Resonance Characteristic Improvement of ZnO-Based FBAR Devices Fabricated on Thermally Annealed Bragg Reflectors

Mun-Hyuk Yim, Dong-Hyun Kim*, Linh Mai and **Giwan Yoon,** *Member, Kimics, *Nonmember*

Abstract—In this paper, we present the thermal annealing effects of the W/SiO_2 multi-layer reflectors in ZnO-based FBAR devices with cobalt (Co) electrodes in comparison with those with aluminum (Al) electrodes. Various thermal annealing conditions have been implemented on the W/SiO_2 multi-layer reflectors formed on p-type (100) silicon substrates. The resonance characteristics could be significantly improved due to the thermal annealing and were observed to depend strongly on the annealing conditions applied to the reflectors. Particularly, the FBAR devices with the W/SiO_2 multi-layer reflectors annealed at 400℃/30min have shown superior resonance characteristics in terms of return loss and quality-factor (Q-factor). In addition, the use of Co electrodes has resulted in further improvement of the resonance characteristics as compared with the Al electrodes. As a result, the combined use of both the thermal annealing and Co electrodes seems very useful to more effectively improve the resonance characteristics of the FBAR devices with the W/SiO_2 multi-layer reflectors.

Index Terms—FBAR, Bragg reflector, Thermal annealing, Cobalt electrode, Return loss, and Q-factor

I. INTRODUCTION

Recently, the rapid development of wireless communications has attracted a huge interest for the electronic devices for radio frequency (RF) and microwave applications. In particular, as the spectrum crowding rapidly increases, the devices and components of even higher performance and smaller size have been of great concern [1]. Currently, the ceramic duplexers and surface acoustic wave (SAW) filters are practical and commercial technologies to meet the rigorous requirements of the front-end RF filtering functions.

Unfortunately, these components have some disadvantages in their size, weight, performance, and applications for future personal communication systems [2]. On the other hand, the film bulk acoustic resonator (FBAR) or its technology has attracted a great attention as a promising technology to fabricate the next-generation RF filters. This is because the FBAR technology can be integrated with the current silicon process technology, enabling the current off-chip type of RF filters to be realized in the type of the microwave monolithic integrated circuits (MMICs) in a significantly miniaturized size [3,4]. Based on the thin-film techniques, the FBAR devices are categorized largely into three groups [5]. First one is a membrane structure supported by the edge of the substrate, second is a structure having an air gap under the resonator, and third is a SMR (solidly mounted resonator) with the quarter-wavelength reflector. The SMR has a Bragg reflector acting as a mirror to prevent a possible energy loss into the substrate from the resonating piezoelectric region. A high-quality Bragg reflector fabrication seems critical to improve the resonance characteristics in the SMR-type FBAR devices. Usually, the Bragg reflectors for the SMR-type FBAR devices have been fabricated by alternately depositing two different materials with high and low acoustic impedances, respectively [6]. Despite some efforts [7-9] that have been made to improve the FBAR characteristics, few comprehensive studies have been reported on the thermal annealing effects of the tungsten/silicon dioxide (W/SiO_2) Bragg reflectors in the FBAR devices. In addition, although the Al, Au, Pt, and Mo electrodes have been frequently used for FBAR devices [10,11], the use of Co electrode for FBAR devices has been rarely reported.

In this work, for the first time, we present the effects of the thermal annealing of the W/SiO_2 multi-layer Bragg reflectors on the resonance characteristics of ZnO-based FBAR devices particularly with Co electrodes in comparison with Al electrodes. In order to improve the resonance characteristics of the FBAR devices, various thermal annealing conditions were implemented on the multi-layered Bragg reflectors formed on silicon (Si) substrates by using a sputtering technique. As a result, the resonance characteristics can be significantly improved by the thermal annealing and are strongly affected by the annealing conditions applied to the Bragg reflectors. In particular, the FBAR devices with the Bragg reflectors annealed at 400℃/30min have shown excellent resonance characteristics in terms of the return loss and quality-factor (Q-factor). Moreover, the use of the Co electrodes could further improve the resonance characteristics of the FBAR devices as compared to the use of the Al electrodes. Based on these findings, the combined use of the Co electrode and thermal annealing will be highly promising for the SMR-type FBAR devices and their applications.

