Fabrication Techniques and Their Resonance Characteristics of FBAR Devices

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ABSTRACT

Film bulk acoustic wave resonator (FBAR) technology has attracted a great attention as a promising technology to fabricate the next-generation RF filters mainly because the FBAR technology can be integrated with current Si processing. The RF filters are basically composed of several FBAR devices connected in parallel and in series, and their characteristics depend highly on the FBAR device characteristics. Thus, it is important to design high quality FBAR devices by device or process optimization. This kind of effort may enhance the FBAR device characteristics, eventually leading to FBAR filters of high performance. In this paper, we describe the methods to more effectively improve the resonance characteristics of the FBAR devices.

Keywords

FBAR, RF filter, resonance characteristics, quality factor

I. Introduction

Recently, a considerable technology progress in microelectronics has enabled most of RF components to be highly integrated in a one-chip or a transceiver. Unfortunately, the RF filters have been used as a single off-chip component for wireless mobile systems. This is because the conventional RF filters can hardly be integrated with current Si-based CMOS process technologies [1-4]. From this point of view, the film bulk acoustic wave resonator (FBAR) devices and their technologies are likely to be a promising candidate to resolve the above issue mainly because the materials and fabrication process of the FBAR device are very compatible with the current Si-based CMOS processing, opening the door for an fully integrated radio solution that include both active elements and filters within the same semiconductor package or eventually on the same chip. Moreover, the FBAR devices have excellent characteristics such as high Q-factor, very small size, good power handling characteristic, low insertion loss, good ESD robustness, and light weight as compared to ceramic or SAW devices. In addition, the FBAR devices can be used for a variety of applications such as RF/IF filters, duplexers, voltage-controlled oscillators [5-8]. General acoustic wave devices based on piezoelectric materials have been in commercial use for over 60 years [9]. FBAR is one of the acoustic wave devices in which an acoustic wave propagating through a piezoelectric film sandwiched between top and bottom electrodes generates the resonance and its dimension is determined by the acoustic wavelength. On the other hand, the ceramic resonators employ an electromagnetic wave and its size is also determined by the electromagnetic wavelength. Recalling the relationship (frequency x wavelength = speed), it will be clear that the acoustic phase velocity of many materials is approximately 3 to 4 orders-of-magnitude less than the electromagnetic phase velocity for a given frequency of resonance. Consequently, the dimensions for an acoustic wave device at a given frequency can be several orders of magnitude smaller than those for an electromagnetic wave device, enabling acoustic wave devices to fit easily for a small semiconductor chip. SAW devices, also one of acoustic wave devices, share this advantage over ceramic resonators. Thus, the FBAR device has very small size, higher device performance, and stronger potential for realization of MMIC or one-chip than any other technology [10,11].

II. Device Fabrication

As shown in Fig. 1, the thin film layers for the FBAR devices were deposited in an RF/DC magnetron sputtering system where four different materials (ZnO, SiO_2, W, and Co) were deposited. Besides, an electric dehydrate furnace was used to investigate the effects of various annealing methods on the FBAR characteristics. The acoustic Bragg reflector having SiO_2/W multilayers was formed by the thin-film deposition method on 4-inch silicon wafers. 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. In order to further improve the resonance characteristics of the FBAR devices, a thermal annealing process was additionally employed for the W/SiO_2 multi-layered Bragg reflectors immediately after they were deposited on a silicon substrate using an RF sputtering technique. As a result, the resonance characteristics of the FBAR devices were observed to strongly depend on the annealing conditions applied to the Bragg reflectors. In addition, the FBAR devices with the Bragg reflectors annealed at 400℃/30 min have shown excellent resonance characteristics in terms of return loss and Q-factor. Based on these findings, the optimum thermal annealing condition seems to be around 400℃/30 min and this approach seems very useful for improving the resonance characteristics of SMR-type FBAR devices with the multi-layer Bragg reflectors. Finally, 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. We fabricated the two devices, which are Al-FBAR and Co-FBAR devices for comparing their resonance characteristics. Compared with Al-FBAR devices, the resonance characteristics are more improved in Co-FBAR devices, indicating that the ZnO/Co has highly preferred orientation towards c-axis as compared to the ZnO/Al. Consequently, the resonance characteristics can be further improved by using Co electrodes, instead of using Al electrodes. The combination of both 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.

