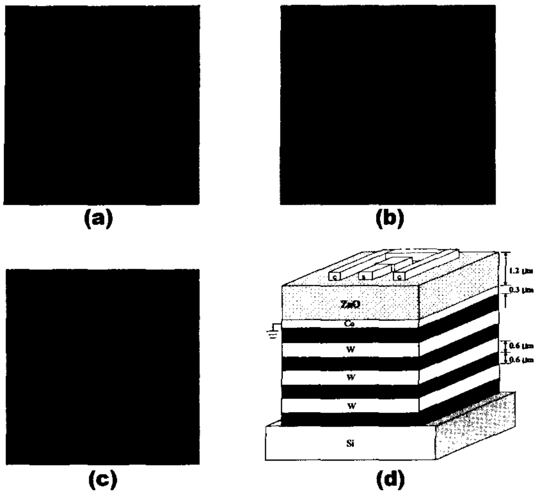

Fig. 1 Three kinds of top-view patterns ((a) pattern 1, (b) pattern 2, and (c) pattern 3) of the FBAR devices, and (d) a 3-dimensional schematic of one-port FBAR device with the pattern 2.

temperature and under Argon/oxygen gas mixture (2:1) of 10 mTorr and RF power of 260 Watts for 100 minutes. This ZnO film was deposited to be the half wave-length ($\lambda/2$) thickness of the resonance frequency. The conventional photolithography technique using pattern masks defined the AZ1512 photoresist (PR) film followed by deposition of 0.3μm-thick the top electrode (Co) on the ZnO piezoelectric film under the same deposition condition as the bottom electrode. The three different top electrode patterns were completed by the lift-off processing to strip off the remaining PR layers. The top electrode patterns and a 3-dimensional schematic of the one-port FBAR resonator are shown in Fig. 1. Before post-annealing process, the return loss S_{11} of four resonators was measured by using Network Analyzer-System Agilent/ HP 8510C and a probe station. Then, two samples without any annealings on the Bragg reflectors were also annealed in electronic dehydrate furnace at 200°C for 2 hours (post-annealing process). Therefore, for the four FBAR devices fabricated under four different conditions, the return loss S_{11} values of post-annealed four samples were also extracted. The four samples and annealing methods are summarized in Table 1.

Table 1. Four different samples

Sample name	Annealing type
Sample 1	Non-annealing
Sample 2	Bragg reflector (BR) annealing (400°C/30min)
Sample 3	Post-annealing (200°C/2h)
Sample 4	BR annealing + Post-annealing

III. RESULTS AND DISCUSSION

We measured the return loss (S_{11}) of four FBAR devices after Bragg reflector annealing and post-annealing were completed, respectively. Thus, 6 different measurement results were obtained from the four samples by non-annealing of sample 1, Bragg reflector-annealing of sample 2, non-annealing and post-annealing of sample 3, Bragg reflector-annealing and combined-annealing of sample 4. In Figs. 2, 3, and 4, the return loss S_{11} measurements were plotted for the comparison of the annealing effects according to three different methods. First, we compared the return loss S_{11} of sample 1 with that of sample 2 in Fig.2. The return loss S_{11} measurement results of the sample 3 between the non-annealing and Bragg reflector-annealing and that of sample 4 between the Bragg reflector-annealing alone and combined-annealing of Bragg reflector-annealing as well as post-annealing were also shown in Figs. 3 and 4. In Fig. 2, a significant improvement of the return loss S_{11} is shown by the Bragg reflector-annealing. The return losses of sample 2 were around -10.9, -12.9, and -14.1dB, while those of sample 1 were -3.9, -4.7, and -5.8dB. In other words, the return losses of sample 2 annealed on Bragg reflector were around 7.0, 8.2, and 8.3dB better than those of non-annealed sample 1 for pattern 1, 2, and 3 of

