ABSTRACT

The rapid expansion of the wireless market has led to a huge growth of more advanced mobile communication systems. Especially, the miniaturized mobile phones have been developed that have multi-functions with higher operating frequencies. Complying with the recent trends, there has been a great demand particularly for ultra-miniaturization and monolithic integration of RF filters as one of core components in mobile communication systems. Typical filters used in RF front-end for commercial wireless handsets are ceramic or surface acoustic wave (SAW) resonators. However, neither of them is compatible fully with the standard IC-technology.

Film bulk acoustic wave resonator (FBAR) devices and their related fundamentals can play an important role for the fabrication of the next generation radio-frequency (RF) filters. The FBAR devices basically utilize the acoustic resonant characteristics of piezoelectric materials such as AlN or ZnO. Compared with the so-called Surface Acoustic Wave (SAW) filters, FBAR device filters can also be realized to have smaller size and higher performance especially in power handling capability.
The typical FBAR device is composed of a thin piezoelectric film sandwiched between top and bottom conductor plates (electrodes). The devices must have two acoustically reflecting surfaces in order to trap energy and produce a resonating characteristic. As the reflecting surfaces for FBAR devices, the solidly mounted-type has a Bragg reflector part which is made up of alternating thin-film layers of both low and high acoustic impedance materials.

The ZnO-based FBAR devices are made up of a piezoelectric ZnO film sandwiched between top and bottom electrodes (e.g., aluminum) deposited on 5-layer W/SiO$_2$ Bragg reflectors. The 5-layer W/SiO$_2$ Bragg reflectors were fabricated by alternately depositing the tungsten (0.57 µm-thick) of high acoustic impedance material and SiO$_2$ films (0.6 µm-thick) of low acoustic impedance material on a 4-inch Si wafer. After depositing five layers (SiO$_2$/W/SiO$_2$/W/SiO$_2$) of Bragg reflectors, the Al bottom electrodes (1.2 µm-thick) were deposited on the 5-layer Bragg reflectors. Then, 1.2 µm-thick ZnO piezoelectric films were deposited on the bottom electrodes. Next, the top electrodes were patterned on the piezoelectric film using a conventional photolithography technique and then, aluminum top electrodes (0.2 µm-thick) were deposited. The three different top electrode patterns were completed by the lift-off processing to strip off the remaining PR layers. The return losses ($S_{11}$) of three resonators were measured by using the Network Analyzer-System Agilent HP 8510C and a probe station.

In this work, very effective methods to improve the resonance characteristics of FBAR devices as well as an approach for inductor fabrication based on Bragg reflectors were proposed.

First, Cr films (300 Å – thick) between SiO$_2$ film and W film were formed by deposition in a metal sputter in order to enhance the adherence at their interfaces. As a result, the addition of Cr adhesion layers seems to enhance the adhesion quality between SiO$_2$ and W layers in the Bragg reflectors, eventually leading to improvements of resonance characteristics.

Second, the use of the thick bottom electrodes (1.2 µm) in FBAR devices appears to further improve the resonance characteristic ($S_{11}$) and increase the
resonance frequency. The measured S-parameters indicate that the FBARs can be used for the application of 2.7~3 GHz broadband WiMAX.

Third, to investigate the annealing effects on resonance characteristics of FBAR devices, four different thermal annealing samples were performed. In sample A, no thermal annealing treatment was done in the whole steps. The first thermal annealing process, called inter-fab annealing as in sample B, is used to anneal the sample in an electronic dehydrate furnace at 200 °C for one hour before the deposition of top electrodes. After the top electrodes deposition, the sample C is annealed at 200 °C for 2 hours, called post-annealing process. The last process, the combination of inter-fab annealing (200 °C/1 hour) & post-annealing (200 °C/2 hours) was performed on the sample D. According to the measurement results, the addition of the post-annealing for the sample D, already treated by inter-fab annealing (200 °C/1 hour), is shown to further improve return loss ($S_{11}$). Regardless of the annealing processes, the resonance frequency of three different FBAR devices was ~ 1.71 GHz. As a result, the resonance characteristics ($S_{11}$) are observed to be improved by the thermal annealing in the ZnO-based FBAR devices with 5-layered Bragg reflectors. Also, this approach will be very promising for the future FBAR device applications.

On the other hands, in this work, a novel approach to realize inductor based on Bragg reflectors is proposed. By using Bragg reflectors, the parasitic effects of the inductor can be reduced in terms of substrate losses because the multi-layer Bragg reflectors of FBAR have the special characteristics by acting as a mirror to prevent the losses into the substrate. The effects of the multi-layer Bragg reflectors and inductor patterns on the characteristics of inductors were investigated. The measurement results showed that the inductors fabricated on the Bragg reflector result in a significant improvement in terms of the $S_{11}$ parameter. This approach seems highly feasible and promising for future Si-based RF IC applications.
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I. Introduction

1.1 Motivation

The huge growth of wireless market has demanded more advanced mobile communication devices and systems. Moreover, small and low loss microwave filters have become increasingly desirable for radar, communications and electronic warfares. The performance requirements of front-end filters, particularly those operating above 1 GHz, are increasingly difficult to meet with traditional approaches of lumped element, dielectric, or surface acoustic wave filters.

Also, the increasingly sophisticated electronic circuitry has needed various forms of aggressively scale-downed devices to meet the rigorous design requirements. With the rapid advancement of integrated circuits (ICs) technology, even more number of devices and components could be integrated together. This allows the printed circuit boards and other substrates to be further reduced in size.

More recently, the ICs technology has been developed to the degree to which virtually entire systems can be integrated in one die or chip. In other words, integration of RF devices on a silicon wafer has been required to eventually realize a one-chip radio or a transceiver because the higher performance generally can be achieved by realizing a system with lower power consumption, better signal integrity, and smaller size. Fig. 1.1 illustrates the simplified block diagram of a traditional super-heterodyne transceiver.

Furthermore, the dramatically rapid development of the wireless communication area has demanded more advanced brand-new filters with higher performance to protect receivers from undesirable adjacent channel interferences and noises [1, 2].
1.2 Needs for FBAR

In general, the typical filters used in RF front-end of the commercial wireless handsets have mostly exploited the ceramic or surface acoustic wave (SAW) resonators. Unfortunately, neither of them is fully compatible with the standard IC-technology [3, 4].

On the other hand, the film bulk acoustic resonator (FBAR) filter has recently attracted much attention as a promising next-generation novel filter technology mainly because it can be fully integrated with other CMOS/RFIC circuitry, potentially allowing for the realization of a single-chip radio or a transceiver in the future. With the use of this technology, not only the filter
size can be further reduced, but also the higher filter performance can be obtained. In other words, the film bulk acoustic wave resonator (FBAR) devices and their technology are expected to play an important role for the fabrication of the next generation radio-frequency (RF) filters.