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II. EXPERIMENTAL

To investigate the effects of the thermal annealing of the W/SiO_2 Bragg reflectors in a more effective and reliable way, two top Al electrode patterns (namely, (a) pattern 1 and (b) pattern 2) and two top Co electrode patterns (namely, (a) pattern 1 and (c) pattern 3) were designed and also used as the (d) signal and ground electrodes layered at the top of the FBAR device, as shown in Fig. 1 The various FBAR devices are consisted of the ZnO piezoelectric film sandwiched between the top and bottom electrodes on the W/SiO_2 Bragg reflectors formed on a silicon (Si) substrate, as shown in Fig. 1 (d).

From the fabrication point of view, a 4-inch p-type (100) Si wafer with 0.6μm the silicon dioxide (SiO_2) layer was used as a starting material (as a substrate) on which a four-layer Bragg reflector was formed by alternately depositing the SiO_2 and tungsten (W) using a sputtering technique at the room temperature where each layer thickness of SiO_2 and W is 0.6μm and 0.55μm, respectively. Immediately after the Bragg reflector formation, the wafer with the Bragg reflector was divided into four samples for the thermal annealing of the samples at different annealing conditions. Three samples were performed in a furnace at 200℃/30min, 400℃/30min, and 600℃/30min, respectively while keeping one sample non-annealed (as deposited). Then, the 0.13μm thick Co bottom electrodes (acting as floating grounds) were simultaneously deposited on all samples, followed by the 1.5μm thick ZnO films deposition on the bottom Co electrodes while the substrates were rotating at 6 rpm for more uniform film deposition while the distance of the substrate and the target set to be 6.5 cm. The deposition conditions of the ZnO films were RF power of 320W, deposition pressure of 10 mtorr, and O_2 concentration of 25%. The ZnO target used for deposition has a diameter of 4-inch, a thickness of 1/8-inch, and a purity of 99.999%. The base pressure of the deposition chamber was kept to be less than 2.0×10-6 torr using turbo-molecular pump to remove any possibly existing particles and impurities in the chamber, followed by the injection of high purity gases into the chamber. Finally, the patterning for top Co electrodes formation was defined on the ZnO films by the conventional photolithography technique using AZ1512 photoresist (PR) and pattern masks. Then, the Co films were deposited on the patterned PR layer, followed by the so-called lift-off processing to strip off the remaining PR layers. The top Co electrodes patterning completed the fabrication of the FBAR devices. The fabricated FBAR devices were measured to extract the resonance characteristics for the evaluation of the thermal annealing effects of the FBAR devices in three thermally annealed samples and one non-annealed (as-deposited) sample. In the same way, the FBAR devices with Al electrodes were also fabricated.

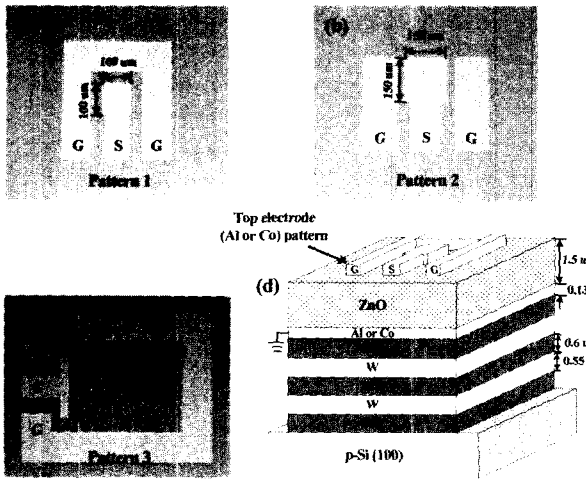

Fig. 1 Three kinds of resonator top-view patterns ((a) pattern 1, (b) pattern 2, and (c) pattern 3) of the FBAR devices, and (d) a 3-dimensional schematic of the one-port FBAR device with the pattern 1.