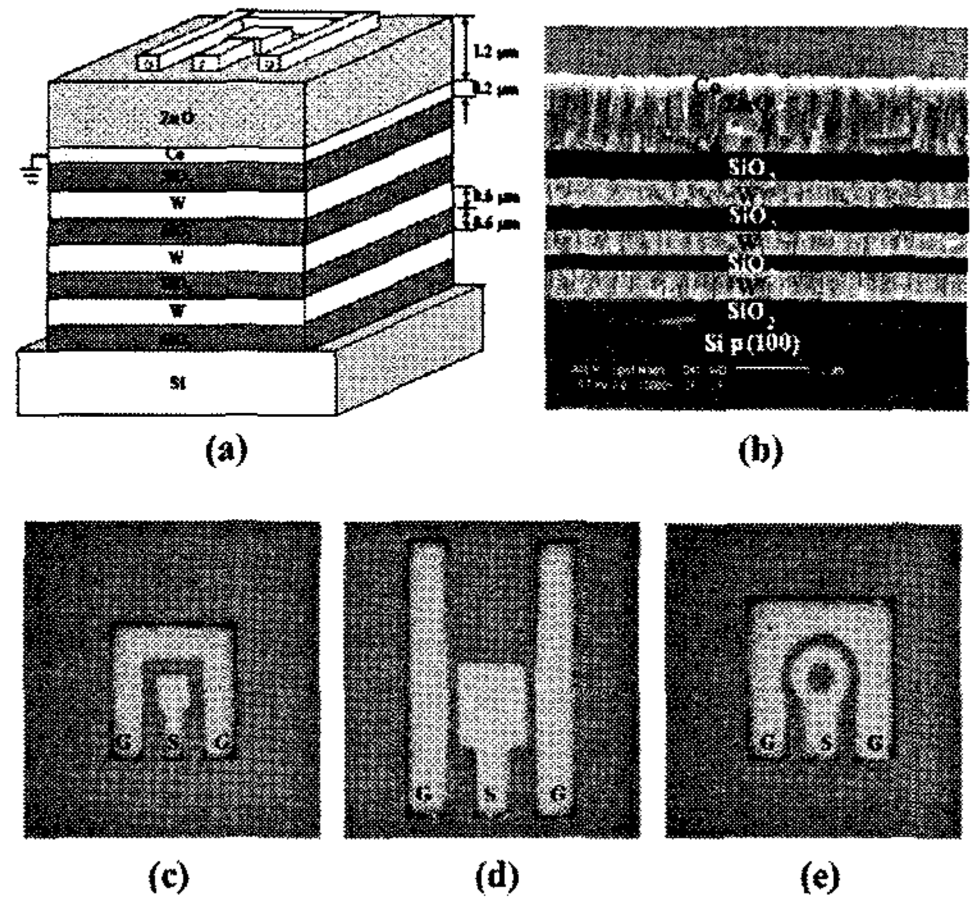

Fig. 1 (a) three-dimensional schematic, (b) cross section SEM picture, and three kinds of top-view patterns [(c) pattern 1, (d) pattern 2, and (e) pattern 3] of FBAR devices

III. Resonance Characteristics

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 1. The resonance characteristics of the three samples annealed by Bragg reflector annealing, post-annealing, and two-step annealing were compared with the non-annealed sample. First, the 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 sample D were around 10.37, 11.614, 12.81 dB increased by proposed two-step annealing. Therefore, the addition of the post-annealing of 200℃/2 hours on the sample D that is already annealed by Bragg reflector-annealing at 400℃/30min might