The FBAR devices basically exploit the acoustic resonant characteristics of the piezoelectric materials (AlN or ZnO films). The advantage of acoustic over electromagnetic filters is generally recognized as their small size resulting from the approximately five orders of magnitude reduction in the acoustic phase velocity. For example, acoustic waves are about 5 to 8 orders of magnitude smaller than electromagnetic waves and thus, this allows for 5 to 8 orders of magnitude decrease in device size as compared to ceramic resonators without any significant sacrifice of device performances. This property is utilized in the fabrication of SAW filters. However, for these filters size and weight must be compromised if low insertion loss is desired. In other words, bulk acoustic resonator filters offer unique advantage since they are at least an order of magnitude smaller than dielectric resonators or lumped elements, and possess much lower insertion loss than surface wave devices. On a superficial level, it would appear that FBAR technology must be inherently superior to SAW technology. Bulk devices have better power handling abilities that the bulk device is fairly insensitive to surface contamination and surface adsorbates. Furthermore, having the electrical fields contained between the two electrodes guarantees minimum coupling of electrical fields with outside metal surfaces and capacitance being determined by the spacing, area and dielectric constant of the piezoelectric. Consequently, compared with the so-called surface acoustic wave (SAW) filters, the FBAR device filters are known to have smaller size and higher performance especially in power handling capability [5].
1.3 Three Compositions of FBAR Device

Film Bulk Acoustic Resonators are fabricated by sputtering of thin films of piezoelectric material such as aluminum nitride or zinc oxide onto semiconductor substrates such as silicon or gallium arsenide. These resonators are referred to variously as TFRs (thin film resonators), SBARs (semiconductor bulk acoustic resonators), or FBARs.

The typical FBAR device is composed of a thin piezoelectric film sandwiched between top and bottom conductors (electrodes), as shown in Fig. 1.2. The devices must have the two acoustically reflecting surfaces in order to trap energy and produce a resonating characteristic. For example, the reflecting surfaces can be realized either two air-to-solid interfaces (ideal FBAR) or an acoustic Bragg reflector and an air-to-solid interface.

At first, the purpose of the electrodes is to establish an equipotential surface which can seed highly textured piezoelectric films. The quality of the piezoelectric layer depends highly on the bottom electrodes film qualities such as the film uniformity, minimizing the stress mismatching, and minimizing the interlayer contamination between the piezoelectric layer and electrodes.

Especially, the most critical factor that determines the characteristics of the FBAR is the piezoelectric property of piezoelectric films, which is directly related to the degree of the c-axis preferred orientation of the deposited piezoelectric films.

In other words, the requirements for the piezoelectric candidate materials are that they result in efficient large area devices and in turn this necessitates thin films with a high degree of orientation and large piezoelectric coupling. Additional materials requirements include high resistivity, good breakdown strength, and reproducibility of film deposition. Materials that satisfy a number of these requirements include CdS, ZnO, AlN, LiNbO₃, LiTaO₃, PZT, and PLZT. Particularly, ZnO and AlN of them have attracted the most attention, because those obtained by magnetron sputtering meet most of the
material requirements described earlier and are primarily used for the piezoelectric layer.

In reflecting surface, the acoustic wave is trapped by the reflecting surface, resulting in the acoustic standing wave which leads to better resonant characteristics. Also, types of FBAR are determined how to realize the reflecting surface [2].

![FBAR composition of ideal FBAR](image)

Fig. 1.2 FBAR composition of ideal FBAR

1.4 Types of FBAR

The thin-film approach contains three possible device configurations. The configuration of Fig. 1.3 (a) is a membrane structure supported by the edge of the substrate. Typical fabrication involves deposition of a piezoelectric film on a supporting substrate followed by removal of a portion of the substrate to form the membrane and thereby define the resonator. The configuration is similar to that used in inverted mesa quartz crystals, where a thin piezoelectric membrane is surrounded by a more rigid supporting is not of the same material as the piezoelectric, leading to the use of composite structure. This
approach is limited to substrate in which the cavity is readily formed and has its roots in silicon micro-machining.

The second configuration in Fig. 1.3 (b) involves fabrication an air gap under the resonator. This may be accomplished by first depositing and patterning an area of temporary support material, next depositing and patterning an overlay piezoelectric resonator with electrodes, and finally removing the temporary support.

The last is the solidly mounted-type which has a Bragg reflector part generally made up of multiple alternating layers of both low and high acoustic impedance materials in Fig. 1.3 (c). The SMR-type FBAR is of a considerably different form than the membrane structures. Since the piezoelectric plate is solidly mounted to the substrate, suggesting a transducer, some means must be used to acoustically isolate the transducer from the substrate if a high-Q resonance is to be obtained. There is a method of attaching a resonator to a substrate so that the resonator is substantially acoustically isolated from the substrate. The technique uses adjacent quarter-wavelength sections of materials, having large effective transmission-line impedance ratios, to form a reflector between the resonator and substrate. The result is a practical isolation of the transducer from the substrate to effect a high-Q resonator rather than a low-Q transducer.

Therefore, the SMR approach requires that the substrate be smooth and able to withstand modest microelectronic processing environments during the fabrication of reflectors, electrodes, and piezoelectric film. The absence of a via or any special substrate preparation for the SMR shows considerable promise for direct integration onto active circuit wafers.

Fabrication of SMR-type has extended over a frequency range of 300 MHz-20 GHz. Limitations on frequency are primarily driven by the ability to fabricate thin films for the reflectors and the piezoelectric transducer. At low frequencies, the main difficulty is in obtaining films of the required thickness in a finite period of time such that the process is economical. At high frequencies, the films can be grown quickly, but accordingly require a higher
degree of absolute film thickness control. Nevertheless, resonators and filters, operating at frequencies in the range of 600 MHz-12 GHz, are in production for use in military and commercial wireless systems [2, 6].

(a) membrane formed by etching a via in the substrate

(b) air gap isolated resonator

(c) SMR using a reflector array to isolate the resonator from the substrate

Fig. 1.3 Resonator configurations suitable for implementation with thin films
1.5 Resonance Condition

Piezoelectric thin films in FBARs convert RF electrical energy into mechanical energy related to acoustic wave by piezoelectricity, as shown in Fig. 1.2. Therefore, the piezoelectricity of ZnO or AlN, the degree of being changeable from RF electrical signal (wave) into acoustic wave, induces the resonance and selects a wanted frequency.

The FBAR consists of a piezoelectric thin film sandwiched by two metal layers. A resonance condition occurs if the thickness of piezoelectric thin film \(d\) is equal to an integer multiple of a half of the wavelength \(\lambda_{res}\). The fundamental resonant frequency \(f_{res} = 1/\lambda_{res}\) is then inversely proportional to the thickness of the piezoelectric material, and is equal to \(v_a/2d\) where \(v_a\) is an acoustic wave velocity at the resonant frequency \(f_{res}\).

\[
f = \frac{v_a}{2d}
\]

(1-1)

For example, when the thickness of piezoelectric thin film of 1.5 \(\mu\text{m}\) and acoustic wave velocity in ZnO film of 6330 m/s is given, the calculated resonant frequency from the equation is around 2.1 GHz.

1.6 Figure of Merits (FOMs)

\(K_{eff}^2\) and \(Q_{s/p}\) are a measure of the filtering performance of a device. Equation (1-2) and (1-3) provide a definition for the two FOMs [7, 8].

\[
K_{eff}^2 = \left(\frac{\pi}{2}\right)^2 \frac{f_p - f_s}{f_p}
\]  \hspace{1cm} (1-2)

\[
Q_{s/p} = \frac{f}{\frac{f}{2} \left| \frac{dZ_{in}}{df} \right|_{f_{s/p}}}
\]  \hspace{1cm} (1-3)
Effective electromechanical coupling coefficient \( (K_{\text{eff}}^2) \) is a measure of the relative spacing between the series and parallel resonance of a given mode, as shown in equation (1-2). It is also a function of the electromechanical coupling constant and the composition of the FBAR.

