A Study of Efficient Thermal Annealing Method for SMR-Type FBAR Devices

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ABSTRACT

In this paper, the resonance characteristics of SMR-type FBAR devices annealed by three different annealing methods are investigated and compared. The resonance characteristics could be effectively improved by the proposed efficient annealing method which can optimize the annealing conditions. It seems very useful for improving the performance of the SMR-type FBAR devices in a cost-effective way.

Keywords

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

Ⅰ. INTRODUCTION

A rapid development of wireless communications has attracted huge 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 piezoelectric material produces mechanical vibrations in response to a voltage being applied between the top and bottom electrodes. However, because of the heavy substrate under the FBAR device, the resonance characteristic of the FBAR device can not be good. Therefore, the FBAR device 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 resonator (SMR) - type having a acoustic Bragg reflector which is used to acoustically isolate piezoelectric material from the substrate. A surface-micromachined type and SMR-type FBAR devices 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 SMR-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].

However, these annealing methods have limitation to get the maximum resonance characteristic of SMR-type FBAR resonator. Accordingly, the efficient annealing method is proposed and the resonance characteristics of the FBAR resonators by three different annealing methods are compared. In this paper, the first method, annealing on only Bragg reflectors, is named "Bragg reflector (BR)-annealing" and the second one, annealing after the completion of the top electrode deposition, is named "post-annealing" . Finally, the proposed efficient annealing method, effectively combined use of the first and second methods is named "efficient annealing"

II. EXPERIMENTS

1. Proposed Efficient annealing method

In [4-5], the effects of annealing on only Bragg reflector to various temperatures was studied. There were three samples thermally annealed in a furnace at 200°C/30 min, 400°C/30 min, and 600°C/30 min, 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/30min 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 the best annealing condition for Bragg reflector-annealing can be 400°C/30 min in order to improve the resonance characteristics.

In [6], the effects of both annealing temperature and annealing time on resonance characteristics were investigated. All annealing processes in this paper were performed after the fabrication of the FBAR resonators was completely finished without annealing on Bragg reflector. Then the return loss S_{11} was affected by annealing temperature as well as annealing time. The first three samples are annealed in a furnace at 100°C/30 min, 200°C/30 min, and 300°C/30min, respectively, while keeping one sample non-annealed. Similar to the results in [4-5], two samples annealed at 100°C/30 min and 200°C/30 min show significant improvements of the resonance characteristics. However the sample annealed at 300°C/30min shows smaller return loss. Therefore, the best annealing temperature for post-annealing process, annealing right after the complete deposition of the top electrode, can be 200°C when annealed during 30 min. However 300°C is lower than 400°C which is the best annealing temperature condition for Bragg reflector. And the second two samples were also annealed at 200°C/30 min, 200°C/2 hours, respectively, while keeping one sample non-annealed. As the annealing time is increased until 2 hours, The resonance characteristics were improved.

Therefore 400°C/30 min is the best condition for Bragg reflector and 200°C/2 hour is the best condition for post-annealing. In conclusion, the resonance characteristics of the SMR-type FBAR resonators can be maximized by following efficient annealing step. First, Bragg reflector-annealing at 400°C/30 min is performed to eliminate any possibly existing imperfect microstructures and incomplete adhesions in the Bragg reflectors. Second, post-annealing at 200°C/2 hour is done to maximize the resonance characteristic to further eliminate remained imperfect microstructures and incomplete adhesions in both FBAR devices and Bragg reflectors, eventually leading to improvements of resonance characteristics. At this point, we believe that the post-annealing at 200°C/2 hours may not affect severely Bragg reflector structure because the resonance characteristics of FBAR resonators were enhanced until 400°C in [4-5].

2. Experimental step

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 from the silicon substrate. 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 methods while keeping one sample non-annealed.

The first method to enhance the resonance characteristics of FBAR resonators is Bragg reflector-annealing. In this method, only two samples were thermally annealed immediately

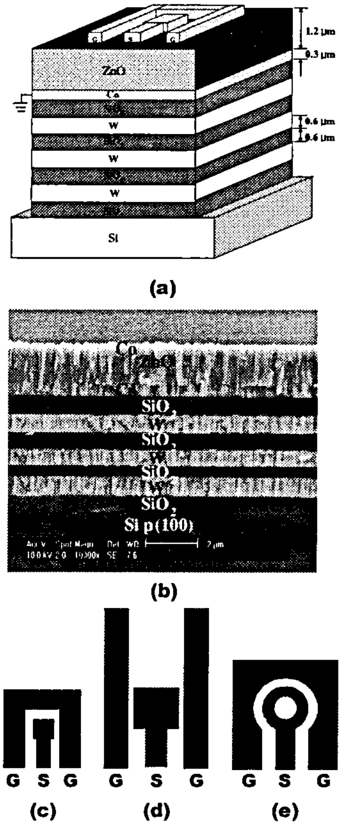

Fig. 1 (a) 3-dimensional schematic, (b) Cross section SEM picture, three kinds of top-vie patterns ((c) pattern 1, (d) pattern 2, and (e) pattern 3) of FBAR resonators

Table 1. Different annealing method for the four samples

Sample Name	Annealing method
Sample A	Non-annealing
Sample B	Bragg reflector(BR)-annealing
Sample C	Post-annealing
Sample D	Efficient annealing -1st : BR-annealing (400°C/30 min) -2nd : Post-annealing (200°C/2 hours)

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 were annealed in electronic dehydrate furnace at 200°C for 2 hours in Ar gas as a post-annealing. 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.