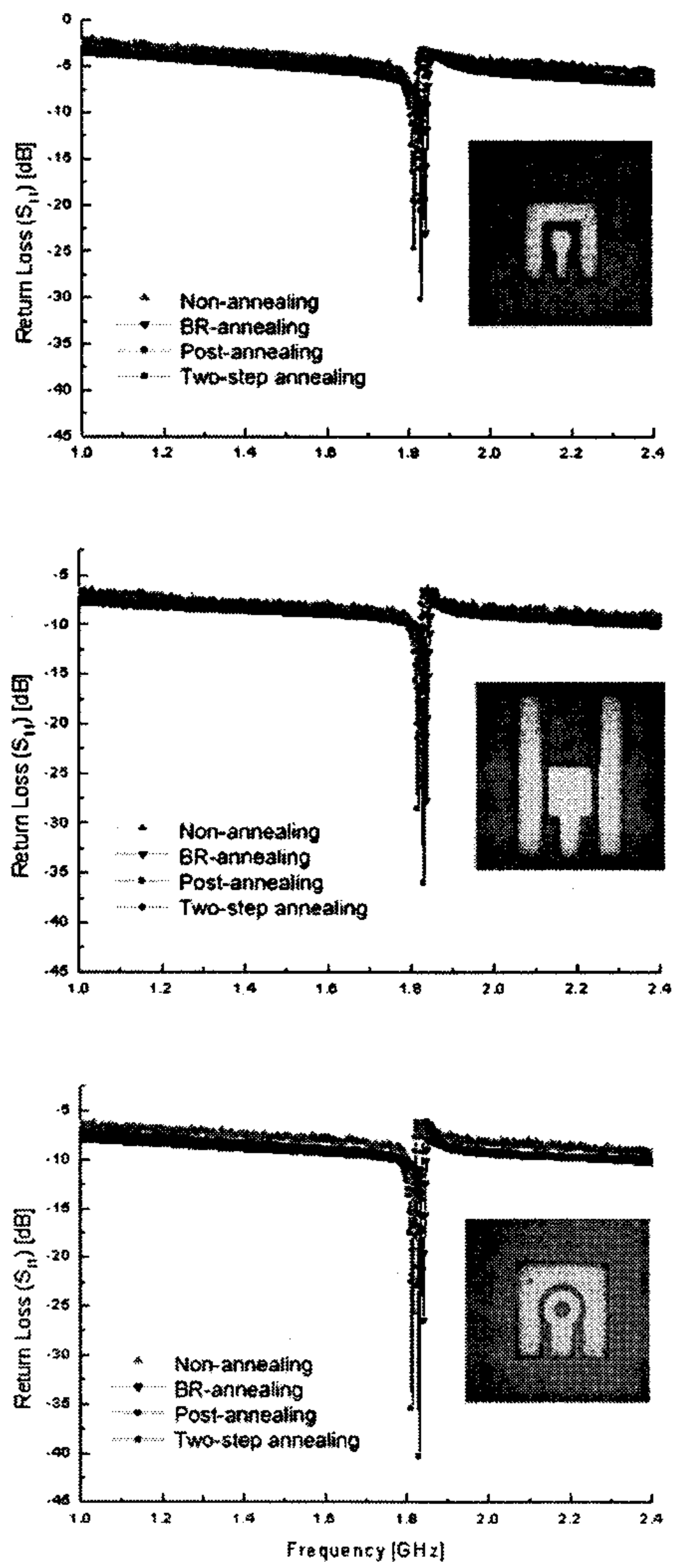

Fig. 2 Return loss S_{11} measurement results against frequency for three different top electrode patterns.

further eliminate any imperfect microstructures and incomplete adhesions in FBAR devices without any significant degradation in the acoustic Bragg reflector.

To estimate the resonator performance, effective electromechanical coupling coefficient and series/parallel quality factors are used as figure of merits (FOMs).

$$K_{eff}^2 = \left(\frac{\pi}{2}\right)^2 \frac{f_p - f_s}{f_p}$$

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

where f_S and f_P are series and parallel resonance frequencies and the $\angle Z_{in}$ is the slope of the input impedance phase. Fig. 3 shows that the slop of $\angle Z_{in}$ as a function of the frequency with the pattern 1 in Fig. 2 and the calculated effective electromechanical coupling coefficient K_{eff2} and series and parallel quality factor $Q_{S/P}$ values for FBAR devices with pattern 1 are tabulated in Table 2.

