Resonance Characteristics of ZnO-Based FBAR Devices by Two-Step Annealings

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ABSTRACT

In this paper, 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. Resonance characteristics could be significantly improved by both Bragg reflector-annealing and/or post-annealing steps. Especially, the use of two-step annealings resulted in most desirable resonance characteristic improvement compared with the Bragg reflector-annealing or post-annealing step alone.

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

Ⅰ. Introduction

A drastic growth of wireless communications markets has led to an explosion in interest in innovative filter design to protect receivers from adjacent channel interferences and noises in the radio frequency (RF) and microwave fields. Film bulk acoustic resonator (FBAR) devices have become one of the most promising next-generation filter technology mainly due to their higher Q-factor, smaller size, and lighter weight and also it can be fully integrated with other CMOS/RFIC circuitry, eventually being able to realize a one-chip radio or a transceiver in the future. The FBAR simply consists of two electrodes and a piezoelectric film. The FBAR should be isolated acoustically from the substrate to obtain a high Q-factor and reduce spurious responses.

There have been three kinds of techniques reported for the acoustic isolation. First configuration 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 a solidly mounted-type having a Bragg reflector part which is used to acoustically isolate piezoelectric material from the substrate. A surface-micromachined type and solidly mounted-type FBAR resonators are suitable for post CMOS process since they can be fabricated by surface processing and do not need to machine the substrate [1-3].

The key issues in excellent high frequency filter development are resonator design, methods of resonator fabrication, and optimization of resonator performance because basic filter layout are already known [1].

For a solidly mounted-type FBAR resonator, there have been several researches for resonance characteristic improvements by thermal annealing on Bragg reflectors prior to the deposition of bottom electrodes [4, 5] and also on the resonator immediately after the deposition of top electrodes [6]. Up to now, no investigation has been reported on the effects of the combined use of these two annealing steps particularly for the ZnO-based FBAR devices with 7-layered Bragg reflectors. In this paper, the first method, annealing on only Bragg reflectors, is named "Bragg reflector (BR)-annealing" step and the second one, annealing after the completion of the top electrode deposition, is named "post-annealing" step. Finally, the combined use of the first and second step is named "Two-step annealings".

II. Experiments

Firstly, SiO_2/W 7 layers Bragg reflector (BR) was alternately deposited on a 4-inch silicon wafer. Each layer has one quarter wave-length ($\lambda/4$) of the resonance frequency in order to acoustically isolate the piezoelectric layer part from the silicon substrate part. The 0.6μm-thick SiO_2 films were deposited at room temperature under the Ar gas pressure of 15 mTorr with RF power of 300 Watts. The 0.6μm-thick W films were also fabricated at room temperature under Ar gas pressure of 15 mTorr with DC power of 200 Watts. The silicon 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 three different annealing processes while keeping one sample non-annealed.

The first process to enhance the resonance characteristics of FBAR resonators is Bragg reflector-annealing step. In this step, only two samples were thermally annealed immediately before the bottom electrode deposition in a sintering furnace at 400°C for 30 minutes in air and the other two samples remained non-annealed. Then, the 0.3μm-thick cobalt bottom electrode was deposited on four samples at the same time at room temperature under Ar gas pressure of 20 mTorr with DC power of 130 Watts. And 1.2μm-thick ZnO piezoelectric film was deposited on the bottom electrode at room temperature under Argon/oxygen gas mixture (2:1) of 10 mTorr with RF power of 260 Watts. This ZnO film was fabricated 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 cobalt top electrode on the ZnO piezoelectric film under the same deposition condition as the bottom electrode. The three different top electrode patterns were completed by the so-called lift-off processing to strip off the remaining PR layers. A 3-dimensional schematic, cross sectional SEM (scanning electron microscope) picture, and three different top electrode patterns of the one-port FBAR resonator are shown in Fig.1.

Then, two samples with and without Bragg reflector annealing step were annealed in electronic dehydrate furnace at 200°C for 2 hours in Ar gas as a post-annealing step. Therefore, the four FBAR devices fabricated under four different thermal conditions were prepared and the return loss S_{11} values of four samples were extracted using network Analyzer-System Agilent/HP8722D and a probe station. Different annealing steps for the four samples are tabulated in Table 1.

