2.5 GHz ZnO-based FBAR Devices and Their Thermal Improvements

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ABSTRACT

In this paper, we study ZnO-based a film bulk acoustic resonator (FBAR) using a multi-layered Bragg reflector. We insert chromium adhesion layers of 0.03 mm-thick to the Bragg reflector and improve the performance using thermal treatments. At operating frequency about 2.5 GHz, excellent resonance characteristics are observed in terms of good return loss and high quality factor.

Keyword

Bragg reflector, FBAR, post-annealing, Q-factor, resonator, return loss

Ⅰ. Introduction

Recent technological innovations have shown a great promise for mobile broadband users. The WiMAX broadband wireless access technology, based on the IEEE 802.16 standard, is at the origin of great promises for many different markets covering fixed wireless internet access, backhauling and mobile cellular networks. Currently, the 2.3-3.6 GHz band assignment for WiMAX is considered as one of the best choices for the transmission of multimedia services (voice, Internet, email, games and others) at high data rates [1]. Therefore, new bandpass filters may be required that are smaller, consume less power, have lower insertion loss and operate at higher frequencies. The thin film bulk acoustic wave resonator (FBAR) technology has the capabilities needed to achieve these requirements simultaneously. The FBAR devices, one of resonant piezoelectric devices, have been well-known for resonating in a few GHz frequency regimes. Typical FBAR comprises a piezoelectric film sandwiched between top and bottom electrodes. When RF signal is applied across the device, it produces a resonance [2]. Based on the thin film techniques, FBAR devices are classified into three groups [3]. The first is membrane structure back-etched type supported by the edge of the substrate, the second one is an air-gap type having an air gap under the resonator, and the last is a solidly mounted resonator (SMR)-type with a Bragg reflector. In SMR-type, the Bragg reflector can act as a mirror to isolate a possible energy loss from piezoelectric layer into the substrate, enabling the FBAR device to have high quality factor (Q). A high quality Bragg reflector fabrication will be critical to yield high-Q devices. Bragg reflectors for conventional SMR-type FBAR devices have been fabricated by alternately depositing both high and low impedance materials. Even though some studies [4]-[8] have been done to improve the FBAR characteristics, few have been reported on the methods to improve the quality of the tungsten/silicon dioxide (W/SiO_2) multi-layered Bragg reflectors, and also to the best of our knowledge, no studies have been reported on the effects of the thermal annealing on there sonator performances at~2.7GHz regime.

In this paper, the ZnO-based FBAR devices were fabricated on a specially designed Bragg reflector formed by inserting very thin Cr adhesion layers between tungsten and silicon dioxide (W/SiO_2). In addition, various thermal treatments were performed to further improve the characteristics of the FBAR devices and their effects on the device characteristics were also investigated. At the operating frequency of about 2.7 GHz, excellent device characteristics were observed in terms of return loss and Q-factors.

Ⅱ. Design and Experiment

Fig. 1 shows the schematic structure of a ZnO-based FBAR device in the SEM cross-sectional image and two top electrode patterns. The device consists of a multi-layered BR on Si substrate and a piezoelectric (ZnO) film positioned between the top and bottom Al electrodes. The bottom electrode was also designed to act as a floating ground plane with the thickness of 1.0 μm. The FBAR devices were fabricated on a 4-inch, p-type Si wafer as follows. First, a multi-layered Bragg reflector was prepared by sequentially depositing several thin film layers of SiO_2, Cr, W, SiO_2, Cr, W, and SiO_2. Those SiO_2 layers (0.6 μm-thick) were deposited by a chemical vapor deposition (CVD) technique. The Cr (0.03 μm-thick) and W (0.6μm-thick) layers were deposited using sputtering technique. Then, the 1.0 μm-thick Al bottom electrode was formed by depositing on the Si wafer, followed by 1.2 μm-thick ZnO film deposition using a sputtering system. Subsequently, the Si wafer was divided into seven samples (S1 to S7). In order to investigate the thermal treatment effects, six samples (named S2 to S7) were thermally treated under various annealing conditions, whereas sample S1 was not thermally treated in order to use it as a reference sample. Immediately after the ZnO film deposition, the first thermal annealing (called inter-fabrication annealing) was carried out for six samples (S2 to S7), all at 200°C for 120 minutes in argon (Ar) gas ambient of an electric dehydrate furnace (EDF) equipment. Then, the deposition and patterning of the top Al electrodes (0.2 μm-thick) on top of the ZnO film completed the FBAR device fabrication. Finally, the seven FBAR device samples (S1 to S7) were obtained. Next, the second annealing (named post-annealing) was done for five samples S3 to S7 in the EDF equipment at 220, 250, 260, 280, and 300°C for 120 minutes, respectively. Here, two different resonator layout patterns 1 and 2 (with areas of 37500 and 40000 μm^2, respectively) were designed for second order resonance at about 2.5 GHz. The return loss(S_{11}) characteristics were extracted from all the fabricated resonators by using a probe station and Hewlett Packard 8722D network analyzer.