On the other hands, series/parallel quality factor \( (Q_{s/p}) \) is a measure of ‘loss’ within the device, as shown in equation (1-3). This ‘loss’ can result from ohmic resistance in the electrodes, acoustic loss within the acoustic stack, scattering of the acoustic waves from rough surfaces or grain boundaries, and acoustic radiation into the surrounding area of the device. Therefore, \( Q \) impacts the insertion loss and the width of the transition band.

1.7 Thesis Contribution and Overview

Film bulk acoustic resonator (FBAR) filter has recently attracted much attention as a promising next-generation novel filter technology mainly because it can be fully integrated with other CMOS/RFIC circuitry, potentially allowing for the realization of a single-chip radio or a transceiver in the future. With the use of this technology, not only the filter size can be further reduced but also the higher filter performance can be obtained. In other words, the film bulk acoustic wave resonator (FBAR) devices and their technology are expected to play an important role for the fabrication of the next generation radio-frequency (RF) filters.

1.7.1 Approach for Better Performance of FBAR Devices

In order to analyze the resonance characteristics in term of existence of Cr adhesion layer, the resonance characteristics of the ZnO-based FBAR devices have been investigated and deposited on the 5-layer Bragg reflector without
Cr adhesion layer. The Cr adhesion layer between SiO₂ and W layers was formed by deposition to enhance the adherence between the tungsten (W) and SiO₂ films.

To investigate the effects of thick bottom electrodes on ZnO based FBAR devices, three kinds of resonator top-view patterns were designed and also used as the signal and ground electrodes layered at the top of the FBAR devices. Based on the measurement results, the use of the thick bottom electrodes in FBAR devices appears to further improve the resonance characteristic (S₁₁) and increases the resonance frequency.

The measured S-parameters indicate that the FBARs may be used for the application of 2.7~3 GHz broadband WiMAX (worldwide interoperability for microwave access) that has been demonstrated to have its high potential not only to bridge the gap between fixed and mobile access but also to offer the same subscriber experience whether on a fixed or a mobile network.

In this work, to investigate the annealing effects, four different thermal annealing samples were performed. In sample A, no thermal annealing treatment was done in the whole steps. The first thermal annealing process, called inter-fab annealing as in sample B, is used to anneal the sample in an electronic dehydrate furnace at 200°C for one hour before the deposition of top electrodes. After the top electrodes deposition, the sample C is annealed at 200°C for 2 hours, called post-annealing process. The last process, the combination of inter-fab annealing (200°C/1 hour) & post-annealing (200°C/2 hours) was performed on the sample D.

According to the measurement results, the return losses of both sample B and sample C are significantly improved than the sample A. However, the annealing method of the sample C seems to further affect the return losses than that of the sample B, in terms of the improved resonance characteristic. Moreover, the addition of the post-annealing for the sample D, already treated by inter-fab annealing (200°C/1 hour), is shown to further improve return loss
(S_{11}).

1.7.2 Approach for Application of RF Inductor Based on Bragg Reflectors

This work proposed a novel approach to realize inductor based on Bragg reflectors. Parasitic effects of the inductor in terms of substrate losses can be reduced by using Bragg reflectors, because multi-layer Bragg reflectors of FBAR have special characteristics of acting a mirror to prevent the losses into the substrate. The effects of the multi-layer Bragg reflectors and inductor patterns on the characteristics of inductors are studied. The measurement results show that the inductors fabricated on the Bragg reflector result in a significant improvement in terms of the S_{11} parameter. This approach seems highly feasible and promising for future Si-based RF IC applications.
II. FBAR Fabrication

2.1 Mask Design

The top electrode patterns of FBAR devices are performed by using ADS (Advanced Design System), also considering the various resonant area, S (signal) – G (ground) distance, and pattern shape in order to perform in a more effective methods, as shown in Fig. 2.1(a).

Fig. 2.1(b) shows the mask layout of top-view patterns in one-port FBAR devices.

Fig. 2.1 (a) various top-view patterns, (b) mask layout of the top electrode patterns
2.2 Device Structures and Fabrications

In order to realize the ZnO-based FBAR device, there are several steps such as deposition, lift-off process, and photolithography. Also, FBAR fabrication involves materials for the piezoelectric film, Bragg reflector, and electrodes. The material requirements, while common in some respect, are different for each of these layers. All these layers should have good adhesion, and be smooth, and dense [2].

The ZnO-based FBAR devices are made up of a piezoelectric ZnO film sandwiched between top and bottom electrodes (aluminum) deposited on multi-layer W/SiO₂ Bragg reflectors. The multi-layer W/SiO₂ Bragg reflectors were fabricated by alternately depositing the tungsten (W) of high acoustic impedance material and SiO₂ films of low acoustic impedance material on a 4-inch Si wafer. Each layer of the Bragg reflectors has around quarter-wavelength thickness of the resonance frequency in order to acoustically isolate the piezoelectric layer part from the substrate.

Therefore, the SiO₂ films of 0.6 μm-thick and the tungsten (W) films of 0.57 μm-thick were also deposited. In addition, the Cr films (300 Å – thick) between SiO₂ film and W film were formed by deposition in a metal sputter in order to enhance the adherence at their interfaces. After depositing multi layers of Bragg reflectors, the Al-thin bottom electrodes (1 μm-thick) of were deposited on the multi-layer Bragg reflectors.

Moreover, the ZnO films, which play an important role in determining the characteristics of the FBAR in terms of the piezoelectric property of piezoelectric films, were deposited to be a half-wavelength thickness of the resonance frequency. Therefore, 1.2 μm-thick ZnO piezoelectric films were deposited on the bottom electrodes.

Especially, lithography process for FBAR devices is important to obtain precise patterns. PR coating means that dispensed liquid is covered on the substrate as a form of thin film. Also, positive PR is used to destroy polymer of exposed parts. After covering ZnO piezoelectric film by the photoresist,
soft baking is required at 90°C for 3 minutes in order to remove solvent and harden. Then, the substrate covered by PR is exposed for 35 seconds by ultraviolet light of aligner with patterns mask. Moreover, by using developer, weak polymer of the exposed parts is destroyed so that unexposed parts of the substrate remained for the wanted patterns.

In other words, the conventional photolithography technique with patterns mask was used to define the AZ5214E photoresist (PR) film followed by deposition of 0.2 µm-thick aluminum top electrodes on the ZnO piezoelectric film under the same deposition condition as the bottom electrodes. The different top electrode patterns were completed by the lift-off processing to strip off the remaining PR layers by acetone.

Fig. 2.2 illustrated the process flow of the FBAR fabrications from Si wafer cleaning to top electrodes patterning.
Fig. 2.2 Process flow of the FBAR fabrications: (a) Si wafer cleaning, (b) UV exposure by patterns mask on ZnO/Al/Bragg reflector, (c) development of exposed parts, (d) top metal (Al) deposition by sputtering, (e) lift-off process by acetone, (f) top electrodes pattern on ZnO based Bragg reflectors.
2.3 FBAR Devices Fabrications with 3 and 7 Reflector Layers

In order to present the effects of the multi-layer Bragg reflectors on the ZnO-based FBAR devices, FBAR devices fabrication and performance between 3 and 7 reflector layers were compared. All of the FBAR devices are with the high quality ZnO films deposited at the optimal temperature.