III. RESULTS AND DISCUSSION

The fabricated FBAR devices were divided into four groups as follows; the non-annealed group as A-type sample, the annealed group at 200℃/30min as B-type sample, the annealed group at 400℃/30min as C-type sample, and the annealed group at 600℃/30min as D-type sample. The return loss (S_{11}) values were extracted from the two top electrode patterns (pattern 1 and pattern 2) with Al electrodes and two (pattern 1 and pattern 3) with Co electrodes on each of the 4 samples (A-type, B-type, C-type, and D-type). The resonance areas of the three resonator patterns in the fabricated FBAR devices are (a) 21,200μm^2, (b) 37,500μm^2, and (c) 23,500μm^2, respectively, as shown in Fig. 1 HP 8722ES S-parameter Network Analyzer and KarlSuss KSM PM5 probe station were used to measure the S-parameter for each one-port resonator. Prior to the S-parameter extraction, the RF probing system has been precisely calibrated using the calibration kits. The RF signals were applied to the top electrodes with signal and ground contacted using G-S-G probe tip, as shown in Fig. 1 (d).

Fig. 2 shows the S_{11} characteristics of the one-port FBAR devices with Al electrodes (Al-FBARs) as a function of the frequency for various annealing conditions. Fig. 2 (a) and (b) indicate the return loss characteristics of the Al-FBARs with the resonator pattern 1 and pattern 2, respectively, fabricated on the non-annealed, 200℃/30min-annealed, 400℃/30min- annealed, and 600℃/30min-annealed Bragg reflectors. In particular, the significant improvements of the return loss characteristics were observed at 400℃/30min annealing compared with other annealing conditions, although the return loss characteristics are slightly dependent on resonator patterns, probably due to a difference in the resonance area and pattern shape of each resonator. Fig. 3 (a) and (b) illustrate the S_{11} characteristics of the one-port FBAR devices with Co electrodes (Co-FBARs) of the resonator pattern 1 and pattern 3, respectively. Similarly with the Al-FBARs, the significant improvements of the return loss characteristics were observed at 400℃/30min annealing.

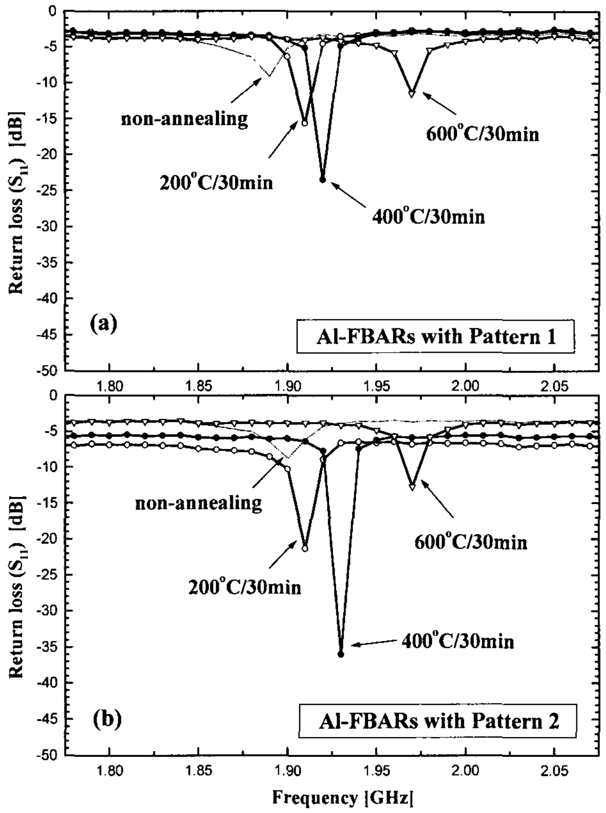

Fig. 2 Return loss characteristics of the Al-FBARs with the (a) pattern 1 and (b) pattern 2 as a function of the frequency for various annealing conditions.

