Comparison of Resonance Characteristics in FBAR Devices by Thermal Treatments

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

Abstract—The paper presents some methods to improve characteristics of film bulk acoustic resonator (FBAR) devices. The FBAR devices were fabricated on Bragg reflectors. Thermal treatments were done by sintering and/or annealing processes. The measurement showed a considerable improvement of return loss (S_{11}) and quality factor ($Q_{s/p}$). These thermal treatment techniques seem very promising for enhancing FBAR resonance performance.

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

I. INTRODUCTION

With the rapid growth of wireless communication in the range from 0.5 GHz to 6 GHz, there has been an increased demand for the integration of microwave devices on a silicon wafer. Thin-film bulk acoustic wave resonator (FBAR) filters are very suitable devices for microwave monolithic integrated circuits (MMICs) since they can be realized on Si or GaAs substrates [1]-[5]. The basic FBAR form consists of a piezoelectric thin-film sandwiched between top and bottom electrodes. There is a resonance in this sandwiched structure when an electric field is applied onto electrodes [6]-[8]. Therefore, the piezoelectric thin film may play a critical role in determining the resonance characteristics of the FBAR devices. Lakin K. M. et al. reported that the solidly mounted resonator (SMR) has Bragg reflector as a mirror, usually fabricated by alternately depositing two different high and low impedance materials, respectively [9], [10]. Even though there were several researches [11]-[16] related to improvements of FBAR device characteristics, no comprehensive reports have been made on thermal annealing treatments on such devices.

In this research, we present the first time a comprehensive study on FBAR's thermal treatments for improving significant characteristics of the devices. Thermal annealing processes were employed to improve the resonant characteristics. It was found that the resonant factors depend significantly on the annealing conditions and areas of the electrodes as well. Thus, these resonant factors could be improved considerably by proper thermal treatments as well as by choosing suitable resonance area of electrode.

II. EXPERIMENTAL

Fig. 1 shows the schematic structure of the FBAR device. Initially, SiO_2/W seven layers Bragg reflector (BR) was formed on a silicon wafer by using RF magnetron sputtering technique. The multi-layered SiO_2 and W films were alternately deposited on a Si wafer of 4 inches. The 0.6 μm thick W films were deposited at room temperature, 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. This silicon wafer with BR of seven layers then was divided into five pieces, named sample N1 to N5. Then, these samples were used for the fabrication of FBAR. In order to investigate the temperature effect on FBAR devices, four samples were treated under different thermal annealing processes (samples N2 to N5), whereas the last one (sample N1) had no thermal treatment. The first thermal annealing process was carried out as follows: only two BR substrates of samples N3 and N4 were sintered for 30 minutes at 400^0C in air, as shown in [14], [15], and sample N5 was also sintered for 30 minutes at 400^0C, but in Ar gas ambient by employing electric dehydrate furnace equipment. Then, 0.2 μm Co bottom electrodes (as floating grounds) were deposited on all samples under the condition of 20 mTorr Ar gas pressure and 150-Watts DC power. Above the bottom electrode is the 1.2 μm ZnO film. The ZnO film was deposited at room temperature, in 10 mTorr of Ar/O_2 high-purity mixture gas, and at RF power of 300 Watts. The second annealing process (called inter-fabrication annealing) was made when the formation of ZnO layer was finished. Three samples N2, N4, and N5 were annealed for 60 minutes at 200^0C in Ar ambient by the furnace. The deposition and patterning of the top Co electrodes (0.2 μm) on top of the ZnO film completed the FBAR device fabrication. As a result, we have 5 resonator samples,

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Linh Mai is Ph.D course student in School of Engineering, Information and Communications University (ICU), 119, Munjiro, Yuseong-gu, Daejeon, 305-732, Republic of Korea, (e-mail : mailinh@icu.ac.kr)

Hae-il Song is M.S. course student in School of Engineering, Information and Communications University (ICU), 119, Munjiro, Yuseong-gu, Daejeon, 305-732, Republic of Korea, (e-mail : hisong@icu.ac.kr)

Giwan Yoon is associate professor in Information and Communications University (ICU), 119, Munjiro, Yuseong-gu, Daejeon, 305-732, Republic of Korea, (e-mail : gwyoon@icu.ac.kr)

namely, R1, R2, R3, R4, and R5 corresponding to BR samples N1, N2, N3, N4, and N5 were fabricated.

All the resonator samples were measured to get return loss, S_{11} factor, by the combined-equipment probe station and network analyser-Hewlet Packard/HP 8722D. Then, the third annealing process-called post-annealing process was done with the selected-four samples R2 to R5 by EDF at 200^{0}C for 120 minutes. Finally, the return loss values were extracted from every resonator patterns on each of four post-annealed samples for comparison of FBAR device characteristics. Annealing treatment conditions for the five samples R1 to R5 are summarized in table 1 as follows.