2.3.1 Device Structures

![Cross-sectional SEM images of FBAR device structures: (a) 7-layer, (b) 3-layer of Bragg reflectors](image)

Fig. 2.3 Cross-sectional SEM images of FBAR device structures: (a) 7-layer, (b) 3-layer of Bragg reflectors

2.3.2 Performance Comparisons

In this work, according to the number of layers of Bragg reflectors, the return losses ($S_{11}$) between 3-layer Bragg reflectors and 7-layer Bragg
reflector were compared with four different top electrode patterns in Fig. 2.4. A significant improvement of the return loss is shown in the 7-layer Bragg reflectors. The return losses of 7-layer Bragg reflectors were around -21.92 dB, -20.44 dB, -20.02 dB, and -24.32 dB, while those of 3-layer Bragg reflectors were around -17.63 dB, -16.31 dB, -14.08 dB, and -14.31 dB. The return losses of 7-layer Bragg reflectors are around 4.29 dB, 4.13 dB, 5.94 dB, and 10.01 dB better than those of 3-layer Bragg reflectors for patterns 1, 2, 3, and 4 of top electrodes. In case of 3-layer Bragg reflectors, the resonance frequency of four different FBAR devices was around 2.893 GHz. However, the resonance frequency increased to around 2.9 GHz in 7-layer Bragg reflectors. It is shown that the number of layers of Bragg reflectors could affect the resonance frequency. From the above measurement results, it is believed that the resonance characteristics of FBAR devices can be significantly improved in terms of return loss ($S_{11}$) by 7-layer Bragg reflectors.

On the other hand, according to equation (1-3), the calculated series and parallel Q-factor values for FBAR resonators with four different patterns are tabulated in Table 2.1. Series and parallel quality factors of 7-layer Bragg reflectors were significantly improved.

As a result, the resonance characteristics ($S_{11}$) of the ZnO-based FBAR devices were found to have a strong dependence on the number of layers of Bragg reflectors.

<table>
<thead>
<tr>
<th>Pattern Name</th>
<th>3-layer</th>
<th>7-layer</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$Q_s$</td>
<td>$Q_p$</td>
</tr>
<tr>
<td>Pattern 1</td>
<td>5044</td>
<td>4396</td>
</tr>
<tr>
<td>Pattern 2</td>
<td>4163</td>
<td>4988</td>
</tr>
<tr>
<td>Pattern 3</td>
<td>2795</td>
<td>3006</td>
</tr>
<tr>
<td>Pattern 4</td>
<td>3456</td>
<td>3259</td>
</tr>
</tbody>
</table>

Table 2.1 Series and parallel Q factors for four different patterns
Fig. 2.4 Top electrodes patterns and return loss ($S_{11}$) measurement results for the comparison between 3-layer and 7-layer Bragg reflectors.
III. Effective Methods to Improve Resonance Characteristics of FBAR Devices

In this work, we performed several methods to improve the resonance characteristics of FBAR devices such as addition of Cr adhesion layer, thick bottom electrodes, and thermal annealing. Fig. 3.1 shows device structure of FBAR in terms of addition of Cr adhesion layer and thick bottom electrodes.

![Fig. 3.1 3-dimensional structure of the one-port FBAR resonator](image)

3.1 Effects of Cr Adhesion Layer

3.1.1 Device Structures and Fabrications

To investigate the effects of Cr adhesion on ZnO based FBAR devices, three kinds of resonator top-view patterns were designed and also used as the signal and ground electrodes layered at the top of the FBAR devices, as shown in Fig. 3.2 (b).

The ZnO-based FBAR devices are made up of a piezoelectric ZnO film sandwiched between top and bottom electrodes (aluminum) deposited on 5-layer W/SiO₂ Bragg reflectors. The 5-layer W/SiO₂ Bragg reflectors were
fabricated by alternately depositing the tungsten (W) of high acoustic impedance material and SiO₂ films of low acoustic impedance material on a 4-inch Si wafer. The SiO₂ films of 0.6 µm-thick and the tungsten (W) films of 0.57 µm-thick were also deposited. In addition, the Cr films (300 Å – thick) between SiO₂ film and W film were formed by deposition in a metal sputter in order to enhance the adherence at their interfaces. After depositing five layers (SiO₂/W/SiO₂/W/SiO₂) of Bragg reflectors, the Al bottom electrodes (0.2 µm-thick) were deposited on the 5-layer Bragg reflectors. Furthermore, 1.2 µm-thick ZnO piezoelectric films were deposited on the bottom electrodes. Next, the top electrodes were patterned on the piezoelectric film using a conventional photolithography technique and Aluminum (Al) top electrodes (0.2 µm-thick) were deposited. The three different top electrodes patterns were completed by the lift-off processing to strip off the remaining PR layers. The return losses (S₁₁) of three resonators were measured by using the Network Analyzer-System Agilent HP 8510C and a probe station.
Fig. 3.2 (a) cross-sectional SEM image of Al-thick bottom electrode layers on 5-layer Bragg reflectors of FBAR device, (b) three different top electrode patterns of FBAR device
3.1.2 Improvement of Resonance Characteristics

In order to analyze the resonance characteristics in term of existence of Cr adhesion layer, the resonance characteristics of the ZnO-based FBAR devices have been investigated as ref. [9], where FBAR device was deposited on the 5-layer Bragg reflector without Cr adhesion layer.

In case of non-annealing (meaning that no thermal annealing treatment are used) of ref. [9], the return loss of three different devices without Cr adhesion layer were below -10 dB and their resonance frequency was around 1.9 GHz.

On the other hand, the Cr adhesion layer between SiO₂ and W layers was formed by deposition to enhance the adherence between the tungsten (W) and SiO₂ films. In case of addition of Cr adhesion layer, return losses ($S_{11}$) are over -20 dB for three different resonators and their resonance frequency was around 1.71 GHz. Table 3.1 shows the comparison of return losses according to the Cr adhesion layer. As a result, the resonance characteristics of FBAR with Cr adhesion layer are much more improved than those of ref. [9]. In spite of the additionally formed Cr layers, no significant deterioration in device performance was observed. From this perspective, FBAR devices without adhesion layers may have some imperfect adhesions at the interface between the physically deposited films, possibly leading to the degradation in the device performance. However, the use of Cr adhesion layers seems to enhance the adhesion quality between SiO₂ and W layers in the Bragg reflectors, eventually leading to improvements of resonance characteristics.

Table 3.1 Comparison of return losses according to the Cr adhesion layer

<table>
<thead>
<tr>
<th>Return loss</th>
<th>Without Cr adhesion layer (ref. [9])</th>
<th>With Cr adhesion layer (This work)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pattern 1</td>
<td>-8 dB</td>
<td>-18.21 dB</td>
</tr>
<tr>
<td>Pattern 2</td>
<td>-11 dB</td>
<td>-22.43 dB</td>
</tr>
<tr>
<td>Pattern 3</td>
<td>-9 dB</td>
<td>-19.38 dB</td>
</tr>
</tbody>
</table>
3.2 Effects of Thick Bottom Electrodes

3.2.1 Device Structures and Fabrications

To investigate the effects of thick bottom electrodes on ZnO based FBAR devices, three kinds of resonator top-view patterns were designed and also used as the signal and ground electrodes layered at the top of the FBAR devices, as shown in Fig. 3.2 (b).