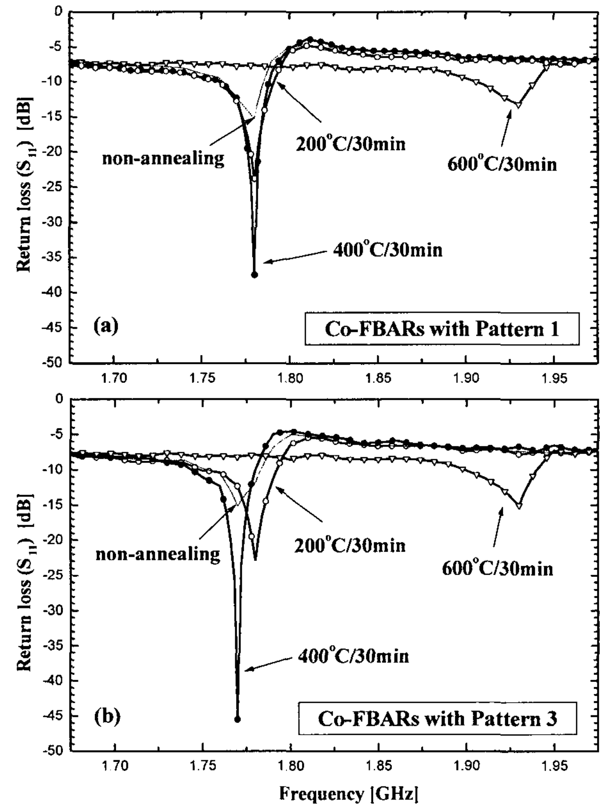

Fig. 3 Return loss characteristics of the Co-FBARs with the (a) pattern 1 and (b) pattern 3 as a function of the frequency for various annealing conditions.

Two phenomena can be observed from Fig. 2 and Fig. 3. Firstly, compared with Al-FBARs, the return loss characteristics are more improved in Co-FBARs. This can be confirmed further from the cross sectional scanning electron microscopy (SEM) images of the ZnO films deposited on (a) Al electrodes and (b) Co electrodes, and the (c) x-ray diffractometer (XRD) θ-2θ scan results and (d) rocking curves of the ZnO films deposited on Al and Co electrodes, as shown in Fig. 4. These indicate that the ZnO film deposited on Co electrode (ZnO/Co) is shown to have more highly preferred orientation towards c-axis than that deposited on Al electrode (ZnO/Al). As seen in XRD θ-2θ scan results, the only (002) peaks of the ZnO films were observed in displayed 2θ scope, and the ZnO/Co film have much larger intensity than that of the ZnO/Al flim. The existence of the larger intensity of the (002) peak indicates that the ZnO/Co film more strongly orients towards the c-axis perpendicular to the surface of the substrate compared with ZnO/Al flim. Also, the rocking curve of the ZnO/Co film follows the Gaussian distribution. But the rocking curve of the ZnO/Al film deviates from Gaussian distribution, thus indicating much less preferred c-axis orientation growth.

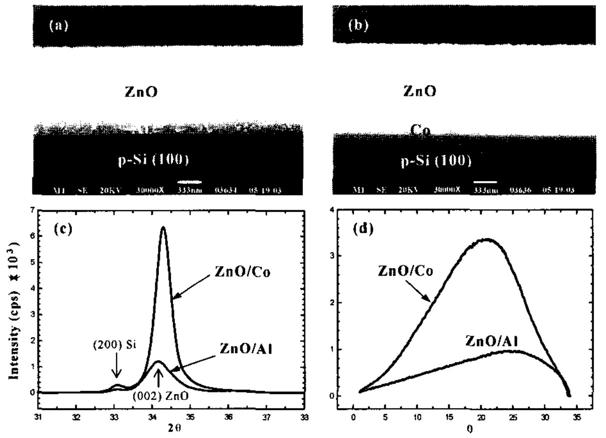

Fig. 4 Cross-sectional SEM images of the ZnO films deposited on (a) Al electrodes and (b) Co electrodes, and comparisons of the (c) XRD θ-2θ scan results and (d) rocking curves of the ZnO films deposited on Al and Co electrodes.