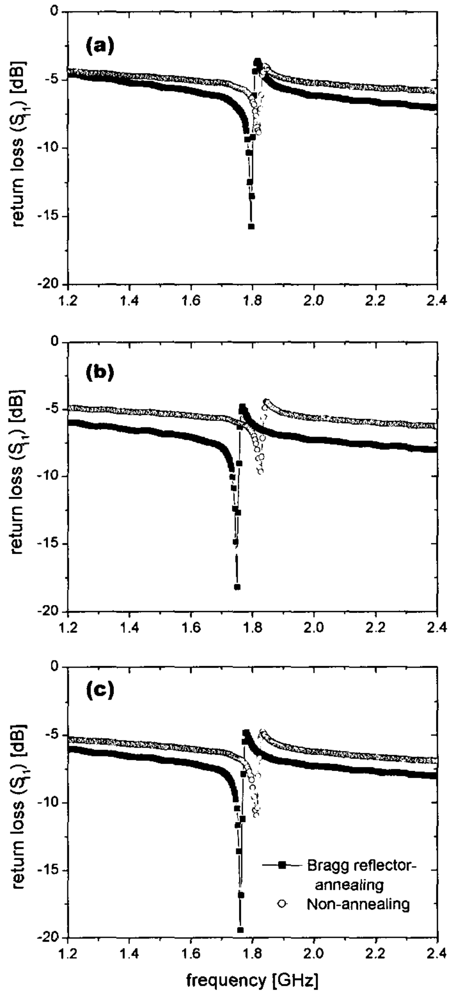

Fig. 2 Return loss S_{11} measurement results of two samples with non-annealing and Bragg reflector-annealing for three different patterns
(a) Pattern 1, (b) Pattern 2, (c) Pattern 3

top electrode. It is speculated [4] that the non-annealed Bragg reflector may have some physical imperfections in the film microstrucures and some imperfect adhesions at interfaces between the physically deposited films, degrading the device performance. However, a Bragg reflector-annealing may eliminate any possibly exiting imperfect microstructures and incomplete adhesions in the Bragg reflectors, eventually leading to improvements of resonance characteristics. Fig. 3 also shows the considerable improvement of the return loss S_{11} of sample 3 by post-annealing. Sample 3 was post-annealed at 200°C for 2 hours [6]. Return losses of the sample 3 after post-annealing were around -15.4, -14.3, and -27.2dB, while those before post-annealing were -12.0, -12.3, and -20.5 dB. Therefore, return losses of sample 3 were around 3.4, 2.0, and 6.7 dB increased by post-annealing method. In Fig. 4, the measurement results by combined method on sample 4 were shown. Return losses of the sample 4 by the combined-annealing method were around -16.9, -20.1, and -27.5 dB, while those by only Bragg reflector annealing-method were around -13.6, -16.7, and -20.8 dB. So, the return losses of sample 4 were around 3.3, 3.4, and 6.7 dB improved by additional post-annealing process after Bragg reflector-annealing.

In [5], there were three samples thermally annealed in a furnace at 200°C/30 min, 400°C/30 min, and 600°C/ 30min, respectively, while keeping one sample non-annealed. Two samples annealed at 200°C/30 min and 400°C/30 min showed significant improvements of the resonance characteristics. However the sample annealed at 600°C/30 min showed smaller return loss, which seems to come from the inter-diffusion between W and SiO_2. The oxidized upper W layer is believed to lose its intrinsic material property of high impedance. This may lead to an ineffective Bragg reflector with a poor acoustic isolation, resulting in inferior resonance characteristics.

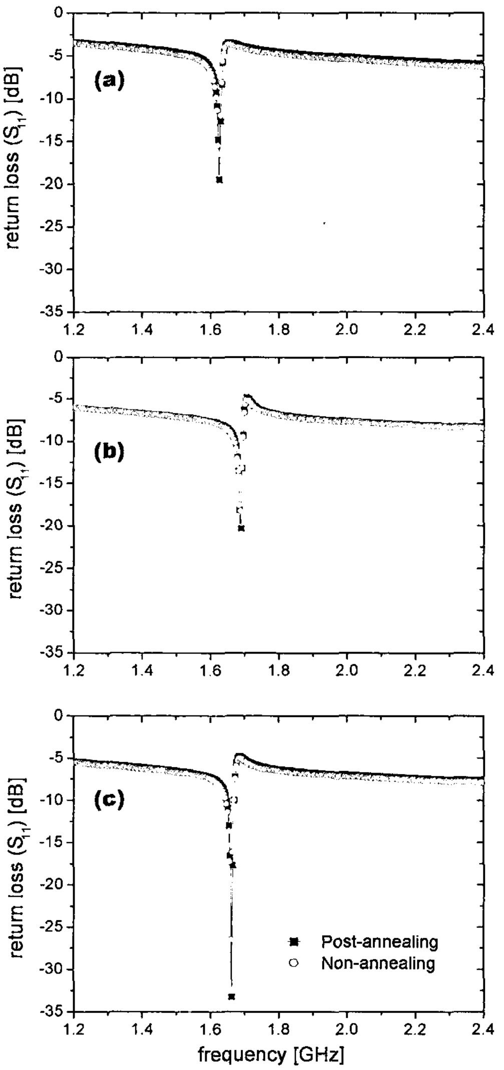

Fig. 3 Return loss S_{11} measurement results of sample 2 with three different patterns by non-annealing and post-annealing
(a) Pattern 1, (b) Pattern 2, (c) Pattern 3