The ZnO-based FBAR devices are made up of a piezoelectric ZnO film sandwiched between top and bottom electrodes (aluminum) deposited on 5-layer W/SiO₂ Bragg reflectors. Each layer of the Bragg reflectors has around quarter-wavelength thickness of the resonance frequency in order to acoustically isolate the piezoelectric layer part from the substrate. Moreover, the ZnO films, which play an important role in determining the characteristics of the FBAR in term of the piezoelectric property of piezoelectric films, were deposited to be a half-wavelength thickness of the resonance frequency. In accordance with the fabrication of each layer, various fabrication equipments were employed such as P5000 TEOS CVD, metal sputter, and E-gun evaporator. A 3-dimensional schematic of one-port 5-layer FBAR device is shown in Fig. 3.1.

The 5-layer W/SiO₂ Bragg reflectors were fabricated by alternately depositing the tungsten (W) of high acoustic impedance material and SiO₂ films of low acoustic impedance material on a 4-inch Si wafer. With P5000 TEOS CVD, the SiO₂ films (0.6 µm-thick) were deposited at 390°C, under the operation pressure of 9 Torr and RF power of 350 W. On the other hand, the tungsten (W) films (0.57 µm-thick) were also deposited at room temperature and with RF power of 250 W by metal sputter. In addition, the Cr films (300 Å – thick) between SiO₂ film and W film were formed by deposition in a metal sputter in order to enhance the adherence at their interfaces. After depositing five layers (SiO₂/W/SiO₂/W/SiO₂) of Bragg reflectors, the Al
bottom electrodes (1.2 µm-thick) were deposited on the 5-layer Bragg reflectors in an E-gun evaporator with power supply of 5 kW. Furthermore, 1.2 µm-thick ZnO piezoelectric films were deposited on the bottom electrodes at room temperature for 100 minutes under an argon/oxygen gas mixture (2:1) of 10 mTorr and RF power of 260 Watts. Next, the top electrodes were patterned on the piezoelectric film using a conventional photolithography technique and Aluminum (Al) top electrodes (0.2 µm-thick) were deposited. The three different top electrode patterns were completed by the lift-off processing to strip off the remaining PR layers. A cross-sectional SEM image of the thick bottom electrodes on 5-layer Bragg reflectors of FBAR device is shown in Fig. 3.2 (a). The return losses (S_{11}) of three resonators were measured by using the Network Analyzer-System Agilent HP 8510C and a probe station.

3.2.2 Improvement of Return Loss Characteristics

For the different resonator patterns, the return losses (S_{11}) of 5-layer FBAR devices were shown in Fig. 3.3. The return losses of 5-layer Bragg reflectors were around -24.45 dB, -24.67 dB, -26.63 dB for patterns 1, 2, and 3 of top electrodes, respectively. The resonance frequency of three different FBAR devices was around 2.725 GHz.

Previously, the resonance characteristics of the ZnO-based FBAR devices have been investigated for various thermal-annealing conditions, ref. [9], where the thinner bottom electrodes (0.2 µm-thick) were deposited on the 7-layer Bragg reflector. In case of non-annealing process of ref. [9] (meaning that no thermal annealing treatment are used), the return losses of three different devices were below -10 dB and their resonance frequency was around 1.78 GHz. Based on this finding, the use of the thick bottom electrodes in FBAR devices appears to further improve the resonance characteristics (S_{11}) and increases the resonance frequency.
The measured S-parameters indicate that the FBARs may be used for the application of 2.7~3 GHz broadband WiMAX (worldwide interoperability for microwave access) that has been demonstrated to have its high potential not only to bridge the gap between fixed and mobile access but also to offer the same subscriber experience whether on a fixed or a mobile network. Currently, the 2.3~3.6 GHz band assignment for the WiMAX application is being considered as one of the best choices for mobile broadband deployments as it has been widely reserved for mobile services [10].

### 3.2.3 Improvement of Q-factor Characteristics

The calculated series and parallel Q-factor values for FBAR resonators with three different patterns and the calculated effective electromechanical coupling coefficient $K_{\text{eff}}^2$ are tabulated in Table 3.2. Fig. 3.4 represents the slope of input impedance phase ($\angle Z_{in}$) as a function of the frequency, plotted for three resonator patterns of 5-layer Bragg reflector on FBAR devices.

<table>
<thead>
<tr>
<th>Pattern</th>
<th>$Q_s$</th>
<th>$Q_p$</th>
<th>$K_{\text{eff}}^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pattern 1</td>
<td>5724</td>
<td>5520</td>
<td>2.71 %</td>
</tr>
<tr>
<td>Pattern 2</td>
<td>7195</td>
<td>5232</td>
<td>1.80 %</td>
</tr>
<tr>
<td>Pattern 3</td>
<td>6204</td>
<td>5678</td>
<td>4.51 %</td>
</tr>
</tbody>
</table>
Fig. 3.3 Return loss ($S_{11}$) measurement results for three different resonator patterns
Fig. 3.4 Slope of $\frac{\partial Z_{in}}{\partial f}$ as a function of the frequency for the resonator pattern 1, 2, and 3.
3.3 Effects of Thermal Annealing

3.3.1 Device Structures and Fabrications

In this experiment, to investigate the annealing effects on resonance characteristics of FBAR devices, four different thermal annealing methods were performed.

The ZnO-based FBAR devices are composed of the piezoelectric ZnO film sandwiched between the top and bottom electrodes (Al) deposited on 5-layered W/SiO$_2$ Bragg reflector. In order to fabricate each layer, various kinds of machines were employed such as P5000 TEOS CVD, metal sputter, and E-gun evaporator. The 5-layered W/SiO$_2$ Bragg reflectors were fabricated by alternately depositing tungsten (W) and SiO$_2$ films on a 4-inch Si wafer. Each layer has around quarter wavelength thickness of the resonance frequency in order to acoustically isolate the piezoelectric layer part from the substrate. By using P5000 TEOS CVD with deposition rate of 153 Å/sec, the SiO$_2$ films of 0.6 µm-thick were deposited at 390 °C, under operation pressure of 9 Torr and RF power of 350 W. On the other hand, the tungsten (W) films of 0.57 µm-thick were also deposited at room temperature, RF power of 250 W and deposition rate of 100 Å/min by metal sputter. In addition, the Cr films of 300 Å-thick between SiO$_2$ film and W film were deposited by metal sputter in order to enhance the adherence at their interfaces. Then, the Al bottom electrodes of 1 µm-thick were deposited on the 5-layered Bragg reflector in an E-gun evaporator with power supply of 5 kW and deposition rate of 10 Å/sec. Then, 1.2 µm-thick ZnO piezoelectric films were deposited on the bottom electrodes at room temperature for 100 minutes under an argon/oxygen gas mixture (2:1) of 10 mTorr and RF power of 260 Watts. The ZnO films were deposited to be half wavelength thickness of the resonance frequency. A 3-dimensional schematic of one-port FBAR resonator is shown in Fig. 3.1.

In this work, to investigate the annealing effects, four different thermal annealing samples were performed. In sample A, no thermal annealing
treatment was done in the whole steps. The first thermal annealing process, called inter-fab annealing as in sample B, is used to anneal the sample in an electronic dehydrate furnace at 200°C for one hour before the deposition of top electrodes. After the top electrode deposition, the sample C is annealed at 200°C for 2 hours, called post-annealing process. The last process, the combination of inter-fab annealing (200°C/1hour) & post-annealing (200°C/2 hours) was performed on the sample D. Fig 3.5- shows process flow for preparation of different annealing samples and four different annealing samples are tabulated in Table 3.3.