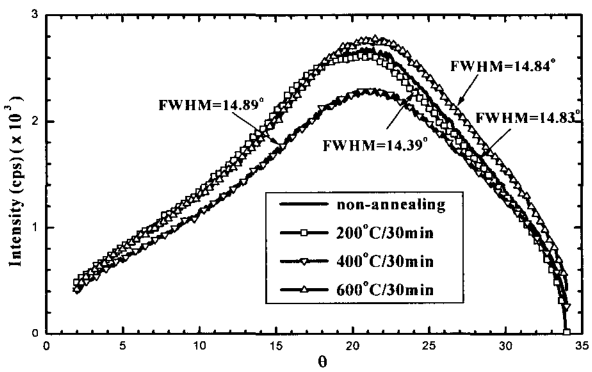

Fig. 5 FWHM values of the rocking curves of the ZnO films deposited on Co electrodes on BRs annealed at various conditions.

The second phenomenon is that the resonance characteristics can be significantly improved due to the thermal annealing and are strongly affected by the annealing conditions applied to the Bragg reflectors. This can be confirmed from the full width at half maximum (FWHM) values of the rocking curves of the ZnO films deposited on Co electrodes on Bragg reflectors annealed at various conditions, as shown in Fig. 5.

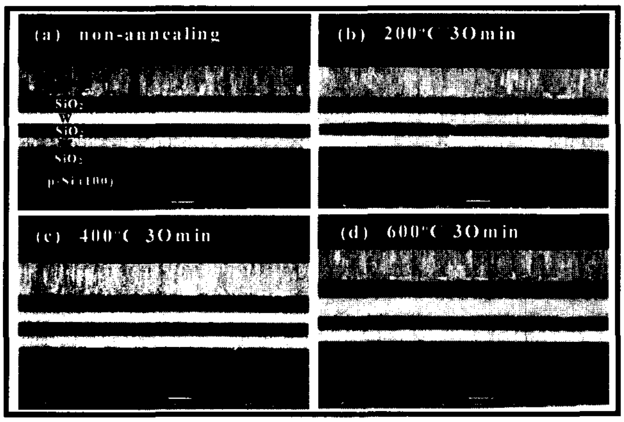

Fig. 6 Cross-sectional SEM images of the fabricated Co-FBARs with the (a) non-annealed, (b) 200℃/30min-annealed, (c) 400℃/30min-annealed, and (d) 600℃/30min-annealed Bragg reflectors.

The FWHM values are approximately equal to 14.39~14.89°, indicating that the fabricated FBAR devices have the ZnO films of a similar performance. Two critical factors that determine the ZnO-based FBAR characteristics are the performance of Bragg reflector and the piezoelectric property of the ZnO film. Consequently, the improvement of the resonance characteristics in FBAR devices seems to be due to a possible improvement of the Bragg reflector performance according to the thermal annealing conditions. Thus, the quality of the Bragg reflectors appears to have a considerable impact on the FBAR characteristics. It is speculated that prior to the thermal annealing, the non-annealed W/SiO_2 multi-layer Bragg reflectors may have some physical imperfections in the film microstructures and/or some imperfect adhesions at interfaces between the films physically deposited at the room temperature, degrading the device performance. At this point, we believe that the thermal annealing of W/SiO_2 reflectors in FBAR devices may eliminate any possibly existing imperfect microstructures and incomplete adhesions in the multi-layer reflectors, eventually leading to the improvements of the resonance characteristics. But the annealing at 200℃/30min and 600℃/30min show much smaller return loss values as compared to the annealing at 400℃/30min. In particularly, the annealing at 600℃/30min shows higher resonance frequency compared with any other annealing cases. For more clarity of these findings, Fig. 6 show the cross-sectional SEM images of the fabricated Co-FBARs with the (a) non-annealed, (b) 200℃/30min-annealed, (c) 400℃/30min-annealed, and (d) 600℃/30min-annealed Bragg reflectors. The annealing at 200℃/30min may not be enough to eliminate the harmful factors. Whereas, the annealing at 600℃/30min appears to be an excessively severe annealing condition from the fact that the upper W layer in the Bragg reflector has grown conspicuously thicker than others. It seems that the thickness of the upper W layer increases due to the inter-diffusion between W and SiO_2, and its oxidation during the annealing at a relatively high temperature of 600℃. This explanation can be more clarified by comparing the SEM images of the several Bragg reflectors annealed at various conditions, as shown in Fig. 7 The SEM images of the Bragg reflectors annealed for different annealing times (30, 60, 120min) at the same temperature (400℃) are compared in Fig. 7 (a). Among the SEM images, no significant differences in the film thickness and morphology are observed, indicating that 400℃ is an appropriate annealing temperature at which no severe oxidation of the upper W layers occurs even for somewhat long anneal time (120min). On the other hand, Fig. 7 (b) compares the SEM images of the Bragg reflectors annealed at different temperatures for the same annealing time (30min). It is clear in this figure that the thickness of the upper W layer increases with the increase of the annealing temperature, indicating that a relatively severe oxidation occurs at the high temperature such as 500℃ or 600℃.