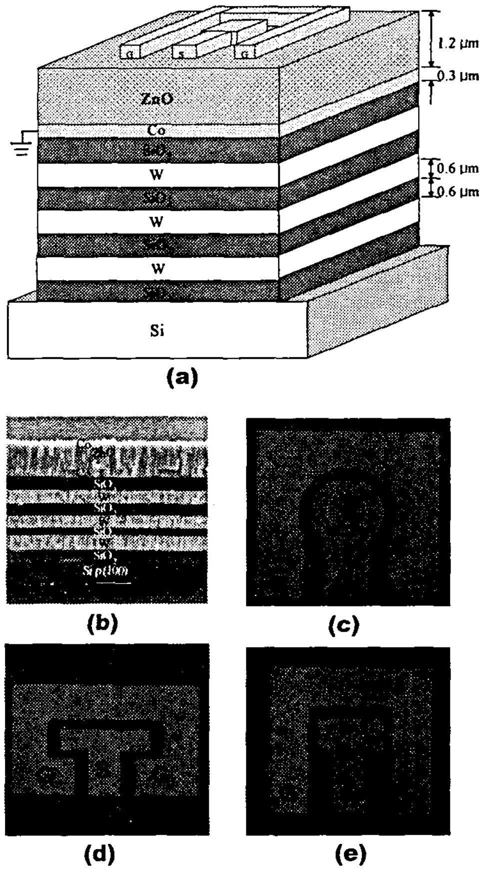

Fig. 1 (a) 3-dimensional schematic, (b) Cross section SEM picture, and three kinds of top-view patterns ((c) pattern 1, (d) pattern 2, and (e) pattern 3) of the FBAR resonators

Table 1. Different annealing steps for the four samples

Sample name	Thermal treatment step
Sample A	Non-annealing
Sample B	Bragg reflector-annealing
Sample C	Post-annealing
Sample D	Two-step annealings (BR-annealing + Post-annealing)

III. Results and Discussion

Four different measurement results were obtained from the four samples by non-annealing of sample A, Bragg reflector-annealing step of sample B, post-annealing step of sample C, two-step annealings of sample D. The return loss S_{11} of three patterns were plotted and summarized for the comparison of the annealing effects according to three different annealing steps in Fig. 2 and Table 2.

The resonance characteristics of the three samples annealed by Bragg reflector-annealing step, post-annealing step, and two-step annealings were compared to the non-annealed sample. First, The return losses of sample B treated by Bragg reflector-annealing step were around 5.71, 1.84, and 8.5 dB better than those of non-annealed sample A. It is speculated in [4] that the non-annealed Bragg reflector may have some physical defects in the film microstructures and some imperfect adhesions at interfaces between the physically deposited films, resulting in degradation of the device performance. However, a Bragg reflector-annealing step may eliminate any possibly existing imperfect microstructures and incomplete adhesions in the Bragg reflectors, eventually leading to improvements of resonance characteristics.

Second, the return losses of sample C were around 2.43, 12.52, and 7.66 dB increased by post-annealing step than those of non-annealed sample A. 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 show significant improvements of the resonance characteristics. However the sample annealed at 600°C/30 min shows smaller return loss, which seems to come from the inter-diffusion between W and SiO_2 layers in Bragg reflector. The oxidized 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. Therefore, Bragg reflctor-annealing step at the temperature below 400°C seems to be helpful in order to improve the resonance characteristics.

Last, The return losses of the sample D were around 9.32, 30.74, and 27.76 dB increased by