To pattern the top electrodes on the piezoelectric films, the conventional photolithography technique using pattern masks was used, followed by deposition of 0.2 µm-thick top electrodes (Al). The top electrode patterns are shown in Fig. 3.2(b). For the post-annealing process, two different samples (samples C and D) of the three different FBAR devices were annealed in the electronic dehydrate furnace at 200°C for two hours. Finally, the return losses of the three resonators were measured by using Network Analyzer-System Agilent HP 8510C and a probe station.

3.3.2 Return Losses by Four Different Thermal Annealing Samples

The return losses (S₁₁) of four different FBAR devices in terms of thermal annealing methods were measured, respectively. In Fig. 3.6, the return loss (S₁₁) measurements were plotted for the comparison of the annealing effects according to four different methods. In other words, measurement results of FBAR devices were obtained from the four different samples with non-annealing of sample A, Inter-Fab annealing(200°C/1 hour) of sample B, post-annealing (200°C/2 hours) of sample C, and Inter-Fab(200°C/1 hour) & post-annealing (200°C/2 hours) of sample D. First, the return losses (S₁₁) of pattern 1 were compared in terms of annealing methods: sample A=-18.45 dB, sample B=-20.49 dB, sample C=-26.60dB, sample D=-28.04 dB. In the second pattern, the return losses (S₁₁) were classified: sample A=-26.35 dB,
sample B = -29.15 dB, sample C = -30.31 dB, sample D = -32.26 dB. Last, the return losses ($S_{11}$) of pattern 3 in terms of four different thermal annealing methods were measured: sample A = -26.68 dB, sample B = -28.98 dB, sample C = -31.41 dB, sample D = -35.83 dB.

According to the above results, the return losses of both sample B and sample C are significantly improved than the sample A. However, the annealing method of the sample C seems to further affect the return losses than that of the sample B, in terms of the improved resonance characteristics. Moreover, the addition of the post-annealing for the sample D, already treated by inter-fab annealing (200°C/1 hour), is shown to further improve return loss ($S_{11}$). Regardless of the annealing processes, the resonance frequency of three different FBAR devices was ~ 1.71 GHz.

Furthermore, the use of the Cr adhesion layers deposited between SiO$_2$ and W films appears to effectively enhance the adherence at their interfaces. In spite of the additional Cr layers, there has been no significant deterioration in device performance.

As a result, it is speculated that the non-annealed FBAR devices without adhesion layers may have some physical imperfections in the film microstructures and some imperfect adhesions at the interfaces between the physically deposited films, possibly degrading the device performance. However, the Bragg reflector, which accompanies the adhesion layers as well as annealing processes, may be able to eliminate any existing imperfect microstructures in the Bragg reflectors, eventually leading to the improvements of resonance characteristics [11].

<table>
<thead>
<tr>
<th>Sample name</th>
<th>Annealing condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample A</td>
<td>non annealing</td>
</tr>
<tr>
<td>Sample B</td>
<td>inter-fab annealing(200°C/1hour)</td>
</tr>
<tr>
<td>Sample C</td>
<td>post-annealing (200°C/2 hours)</td>
</tr>
<tr>
<td>Sample D</td>
<td>inter-fab(200°C/1hour) &amp; post-annealing (200°C/2 hours)</td>
</tr>
</tbody>
</table>
Fig. 3.5 Process flow for preparation of four different annealing samples: (a) non annealing, (b) post annealing, (c) Si wafer, (d) inter-fab annealing before deposition of top electrodes, (e) top electrodes deposition after inter-fab annealing, (f) post-annealing after top electrodes deposition.
Fig. 3.6 The return loss ($S_{11}$) measurement results against frequency for three different top electrodes patterns:
(a) pattern 1, (b) pattern 2, (c) pattern 3
3.3.3 Improvement of Q-factor Characteristics

In order to evaluate the resonance characteristics, the calculated series and parallel Q-factor values for FBAR resonators with three different patterns by equation (1-3) are tabulated in Table 3.4. In case of the sample B or sample C, series and parallel quality factors of FBAR resonators were improved than those of the sample A. Moreover, a significant improvement of quality factor could be obtained in the sample D than those of the sample B or sample C. This indicates that this approach can be a useful method to improve the resonance characteristic of the SMR-type FBAR devices in a cost-effective way.

As a result, the resonance characteristics ($S_{11}$) are observed to be improved by the thermal annealing in the ZnO-based FBAR devices with 5-layered Bragg reflectors. Also, this approach will be very promising for the future FBAR device applications.

<table>
<thead>
<tr>
<th>Sample name</th>
<th>Pattern 1</th>
<th>Pattern 2</th>
<th>Pattern 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$Q_s$</td>
<td>$Q_p$</td>
<td>$Q_s$</td>
</tr>
<tr>
<td>Sample A</td>
<td>6328</td>
<td>6110</td>
<td>6409</td>
</tr>
<tr>
<td>Sample B</td>
<td>6390</td>
<td>6272</td>
<td>6558</td>
</tr>
<tr>
<td>Sample C</td>
<td>6721</td>
<td>6513</td>
<td>6709</td>
</tr>
<tr>
<td>Sample D</td>
<td>6954</td>
<td>6561</td>
<td>6988</td>
</tr>
</tbody>
</table>
IV. Approach for RF Inductor Fabrication Based on Bragg Reflectors

4.1 Motivation

The fast growing of the wireless market has created an urgent demand for smaller and cheaper handsets with increased functionality and performance while still meeting the tight constraints for mass production within a short product life cycle.

The successful achievement of these conflicting trends has been possible due to the development of key technical capabilities in the design and production of each new wireless device generation.

In the baseband section of the handset, the great development experimented by the CMOS processes in the last decade, has shrunk the silicon real estate required for the processor, memory and interface ICs.

In contrast to this situation, the improvement in the passive component content of the handset has been much less dramatic compared to other technical areas. This inertia has not been due to the lack of attention by the set-makers or in the literature.

Furthermore, high quality passive components are specially prevalent in the RF Front-end and radio transceiver sections of the wireless terminal, and these increase proportionally as new standards (GPRS, EDGE, UMTS, Bluetoooth, etc.) are incorporated to the handset. In addition to dominating the component count, size and cost of the terminal the large number of passive components is a major factor in the assembly line production and yield and contribute to unwanted reliability failures. Thus a big research effort has been done in that field in order to reduce the passive component count of the handset [12, 13].
4.2 Difficulty of Integrating an Inductor

A spiral inductor is built by a metal strip spiral shaped as a square, hexagon, etc. The spiral is built by using one of the metal layers embedded in silicon oxide and placed at some distance from the semiconductor substrate.

When an inductor is integrated on Silicon based technology, some undesirable induced effects show up. The reason is that the metallic layers are separated from the semiconductor substrate by a layer of silicon oxide. These effects can be classified in two types, magnetically induced and electrically induced.

4.2.1 Magnetically Induced Parasitic Effects in the Substrate

One of the fundamental properties of an inductor is that generates a magnetic field. This alternating field penetrates into the conductive substrate and induces a voltage difference, which in turn generates a current. This phenomenon diminishes the energy in the coil, decreasing at the same time the quality of the inductor.

Fig 4.1 schematically shows this effect for a cross section cut of an inductor integrated on Silicon technology. It is important to mention that some studies indicate that the radius of the spiral approximately gives the depth of penetration of the magnetic field into the substrate.