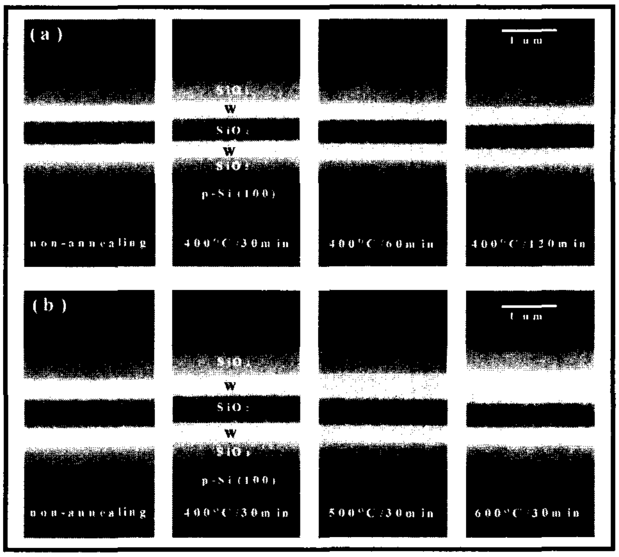

Fig. 7 Comparisons of cross-sectional SEM images of the Bragg reflectors annealed (a) for different annealing times at the same temperature (400℃) and (b) at different temperatures for the same annealing time (30min).

Based on these findings, we believe that the poor resonance characteristics as well as the significant shifts in the resonance frequency, observed in the FBAR devices with the reflector layers annealed at 600℃ /30min, may be attributed to the thickening of the upper W layer, mainly due to its oxidation during annealing. The oxidized upper W layer is believed to lose its intrinsic material property of high impedance, eventually transforming into a relatively low impedance material.

This in turn leads to an ineffective Bragg reflector with a poor acoustic isolation, resulting in inferior resonance characteristics. This result emphasizes the importance of the optimum annealing temperature or condition to more effectively improve the resonance characteristics of the FBAR devices. Here, the optimum annealing condition may be considered to be 400℃.

On the other hand, the performance of the FBAR devices can be calculated by the figure of merit (FOM) in terms of Q-factor, a measure for the resonator loss in series and parallel resonance values [9].

$$Q_{s/p} = \frac{f_{s/p}}{2}\left|\frac{d\angle Z_{in}}{df}\right|_{f=f_{s/p}} \tag{1}$$

According to the empirical definition that uses the local extrema in the slope of the input impedance phase ($\angle Z_{in}$) [3], the series and parallel resonance frequencies (f_s and f_p) and the slope of $\angle Z_{in}$ as a function of the frequency are obtained. Fig. 8 represents the slope of $\angle Z_{in}$ as a function of the frequency, only plotted for the resonator pattern 1 and pattern 3 of the FBAR devices with both Co electrodes and the Bragg reflectors annealed only at 400℃/30min. For comparison, the series and parallel Q-factor values (Q_s and Q_p) from the above formula (1) are extracted and plotted as a function of the annealing temperature for the Al-FBARs and Co-FBARs, as shown in Fig. 9. Q-factor values were observed to improve by using the Co electrodes instead of Al electrodes. Moreover, the FBAR devices with the Bragg reflectors annealed at 400℃/30min show the largest Q-factors. Thus, the resonance characteristics of the FBAR devices can be significantly improved due to the thermal annealing step and are observed to strongly depend on the annealing conditions applied to the Bragg reflectors.