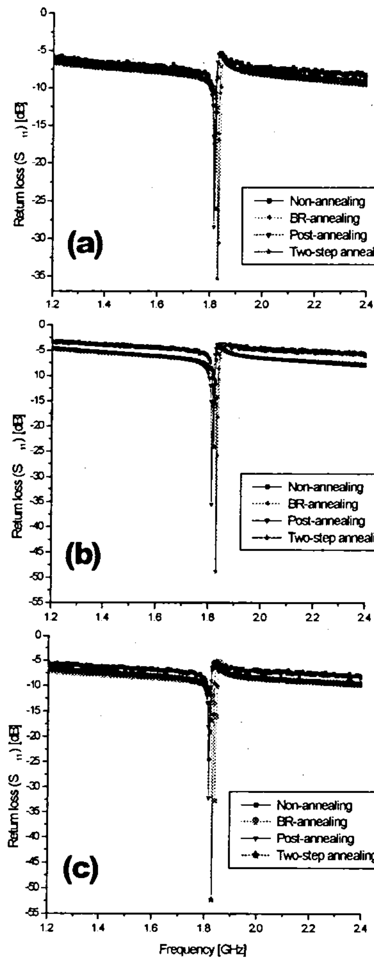

Fig. 2 The return loss S_{11} measurement results against frequency for three different top electrode patterns ((a) Pattern 1, (b) Pattern 2, (c) Pattern 3)

Table 2. Summarized return loss measurement results for three different patterns (Unit : dB)

Sample name	Return loss S_{11} [dB]		
	Pattern 1	Pattern 2	Pattern 3
Sample A	-17.99	-18.07	-19.50
Sample B	-23.70	-19.91	-28.00
Sample C	-20.42	-30.59	-27.16
Sample D	-27.31	-48.81	-47.26

two-step annealins than those of non-annealed sample A. These return losses are much higher values than results of the two samples treated by Bragg reflector-annealing step and post-annealing step alone. 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. In comparison of the return loss of two samples annealed at 200°C during 30 min. and 2 hours, the sample annealed during 2 hours showed better resonance characteristics and the best condition for post-annealing was 200°C/2 hours.

In this experiment, the Bragg reflector of the sample D was annealed at 400°C/30 min. and also post-annealed at 200°C/2 hours after the top electrode was deposited. At this point, we believe that the post-annealing step at 200°C may not affect severely the Bragg reflector structure in spite of relatively long annealing time of 2 hours. The addition of the post-annealing step of 200°C/2 hours for the sample D already annealed by Bragg reflector-annealing step at 400°C/30 min is believed to further eliminate any imperfect microstructures and incomplete adhesions in FBAR devices without any significant degradation effect on the Bragg reflector.

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

$$Q_{s/p} = \frac{f_{s/p}}{2}\left|\frac{d\angle Z_{input}}{df_{s/p}}\right|$$

where the $\angle Z_{input}$ is the slope of the input impedance phase and $f_{s/p}$ are the series and parallel resonance frequencies [7]. Figure 3 shows that the slop of $\angle Z_{input}$ as a function of the frequency with the pattern 2 in fig. 1 and the calculated series and parallel Q-factor values for FBAR resonators with pattern 2 are tabulated in Table 3.

Series and parallel quality factors of resonator annealed by Bragg reflector-annealing step and post-annealing step were significantly improved. Moreover, much more improvement of quality factors could be obtained by Two-step annealings than those of the resonators annealed by Bragg reflector-annealing step or post-annealing step alone.

IV. Conclusion

In this paper, the resonance characteristics of ZnO-based FBAR resonators were investigated and compared for various annealing methods, which are Bragg reflector annealing step, post-annealing step, and Two-step annealings. Return loss S_{11} and $Q_{s/p}$ factors could be considerably improved by each step of Bragg reflector annealing and post-annealing. Especially, the return loss and parallel quality factor when treated by two-step annealings were found to be significantly improved. This approach will be very useful for the future FBAR device applications

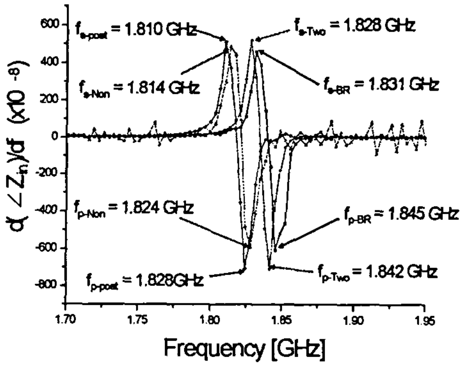

Fig 3. Four slops of $\angle Z_{in}$ as a function of the frequency for different annealing conditions with the pattern B

Table 3. The calculated series and parallel Q-factor values for FBAR resonators with pattern 2

Sample name	Quality factor	
	Q_s	Q_p
Sample A	4405	5438
Sample B	4223	5613
Sample C	4616	6468
Sample D	4821	6538

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