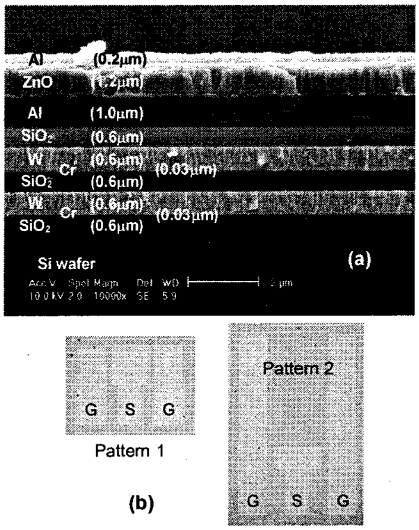

Fig. 1. (a) Cross-sectional SEM image of ZnO-based FBAR device. (b) Two resonator patterns 1 and 2.

Ⅲ. Results and Discussion

Fig. 2(a) and (b) illustrate two resonator patterns 1 and 2 with their measured return loss characteristics at resonance frequency around 2.7 GHz for various thermal annealing conditions, respectively. The S_{11} values of the three post-annealed resonators fabricated on S3 to S5 samples show the same increasing trend in comparison to S_{11} of resonators on S1 and S2 up to 260°C annealing temperature. But at higher temperatures ($\geq$280°C), S_{11} values of resonators on S6 and S7 samples were quickly dropped. Clearly, there is an optimum thermal annealing temperature range (250-260°C/120 minutes) for the enhancement of S_{11} values of the devices. At the optimum annealing condition, S_{11} values were -50.61 dB (at 250ºC) and -51.69 dB (at 260ºC) for the resonator pattern 1 (Fig.2(a)) and 2 (Fig.2(b)), respectively. All the extracted S_{11} values were summarized in Table I.

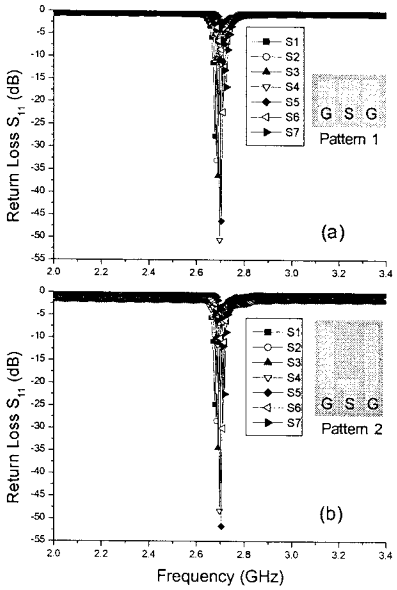

Fig. 2. Return loss characteristics versus frequency for various thermal processes: (a) Pattern 1, (b) Pattern 2.

Table I: Return loss values of electrode patterns

Sample	Return loss S_{11}(dB) Pattern 1	Return loss S_{11}(dB) Pattern 2
S1 (non-annealing)	-27.56	-24.76
S2 (inter-fabrication annealing 200ºC)	-33.00	-28.41
S3 (post-annealing 220ºC)	-36.30	-34.39
S4 (post-annealing 250ºC)	-50.61	-48.30
S5 (post-annealing 260ºC)	-46.43	-51.69
S6 (post-annealing 280ºC)	-22.39	-30.05
S7 (post-annealing 300ºC)	-16.91	-22.45

Fig. 3 shows the measured S_{11} values at resonance frequency of all fabricated resonators. By the inter-fabrication annealing process, the quality of piezoelectric ZnO layer in the FBAR can be enhanced in several aspects such as: grain size, preferred c-axis, and interfacial adhesions between layers of ZnO and Al, thereby enabling lot S2 resonators to have better S_{11}-characteristics than lot S1 resonators. Besides, the proper post-annealing process affects the sandwiched structure of resonator (Al/ZnO/Al); therefore, any possible existing physical imperfections in the film microstructures and some poor adhesions at interfaces between the ZnO layer and the Al layer can be eliminated or reduced, leading to the improved performance of FBAR device.

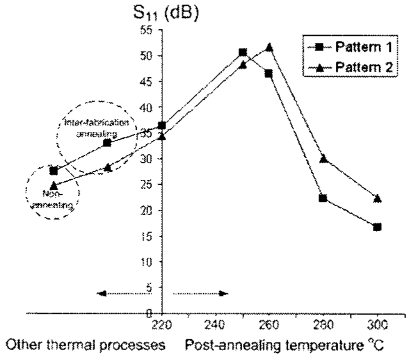

Fig. 3: Comparison of measured S_{11} values at resonance frequency for all fabricated resonators.