K_{eff}^2 and $Q_{S/P}$ of the RBAR resonators annealed by Bragg reflector-annealing and post-annealing methods were improved. Moreover, much more improvement could be obtained by the proposed two-step annealing 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 FBAR devices in a cost-effective way. The resonance characteristics of the FBAR devices were investigated and compared for various annealing methods (Bragg reflector-annealing, post-annealing, and two-step annealing). As a result, return loss S_{11}, series and parallel quality factor $Q_{S/P}$, and effective electromechanical coupling coefficient K_{eff}^2 of the FBAR devices could be significantly improved by two-step annealing method.

Table 1. Summarized return loss measurement results for three different patterns.

Sample Name	Return loss		
	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

Table 2. Calculated series and parallel quality factors and electromechanical coupling coefficients for FBAR devices with pattern 1.

Sample Name	Quality factor		Effective electromechanical coupling coefficient
	Q_s	Q_P	K_{eff}^2
Sample A	5266	5992	1.48%
Sample B	5337	6046	1.86%
Sample C	5775	7314	1.89%
Sample D	8391	7482	2.01%

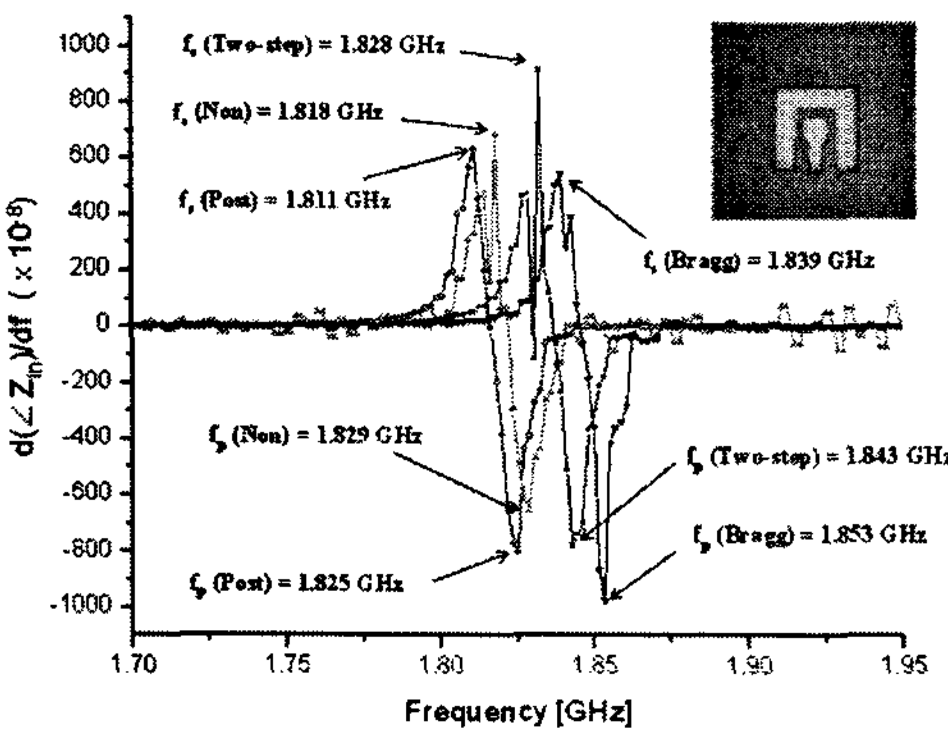

Fig. 3 Four slops of $\angle Z_{in}$ as a function of the frequency for different annealing conditions (FBAR devices with the pattern 1).

IV. Conclusion

In this paper, we present the methods to more effectively improve the resonance characteristics of the FBAR devices. We also demonstrate that the resonance characteristics of FBAR devices can be further enhanced by the optimization of the fabrication processing.

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