Inductance is other parameter affected by the induced currents in the substrate. These currents flow in the opposite direction than the current carried by the coil, resulting in a reduction of the magnitude of the total magnetic field. Therefore, the value of the inductance will decrease, since the inductance is defined as the ratio between the magnetic flux and the current in the spiral.

4.2.2 Electrically Induced Parasitic Effects in the Substrate

Other parasitic effect that shows up in Silicon integrated inductors is the
capacitive coupling between the inductor and the substrate. This effect can be understood by the fact that a capacitor is just two conductive plates (metallic layer from the inductor and semiconductor substrate) separated by a dielectric (Silicon oxide), as shown in Fig 4.2. This leads to a negative effect since a portion of the inductor energy will be stored in this capacitor, depending on the capacity and the frequency. It could even happen that the inductor starts behaving like a capacitor rather than as an inductor. The value of the frequency where this occurs is called the resonance frequency of the inductor (f_{sr}) [12].

In addition, ohmic losses are produced since there are displacement currents induced in the substrate. This is illustrated in Fig 4.3.

![Fig 4.1 Schematic representation of the induced current in the substrate due to the magnetic field penetration](Image)

![Fig 4.2 Schematic representation of the metal-substrate capacitance](Image)
4.2.3 Quality Factor Improvement Methods

One of the fundamental limitations in integrated inductors is the parasitic current induced in the substrate by magnetic and electric fields. One possible solution to this problem is to fabricate the spiral further away from the substrate with thicker oxide. In this way, the parasitic effects are reduced and consequently the quality of the inductor is improved. Another possibility is to increase the resistivity of the substrate, making more difficult the appearance of induced currents and therefore reducing the substrate losses.

The limit case of fabricating an inductor with a large thickness of oxide and with a substrate highly resistive is equivalent to eliminate the substrate underneath the spiral. Finally, it is important to mention that even though the quality of an inductor improves, it is not clear that the commercial viability of this technique exists due to its high fabrication cost.

Therefore, in this work, a novel approach to realize inductor based on Bragg reflectors is proposed. By using Bragg reflectors, some possible parasitic effects of the inductor can be reduced in terms of substrate losses because multi-layer Bragg reflectors of FBAR have the special characteristics
which act a mirror to prevent the losses to the substrate. The effects of the multi-layer Bragg reflectors and inductor patterns on the characteristics of inductors are investigated. The measurement results show that the inductors fabricated on the Bragg reflectors result in a significant improvement in terms of the S11 parameter. This approach seems highly feasible and promising for future Si-based RF IC applications.

4.3 Device Structures of Inductor

In this work, three sets of different spiral inductors are simultaneously prepared on three different silicon-based substrates Si, SiO2/Si, and BR/Si, respectively. Fig. 4.4 shows the different inductor structures implemented in this work: One is inductor on Si substrate (Inductor 1), another is inductor on SiO2/Si substrate (Inductor 2), and the other is inductor on a seven-layered Bragg reflector/Si substrate (Inductor 3). The first spiral inductor type was fabricated directly on Si wafer in order to use it as a reference sample.

Especially, in case of Inductor 3, we described the procedure to fabricate the inductor on a seven-layered Bragg reflector/Si substrate. The multi-layer W/SiO2 Bragg reflectors were fabricated by alternately depositing the tungsten (W) of high acoustic impedance material and SiO2 films of low acoustic impedance material on a 4-inch Si wafer. Each layer of the Bragg reflectors has around quarter-wavelength thickness of the resonance frequency in order to acoustically isolate the piezoelectric layer part from the substrate.

In order to realize the inductor, under-bar of inductor is fabricated for the first time. Therefore, the conventional photolithography technique with pattern masks was used to define the AZ5214E photoresist (PR) film followed by deposition of Aluminum layer on the substrate. The under-bar patterns of inductor were completed by the lift-off processing to strip off the remaining PR layers and shown in Fig. 4.5 (a)

Also, the via-hole of inductor is important to connect under-bar to top spiral pattern. The conventional photolithography technique with pattern masks was
used to define the AZ5214E photoresist (PR) film followed by deposition of ZnO layer on substrate. The via-hole patterns of inductor were completed by the lift-off processing to strip off the remaining PR layers and shown in Fig. 4.5 (b).

Last, there are three different spiral inductor patterns in Fig. 4.6. The three spiral inductor layouts have 2.5 turns, and numbers of sides are 8, 12, and 16, respectively. The width, spacing, and inner diameter of turns have been fixed to 30 µm, 20 µm, and 130 µm, respectively. The conventional photolithography technique with pattern masks was used to define the AZ5214E photoresist (PR) film followed by deposition of Al layer on the substrate. The top spiral patterns of inductor were completed by the lift-off processing to strip off the remaining PR layers and shown in Fig. 4.5 (c). Finally, all the top spiral strips were connected to the under-bar through via-holes.
Fig. 4.4 Cross-sectional 3D structures of the on-chip inductors
Fig. 4.5 Procedure of inductor fabrications

(a) fabrication of under-bar

(b) fabrication of via-hole

(c) fabrication of top spiral pattern
4.4 Device Fabrications and Measurements of Inductor

In order to realize three different inductors, the p-type Si wafer is prepared. The first type (Inductor 1) of spiral inductor was fabricated on Si wafer without any treatment. The second type (Inductor 2) of spiral inductor was fabricated similarly to the first one, but the spiral inductors were separated from the Si substrate by 0.6 \( \mu \)m thick thermal silicon dioxide (SiO\(_2\)). As proposed in this work, for the third type (Inductor 3) of inductor, the seven-layered Bragg reflector consisted of SiO\(_2\) and tungsten (W) films and was prepared by alternate deposition of W and SiO\(_2\) layers in an RF magnetron sputtering system. The 0.6 \( \mu \)m thick W films were deposited under Ar gas pressure of 15 mTorr with DC power of 150 Watts, and the 0.6 \( \mu \)m thick SiO\(_2\) films were deposited under Ar gas pressure of 4 mTorr with RF power of 300 Watts. Each spiral inductor of three different types was fabricated using 0.2 \( \mu \)m thick aluminum (Al) with 1.2 \( \mu \)m thick zinc oxide (ZnO). The 0.2 \( \mu \)m thick Al thin films (under-bar metal strips) were simultaneously deposited on all three substrates under 20 mTorr Ar gas pressure and with 150-Watts DC power. Then, the 1.2 \( \mu \)m-thick ZnO with via-patterning was deposited under 10 mTorr of Ar/O\(_2\) mixed-gases, and with RF power of 300 Watts. The deposition and patterning of the upper Al strips (0.2 \( \mu \)m) on top of the ZnO films completed the spiral-inductor fabrication. All the upper metal strips were connected to the lower ones through via-holes. Finally, the three spiral inductor types, corresponding to the substrates of Si, SiO\(_2\)/Si, and BR/Si, respectively, were fabricated. All the spiral-inductor structures were measured to extract the de-embedded S-parameters using both a probe station and a network analyzer (HP 8722D).