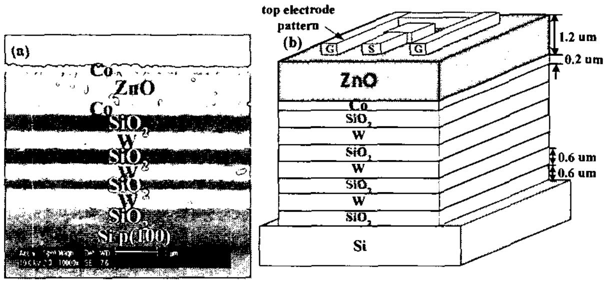

Fig. 1 FBAR device structure
(a) Cross section view image of fabricated FBAR device
(b) 3-D schematic structure of FBAR device

Table 1 Thermal processes

Thermal step	R1	R2	R3	R4	R5
1st - BR annealing 400^{0}C/30min.			Air	Air	Ar
2nd - Inter-fabrication annealing 200^{0}C/60min.		Ar		Ar	Ar
3rd - Post-annealing 200^{0}C/120min.		Ar	Ar	Ar	Ar

III. RESULTS AND DISCUSSION

Fig. 2 shows the three resonator patterns and their return loss (S_{11}) characteristics versus frequency for various annealing conditions. Fig. 2 (a), (b), (c) compare the return loss characteristics of 5 FBAR devices (R1 to R5) with the same resonator pattern fabricated on N1, N2, N3, N4, and N5, respectively.

The S_{11} values in Fig. 2 one more time confirmed the advantage of BR annealing method reported in [14], [15]. By thermal annealing BR just before the deposition of bottom electrodes, the authors in these papers achieved a considerable FBAR device characteristic improvement. Certainly, the return loss values of three resonator patterns have the same increasing trend with from resonators R1 and R2 (non-annealing BR), resonators R3 and R4 (annealed-BR), and resonator R5 (two steps thermal treatment). Thermal annealing is one of important factors to enhance the return loss characteristics. From Fig. 2c, among 5 resonator samples, R1 and R2 have smallest return loss values (S_{11} = -16.55 dB and S_{11} = -17.20 dB, respectively). Meanwhile, the respective return loss values for samples R3, R4, and R5 are: S_{11} = -20.34 dB, -24.7 dB, -31.9 dB, respectively. The reason why return loss values of samples R1, and R2 smaller than R3, R4, and R5, were explained detail in [14] and [15]. In addition, with the different thermal treatments, we get different values of return loss. For example, the resonator R3 fabricated on BR N3 has about 3 dB return loss smaller than the resonator R4 fabricated on BR N4 and added inter-fabrication annealing process. The return loss values of resonators R3 and R4 are about 10 dB and 7 dB smaller than the resonator R5 fabricated on BR N5 and added inter-fabrication thermal annealing process, respectively. Table 2 shows the extracted values S_{11} at frequency 1.833 GHz of all cases in Fig. 2.

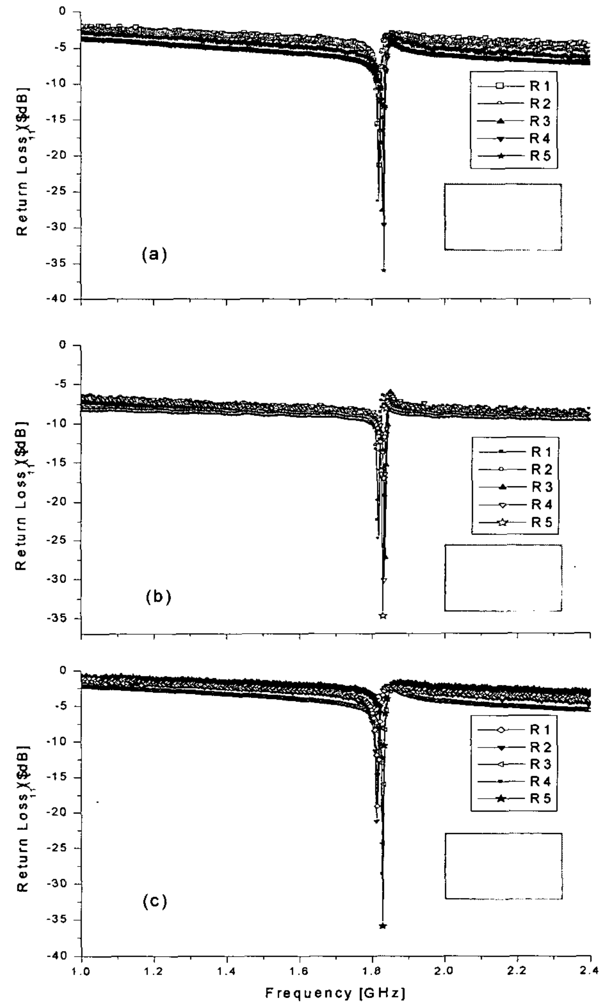

Fig. 2 Return loss characteristics versus frequency for various thermal processes.
(a) Case of pattern 1 (b) Case of pattern 2
(c) Case of pattern 3