As a result, the use of both the Co electrodes and thermal annealing seems very useful to more effectively improve the resonance characteristics of the FBAR devices with the W/SiO_2 multi-layer Bragg reflectors.

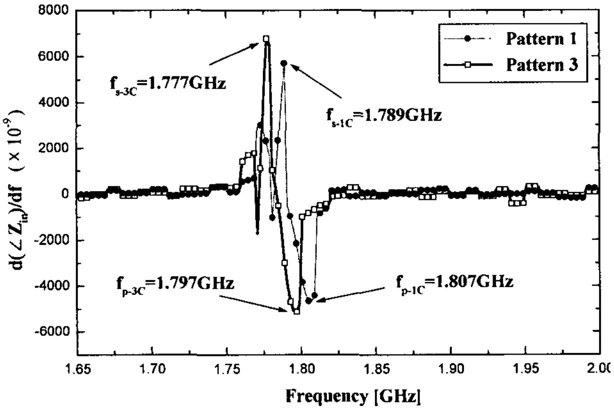

Fig. 8 Slope of $\angle Z_{in}$ as a function of the frequency for the resonator pattern 1 and pattern 3 annealed at 400℃/30min for the Co-FBARs.

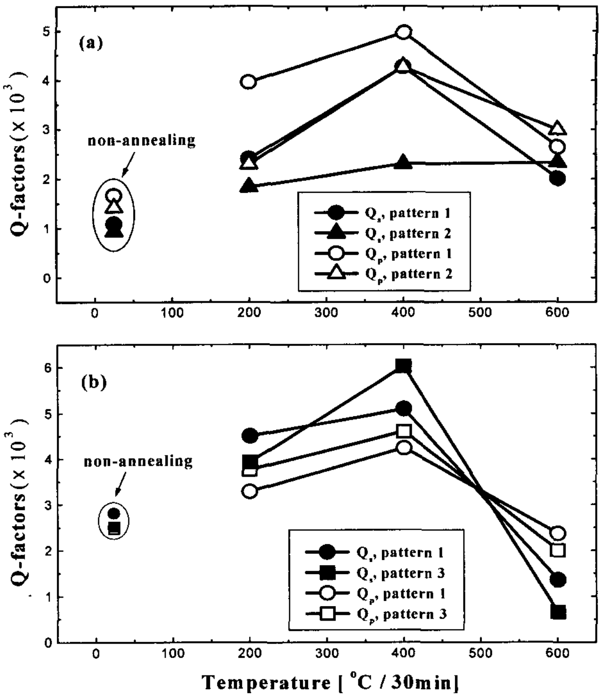

Fig. 9 Comparisons of the series and parallel Q-factors (Q_s and Q_p) plotted as a function of the annealing temperature for the (a) Al-FBARs and (b) Co-FBARs.

IV. CONCLUSIONS

In this work, the effects of the thermal annealing of the Bragg reflectors on the resonance characteristics of the FBAR devices particularly with Co electrodes were investigated and compared with those with Al electrodes.

The significant improvement of the resonance characteristics was observed at 400℃/30min annealing when compared with other annealing conditions in terms of the return loss and Q-factor, indicating that an optimum thermal annealing can conspicuously improve the resonance characteristics. In addition, the resonance characteristics could be further improved by using Co electrodes, instead of using Al electrodes for FBAR devices. The combined use of both the thermal annealing and Co electrodes seems very useful to more effectively improve the resonance characteristics of the FBAR devices with the W/SiO_2 multi-layer reflectors.

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