4.5 Results and Discussion

In this work, three different spiral-inductor layouts were proposed and each spiral layout was fabricated on three different substrate structures, as
described in Fig. 4.4. The measured S-parameter values of the three inductor patterns were plotted as a function of frequency, as shown in Fig. 4.7. The three spiral inductor layouts have 2.5 turns and numbers of sides are 8, 12, and 16, respectively in Fig. 4.6. Also, Fig. 4.7 compared the return loss characteristics of the three spiral inductor structures with the same inductor layout, each fabricated on the Si, SiO₂/Si, and BR/Si substrate, respectively. The comparison of the S₁₁ values clearly shows the relative effect of the substrate structure used. Regardless of the spiral-layout types, the return loss values have the same increasing trend in sequence from the inductors Inductor 1 (Si substrate), Inductor 2 (SiO₂/Si substrate), and Inductor 3 (BR/Si substrate). For three physical inductor structures, the S₁₁ characteristic of the Inductor 2 is better than that of Inductor 1 due to the dielectric layer SiO₂ being incorporated between the spiral inductor and Si substrate for reduction of the substrate loss. Meanwhile, the return loss (S₁₁) value of the Inductor 3 is significantly improved, as compared both Inductor 1 and Inductor 2. This implies that the use of the multi-layer Bragg reflectors can reduce the loss of Si substrate more effectively. Thus, the incorporated seven-layered Bragg reflector seems to have a considerable impact on the spiral-inductor characteristics. Accordingly, the measurement results show that the inductors fabricated on the Bragg reflectors result in a significant improvement in terms of the S₁₁ parameter.

On the other hand, the inductances of three different inductor patterns were extracted from the equation (4-1).

\[ L = \frac{im(1/Y_{11})}{2\pi f} \]  

(4-1)

In pattern A, Inductor 3 has the inductance of 20 nH at 1.2 GHz, whereas Inductor 1 and 2 have the inductance of 8 nH and 18 nH at the same frequency in Fig. 4.8 (a). Also, the resonance frequency is around 500 MHz to 1.5 GHz.
According to the measurement results, the inductances of pattern B and C showed the same characteristics that Inductor 3 (BR/Si) has much more increased inductances than either Inductor 1 or Inductor 2. As a result, Inductor 3 can prevent the signal to leak into the substrate by accompanying the substrate of Bragg reflectors so that the inductances are improved regardless of the same patterns.

In consequence, it is speculated that the BR/Si substrate may play an effective isolation layer role as a reflected substrate underneath the spiral inductor, eventually increasing the resistivity of the Si substrate and thus decreasing the harmful parasitic components between the metal strips and Si substrate. This feasibility study may not be a comprehensive investigation on the impact of the Bragg reflector on the inductor characteristics, particularly for the Si-based RF IC applications. Although further investigation need to be done for a more clear understanding, we strongly believe at this point that the use of Bragg reflector can significantly improve the on-chip inductor performance without any significant incompatible issues from the Si-based process-integration point of view. This approach seems highly feasible and promising for future Si-based RF IC applications.

(a) 8 sides of inductor (pattern A)  
(b) 12 sides of inductor (pattern B)  
(c) 16 sides of inductor (pattern C)

Fig. 4.6 Three different inductor patterns in terms of the number of sides
Fig. 4.7 Return losses plotted on Smith chart for three type inductors

(a) pattern A

(b) pattern B

(c) pattern C
Fig. 4.8 Inductances of three different fabrication methods in terms of inductor patterns
IV. Conclusions

The rapid growing of the wireless market has created an urgent demand for smaller and cheaper handsets with increased functionality and performance while still meeting the tight constraints for mass production within a short product life cycle. Especially, miniaturized mobile phones have been developed that have multi-functions with higher operating frequencies. Complying with the recent trends, there has been a great demand particularly for ultra-miniaturization and monolithic integration of RF filters as one of core components in mobile communication systems.

The typical FBAR device is composed of a thin piezoelectric film sandwiched between two top and bottom conductors (electrodes). The devices must have two acoustically reflecting surfaces in order to trap energy and produce a resonating characteristic. According to the type of reflecting surfaces for FBAR devices, the solidly mounted-type is having a Bragg reflector part which is made up of alternating layers of both low and high acoustic impedance materials.

The ZnO-based FBAR devices are made up of a piezoelectric ZnO film sandwiched between top and bottom electrodes (aluminum) deposited on 5-layer W/SiO₂ Bragg reflectors. The 5-layer W/SiO₂ Bragg reflectors were fabricated by alternately depositing the tungsten (0.57 µm-thick) of high acoustic impedance material and SiO₂ films (0.6 µm-thick) of low acoustic impedance material on a 4-inch Si wafer. After depositing five layers (SiO₂/W/SiO₂/W/SiO₂) of Bragg reflectors, the Al bottom electrodes (1.2 µm-thick) were deposited on the 5-layer Bragg reflectors. Then, 1.2 µm-thick ZnO piezoelectric films were deposited on the bottom electrodes. Next, the top electrodes were patterned on the piezoelectric film using a conventional photolithography technique and Al top electrodes (0.2 µm-thick) were deposited. The three different top electrode patterns were completed by the lift-off processing to strip off the remaining PR layers. The return losses (S₁₁) of three resonators were measured by using the Network Analyzer-System.
In this work, efficient methods to improve the resonance characteristics of FBAR devices as well as an approach for inductor fabrications based on Bragg reflectors were proposed.

First, the Cr films (300 Å – thick) between SiO2 film and W film were formed by deposition in a metal sputter in order to enhance the adherence at their interfaces. As a result, the addition of Cr adhesion layers seems to enhance the adhesion quality between SiO2 and W layers in the Bragg reflectors, eventually leading to improvements of resonance characteristics.

Second, the use of the thick bottom electrodes (1.2 µm) in FBAR devices appears to further improve the resonance characteristic (S11) and increase the resonance frequency. The measured S-parameters indicate that the FBARs may be used for the application of 2.7–3 GHz broadband WiMAX.

Third, to investigate the annealing effects on resonance characteristics of FBAR devices, four different thermal annealing samples were performed. According to the measurement results, the addition of the post-annealing, already treated by inter-fab annealing (200°C/1hour), is shown to further improve return loss (S11). Regardless of the annealing processes, the resonance frequency of three different FBAR devices was ~ 1.71 GHz. As a result, the resonance characteristics (S11) are observed to be improved by the thermal annealing in the ZnO-based FBAR devices with 5-layered Bragg reflectors. Also, this approach will be very promising for the future FBAR device applications.

On the other hand, in this work, a novel approach to realize inductor based on Bragg reflectors was proposed. By using Bragg reflectors, parasitic effects of the inductor can be reduced in terms of substrate losses because multi-layer Bragg reflectors of FBAR have the special characteristics which act a mirror to prevent the losses into the substrate. The effects of the multi-layer Bragg reflectors and inductor patterns on the characteristics of inductors were investigated. The measurement results showed that the inductors fabricated on the Bragg reflectors result in a significant improvement in terms of the S11
parameter. This approach seems highly feasible and promising for future Si-based RF IC applications.
RFIC  Bragg reflector  FBAR  RF Inductor

SMR type Bragg reflector  FBAR  RF Inductor
annealing, Bragg reflector, SiO$_2$, Cr adhesion, SiO$_2$. (bottom electrodes) 2.7 GHz WiMAX -25 dB WiMAX.

RF Inductor, Si Oxide, RF Inductor. Bragg reflector, RF Inductor, acoustic. Bragg reflector, Bragg reflector, SMR type, Bragg reflector, RF Inductor, FBAR, RF Inductor, FBAR. RF Inductor, RF Inductor, RF Inductor, Bragg reflector.
References