Table 2 Return loss values of five types of resonator with different pattern

Sample	R1 [dB]	R2 [dB]	R3 [dB]	R4 [dB]	R5 [dB]
Pattern 1	-18.40	-22.43	-24.60	-26.61	-33.02
Pattern 2	-19.340	-21.83	-24.18	-27.10	-30.69
Pattern 3	-16.55	-17.20	-21.34	-24.70	-31.90

According to [14] and [15], the quality of BRs considerably influences on the FBAR characteristics. Inside the original SiO_2/W multiplayer BR may exist some physical imperfections in the film microstructures and/or some imperfect adhesions at interfaces between the physically deposited films, thereby degrading the device performances. These physical imperfections and imperfect adhesions also exist in the physical structure of resonator. In order to effectively reduce the above imperfect issues, the first step of BR-annealing process and the second step of inter-fabrication annealing process can be applied. As a result, the resonators have better resonance characteristics. There is one more step of thermal process for improving the FBAR device characteristics in our experiment. This third step is named post-annealing process. To investigate the influence of post-annealing on the resonator properties, four resonator samples with the same layout pattern 1 (R2 to R4) were post-annealed by EDF equipment in Ar gas ambient within 120 minutes. The return losses of these samples were extracted and given in table 3. In this table, the return losses of sample R1 are shown for reference.

Table 3 Comparison of return loss values

Sample	Return loss S11 [dB]			|ΔS11| [dB]
	Non annealing	Before post-annealing	After post-annealing	
R1	-17.40			
R2		-22.43	-27.01	4.58
R3		-23.60	-30.75	7.15
R4		-25.61	-32.92	7.31
R5		-32.26	-40.61	8.35

Based on the measured data in table 3, the post-annealing process shows the significant enhancement of the return loss characteristics for each sample R2 to R5. The increased-value ($|\Delta S11| = S_{11}|_{after} - S_{11}|_{before}$) of the return loss from sample R2 to R4 are: 4.85, 7.15, 7.31, and 8.35 dB, respectively. With the post-annealing temperature of 200°C, when compared to the BR annealing at 400°C, it is too small to impact on the properties of BR. Thus, the post-annealing process may only effect on the sandwiched structure of resonator. In practically, as mentioned above, a sandwiched-structure of resonator Co/ZnO/Co always has several physical imperfections caused by the fabrication of device. Therefore, by applying the post-annealing process, we can eliminate any these possibly negative properties, eventually leading to improvements of FBAR device performances.

Area of electrode pattern is one of key factors that effects to the device performances. To investigate the effect of area of electrode pattern on the return loss characteristics, five different resonator layout pattern areas were designed and fabricated on BR N1, namely, pattern P2a, P2b, P2c, P2d, and P2e, respectively. Fig. 3 shows the extracted return loss values versus pattern areas. It seems that, when area of electrode pattern gradually decreased, the return loss values of this resonator increased. The resonator with pattern P2e area of 221600 μm^2 has S_{11} = -22.34 dB and resonator with pattern P2b area of 191.600μm^2 has S_{11} =-34.948 dB, but the resonator pattern P2a area of 181600μm^2 has return loss decreased S_{11} = -25.994 dB. Although further researches need to be carried out to achieve more clarity, we believe at this point that the FBAR device could be achieved good value if its pattern area was designed suitable.

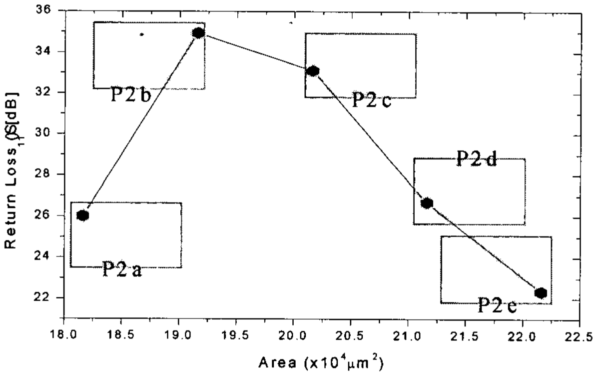

Fig. 3 Return losses versus various resonator pattern areas

The performance of the FBAR devices can be determined by the figure of merit (FOM) [17] in term of Q factor. Based on the empirical definition that uses the local extrema in the slop of the input impedance phase ($\angle Z_{in}$) [18], the series/parallel resonance frequencies ($f_{s/p}$) and the slop of $\angle Z_{in}$ versus frequency are obtained.