Reportedly, the quality of the multi-layered Bragg reflector may have an impact on the FBAR characteristics [4], [5]. In the as-deposited SiO_2/W Bragg reflector, some physical defects may exist and/or some poor adhesions may occur at interfaces between the physically deposited films, hence degrading the device performances. The adhesion issues here can be resolved by inserting very thin adhesion layers between W and SiO_2 layers in the reflector. The inserted layers were additionally deposited films to enhance the adhesion property between W and SiO_2 layers, and they were observed to have no deleterious effects on the Bragg reflectors tructuresor properties. In this work, the Cr adhesion layer is considered a reasonably good choice for the improvement of the adhesion between the W layer and SiO_2 layer, sputter-deposited. The Cr layer was deposited not only due to its good bond-forming abilities, but also due to its having the same crystal structure as W material of the body-centered cubic (bcc) structure. Thus the additionally inserted Cr layer with very thin films (0.03 μm-thick) is expected to considerably improve the multi-layered Bragg reflector quality.

The figure of merit (FOM) of FBAR devices can be demonstrated by the Q-factor [9]. Based on the definition reported elsewhere [10], the series/parallel resonance Q-factors ($Q_{s/p}$) were calculated as follows:

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

According to (1) that uses the local extrema in the slope of the input impedance phase ($\angle Z_{in}$) as a function of the frequency for the resonator pattern 1 and 2, the series and parallel frequencies (f_s and f_p) and the slope of $\angle Z_{in}$ as a function of the frequency are obtained. As a result, the values of FOM of the FBAR devices were achieved and shown in Table II.

Table II: $Q_{s/p}$-factors for the resonator samples

Sample	Pattern 1		Pattern 2	
	Q_s	Q_p	Q_s	Q_p
S1	6049	5848	5980	5724
S2	6889	6152	6129	5876
S3	7322	6258	6328	6186
S4	8214	6745	7945	6347
S5	8036	6581	8119	6325
S6	7362	6176	7082	6142
S7	6925	6072	7120	6247

Ⅳ. Conclusion

In this paper, we present the FBAR devices fabricated on top of the novel SiO_2/Cr/W multilayer Bragg reflector. Their resonance characteristics were investigated for various post-annealing treatments. With a process optimization, excellent return loss and Q-factors were achieved at the resonance frequency of about 2.5 GHz. Therefore, at the resonance frequency, this type of FBAR device can be used for the broadband mobile WiMAX applications.

Ⅴ. Acknowledgment

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References

[1] J.G. Andrews, A. Ghosh, R. Muhamed, *Fundamentals of WiMAX Understanding Broadband Wireless Networking*, Massachusetts: Prentice Hall, 2007.

[2] S.V. Krishnaswamy, J.F. Rosenbaum, S.S. Horwitz, and R.A. Moore, "Film bulk acoustic wave resonator and filter technology," *IEEE MTT-S Dig.* ,pp. 153-155, 1992.

[3] K.M. Lakin, K.T. McCarron, and R.E. Rose, "Solidly mounted resonators and filter," *IEEE Proc. Ultrason. Symp.* ,pp. 905-908, 1995.

[4] M. Yim, D.H. Kim, D. Chai, and G. Yoon, "Significant resonance characteristic improvements by combined used of thermal annealing and Co electrode in ZnO-based FBARs," *IET Electronics Lett.*, Vol. 39, pp. 1638-1640, Nov. 2003.

[5] M. Yim, D.H. Kim, D. Chai, and G. Yoon, "Effects of thermal annealing of W/SiO_2 multilayer Bragg reflectors on resonance characteristics of film bulk acoustic resonator devices with cobalt electrodes," *J. Vac. Sci. Technol. A*, Vol. 22 (3), pp. 465-471, June 2004.

[6] D.H. Kim, M. Yim, D. Chai, and G. Yoon, "Improvements of resonance characteristics due to thermal annealing of Bragg reflectors in ZnO-based FBAR devices," *IET Electronics Lett.*, Vol. 39 (13), pp. 962-964, June 2003.

[7] L. Mai, H-I. Song, L.M. Tuan, P.V. Su, and G. Yoon, "A comprehensive investigation of thermal treatment effects on resonance characteristics in FBAR devices," *Micro wave and Optical Technology Letters*, Vol. 47 (5), pp. 459-462, Dec. 2005.

[8] L. Mai, J.Y. Lee, V.S. Pham, and W. Yoon, "Feasibility Study of ZnO-Based FBAR Devices for Mobile WiMAX Application," presented at the Int. Conf. Solid State Devices and Materials, Japan, Sept. 19-21, 2007, paper P-6-2, pp. 508-509.

[9] K.M. Lakin, G.R. Kline, and K.T. McCarron, "High-Q microwave acoustic resonators and filters," *IEEE Trans. Microwave Theory Tech.* Vol. 41, pp. 2139-2146, 1993.

[10] S.H. Park, B.C. Seo, H.D. Park, and G. Yoon, "Film bulk acoustic resonator fabrication for radio frequency filter applications," *Jpn. J. Appl. Phys.*, Vol. 39, pp. 4115-4119, July 2000.