III. RESULTS AND DISCUSSION

Four different measurement results were obtained from the four samples by non-annealing on sample A, Bragg reflector-annealing on sample B, post-annealing on sample C, and efficient annealing on smaple 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, post-annealing, and efficient annealing were compared to the non-annealed sample. First, the

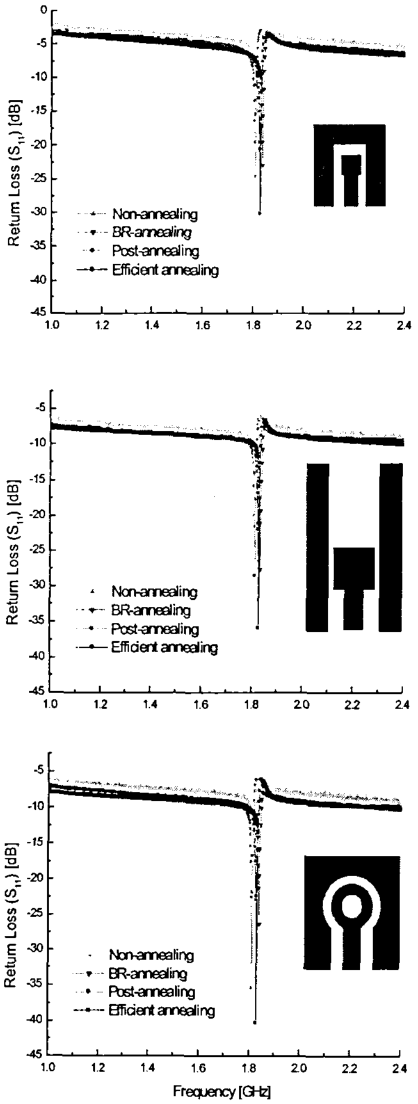

Fig. 2 The return loss S_{11} measurement results against frequency for three different top electrode patterns.

Table 2. Summarized return loss measurement results for three different patterns

Sample Name	Return loss S_{11} [dB]		
	Pattern 1	Pattern 2	Pattern 3
Sample A	14.79	16.32	17.48
Sample B	17.97	17.70	18.44
Sample C	19.66	20.56	26.47
Sample D	25.16	27.93	30.29

return losses of sample B treated by Bragg reflector-annealing were around 3.18, 1.384, 0.96 dB better than those of non-annealed sample A. Second, the return losses of sample C were around 4.87, 4.244, 8.99 dB increased by post-annealing than those of non-annealed sample A. Last, the return losses of the sample D were around 10.37, 11.614, 12.81 dB increased by proposed efficient annealing. Therefore the addition of the post-annealing of 200°C/2 hours for the sample D already annealed by Bragg reflector-annealing 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.

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

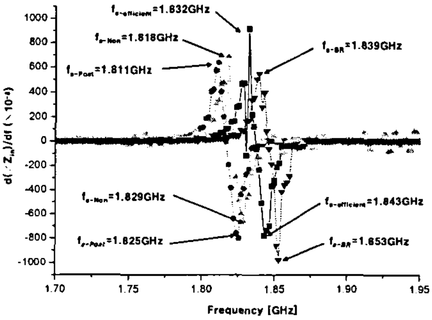

Fig.3 Four slops of ∠Zin as a function of the frequency for different annealing conditions with the pattern 1.

Table 3. The calculated series and parallel Q-factor values for FBAR resonators with pattern 1.

Sample name	Quality factor	
	Q_s	Q_p
Sample A	5266	5992
Sample B	5337	6046
Sample C	5775	7314
Sample D	8391	7482

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 1 in fig. 1 and the calculated series and parallel Q-factor values for FBAR resonators with pattern 1 are tabulated in Table 3.

Series and parallel quality factors of the RBAR resonators annealed by Bragg reflector-annealing and post-annealing methods were improved. Moreover, much more improvement of quality factors could be obtained by the proposed efficient annealing method than those of the resonators annealed by Bragg reflector-annealing or post-annealing alone. It seems very useful for improving the resonance characteristics of the SMR-type FBAR devices as a cost-effective way.

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Ⅳ. CONCLUSION

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

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