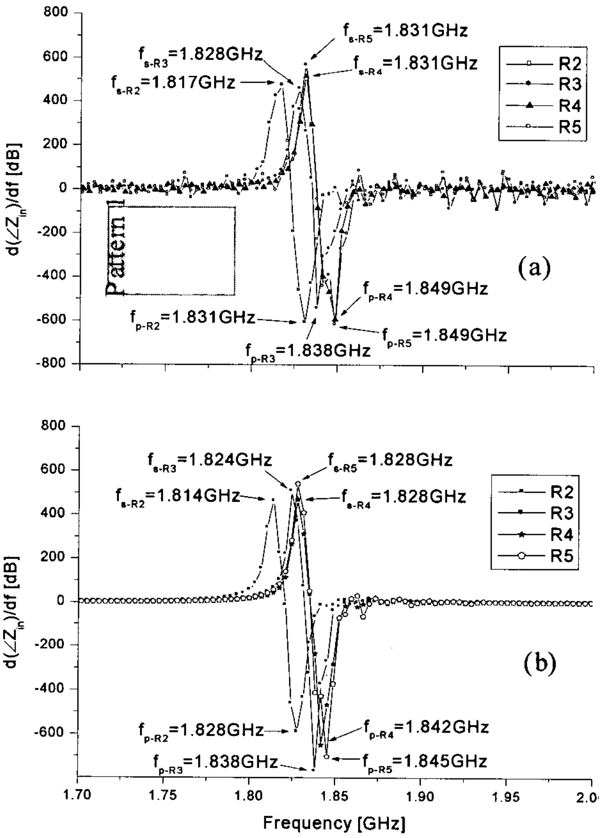

Fig. 4 Slop of input impedance phase ($\angle Z_{in}$) versus frequency for resonator pattern 1 with two cases:
(a) before post-annealing
(b) after post-annealing

Fig. 4 shows the slop of $\angle Z_{in}$ only for resonator pattern 1 before (fig. 4a) and after (fig. 4b) post-annealing process.

The series/parallel resonance frequencies ($f_{s/p}$) in fig. 4, with subscripts –R2, R3, R4, R5 indicate the successional thermal processes in our experiments.

The calculated series and parallel Q-factor values for FBAR resonators were tabulated in table 4. The resonators, which experienced the post-annealing process show larger Q-factors compared to those with before the post-annealed ones.

Table 4 Thermal effect on quality factors

State Sample	Before post-annealing		After post-annealing	
	Q_s	Q_p	Q_s	Q_p
R2	4018	4453	4219	4649
R3	4391	6919	4639	7053
R4	4719	5482	5073	5984
R5	5248	5693	6475	5956

IV. CONCLUSIONS

In this paper, the resonance characteristics of ZnO-based FBAR resonators were studied comprehensively for various thermal treatments. These thermal treatments are Bragg-reflector annealing process, inter-fabrication annealing process, and post-annealing process. The use of these thermal treatments could improve the return loss and quality factors of FBAR devices.

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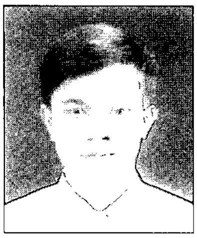

Linh Mai
Received B. S. degree from Natural Science, Hanoi University, Vietnam, in 1996. M.S. Degree in ITIMS, Hanoi, Vietnam, in 1998. From 1998 to summer 2001, he was a teacher of Posts and Telecommunications Institute of Technology, Vietnam. Since 2001 to now, he has been Ph.D. student in Communication and Electronics Lab, Information & Communications University (ICU), Taejon, Korea.

Hae-il Song
Received B. S. degree from Electronic engineering and education, Chungnam National University, Korea, in 2003. Since 2003 to now, he has been M. S. student in Communication and Electronics Lab, Information and Communications University (ICU), Taejon, Korea. The areas of interest are RF MEMS devices, FBAR filter and their design & applications.

Giwan Yoon
Received B.S. degree from Seoul National University (SNU) in 1983 and M.S. degree from The Korea Advanced Institute of Science and Technology (KAIST) in 1985, in Korea, and Ph.D. degree from The University of Texas (UT) at Austin, USA in 1994. From 1985 to 1990, he was an associate engineer in Semiconductor Research Center of LG group, Seoul, Korea. From 1994 to 1997, he was a senior engineer of Digital Equipment Corporation (DEC), USA. Since 1997, he has been a professor of Information & Communications University (ICU), Daejeon, Korea. Presently, he is an associate professor and his areas of interest are intelligent communication electronics and RF technology for wireless applications.