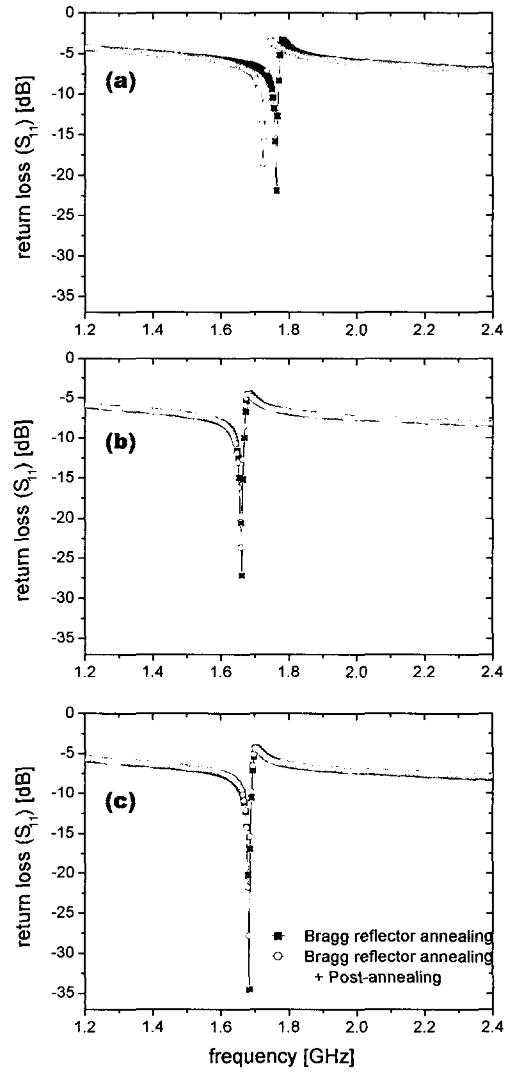

Fig. 4 Return loss S_{11} measurement results of sample 3 with three different patterns by Bragg reflector annealing and combined-annealing (post- annealing as well as Bragg reflector annealing)
(a) Pattern 1, (b) Pattern 2, (c) Pattern 3

Therefore, annealing temperatures below 400°C on Bragg reflector could be helpful for resonance characteristic. However, there was no explanation for thermal annealing time. In [6], the effects of both annealing temperature and annealing time on resonance characteristics were studied. The return loss S_{11} was affected by annealing temperature as well as annealing time and the best condition for post-annealing was 200°C/2 hours. In this experiment, the Bragg reflector of sample 4 was firstly annealed at 400°C/30 min of the best condition for Bragg reflector-annealing. Sample 4 was also post-annealed at 200°C/2 hours after the top electrode was deposited. At this point, we believe that 200°C of post-annealing may not affect severely the Bragg reflector structure in spite of long annealing time of 2 hours because 200°C of annealing temperature is much smaller than 600°C. Post-annealing process at 200°C/2 hours for the sample 4 previously annealed by Bragg reflector-annealing method at 400°C/30 min may only eliminate any imperfect microstructures and incomeplete adhesions of resonator without any significant effect on the Bragg reflector.

To estimate the resonator performance, $Q_{s/p}$ is used as a figure of merit (FOM). Series/parallel quality factor ($Q_{s/p}$) is a measure of loss within the device.

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

where the $\angle Z_{in}$ is the slope of the input impedance phase and $f_{s/p}$ are the series and parallel resonance frequencies [7]. The calculated series and parallel Q-factor values for FBAR resonators with pattern 2 and 3 are tabulated in Table 2. Series and parallel quality factors of two resonators annealed by Bragg reflector annealing-method and post-annealing method were significantly improved and parallel quality factors of the resonators annealed by combined-annealing method were more improved than those of the resonators annealed by only Bragg reflector- annealing method.

Table 2. Series and parallel Q factors for four samples

	Pattern 2		Pattern 3	
Sample Name	Q_s	Q_p	Q_s	Q_p
Sample 1	2075	2575	2222	2623
Sample 2	2895	4364	3204	5693
Sample 3	2694	4923	3150	4337
Sample 4	2804	5781	3141	5853

IV. CONCLUSIONS

In this paper, the resonance characteristics of ZnO-based FBAR resonators were studied for various annealing methods, which are Bragg reflector annealing method, post-annealing method, and combined-annealing method. Return loss S_{11} and $Q_{s/p}$ factors were considerably improved by each method of Bragg reflector annealing and post-annealing. Especially, the return loss and parallel quality factor of the resonator annealed by combined-annealing method were much more improved.

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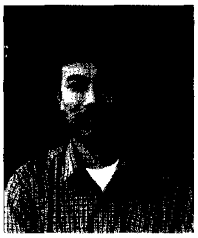

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