

5.4 GHz High-Q Bandpass Filter for Wireless Sensor Network System

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Abstract—This research reveals the realization of 5.4 GHz radio frequency bandpass filter utilizing film bulk acoustic wave resonator (FBAR) technology. It can be applied to wireless sensor network systems. Furthermore, it can also be application for wireless 802.11n and 4G-WiMAX system. In this paper, the 5.4 GHz filter has been demonstrated, which has central frequency of 5406 MHz, bandwidth of 70 MHz, insertion loss of -10 dB, return loss of -18 dB, and stopband attenuation of -36 dB, and size of 0.74 mm \times 0.42 mm.

I. INTRODUCTION

With the development of the wireless communication, high performance radio frequency (RF) bandpass filters and high quality oscillators will be needed. The advantages of film bulk acoustic wave resonator (FBAR) devices contain microminiaturization [1], high quality (Q) factor [2], great power handling [2], complementary metal oxide semiconductor (CMOS) compatibility [3], and high frequency operation [4]. The potential advantages of FBAR devices are attractive to RF microelectronics researchers. It can be application for bandpass filter and oscillator for wireless communication. In addition, with the trending of high sensitive sensors, FBAR can be used in excellent sensing devices for gas sensor, liquid sensor, and biosensor etc. In short, FBAR devices act as key components for wireless communication and sensing network system.

In 1980s, the first FBAR had been presented in 1981 [5]. The design and analysis of ladder type bandpass filters utilizing the FBAR technique were presented in 1992 [6]. In 2000s, with the rapid development of wireless communication field, the study of FBAR devices for communication applications became more and more emphasized. Film bulk acoustic wave (FBAW) filters for 5 GHz had been presented in 2002 [1]. An above-IC FBAW filter for wireless applications was presented in 2006 [3]. It showed the FBAW filter has been integrated and fabricated

as a post-process directly above 0.25 μ m BiCMOS wafers comprising RF circuits for WCDMA, thus the fully-integrated RF front-end was feasible. Design of FBAW filters at high frequency bands was presented in 2006 [4]. RF Bandreject filters made by FBAR technique were presented in 2008 [7].

In this research, 5.4GHz film bulk acoustic wave filters have achieved. The cross-sectional view of film bulk acoustic wave filter structure is shown in Fig. 1. It can be applied to wireless sensor network systems. Meanwhile, it can also be used in 5.4-GHz applications, such as wireless local area network (WLAN) 802.11n and 4G-WiMAX system.

II. THEORY

A. Modeling of Resonator

A FBAW filter consists of several FBAR resonators. However, a FBAR formed on multilayer structure includes a piezoelectric layer sandwiched between a supporting layer, a bottom electrode layer, and a top electrode layer as shown in Fig. 2.

To solve the equation about acoustic wave propagating in bulk acoustic wave resonator with multilayer, there were many methods presented in the past. Among them, the exact solution of equivalent circuit model had been presented by Mason in 1948 [8] shown in Fig. 3. The inclusion of transformer and a negative capacitance in Mason model imposes difficulties in circuit simulation software. In the other way, the acoustic and electric losses of piezoelectric thin film, metal layers and structure layer are not considered in conventional Mason equivalent circuit model. In order to model the layered FBAR structure exactly, this paper adopts the concept of Mason model and KLM model to build up FBAR equivalent circuit model [9].

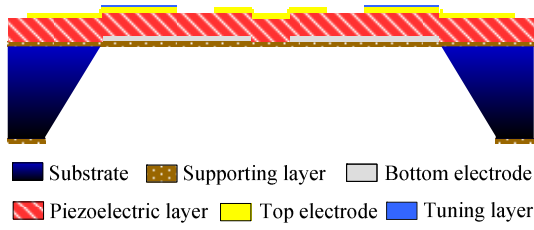


Figure 1. The schematic of FBAW filters structure.

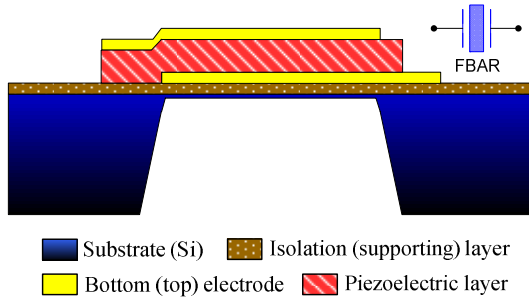


Figure 2. The schematic of basic multilayer FBARs structure.

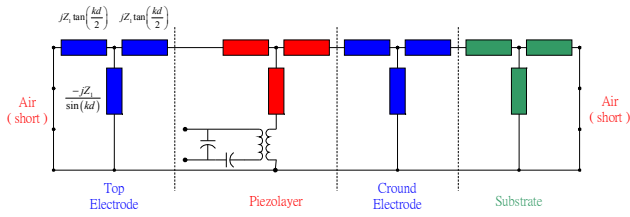


Figure 3. The Mason equivalent circuit model of FBAR.

B. Filter Design Procedure

A ladder type filter is used to meet the design specification. It is composed of the series and shunt FBAR resonators. There are two design methods adopted to design RF filter by use of lumped-element circuits conventionally [10]. In this paper, the insertion loss method is adopted to design the filter structure.

First, it is assumed that one-dimensional model is adequate to express FBAR characteristics. The impedance of FBAR behaves like a capacitance with infinite pole and zero pairs. If the effect of force loaded on both electrode of the FBAR impedance model is ignored, the FBAR impedance can be simplified as

$$Z = \frac{1}{j\omega C} \left(1 - k_t^2 \frac{\tan \frac{d\omega}{2V}}{\frac{d\omega}{2V}} \right) \quad (1)$$

$$k_t^2 = \frac{h_{23}^2 \epsilon_{zz}^S}{C_{33}^D} \quad V = \sqrt{\frac{C_{33}^D}{\rho}} \quad C = \frac{A \epsilon_{zz}^S}{d}$$

where k_t is electromechanical coupling coefficient, h_{23}^2 is piezoelectric coupling coefficient, C_{33}^D is elastic constant, ϵ_{zz}^S is dielectric constant, ρ is density, and d is thickness.

Then, for series connected LC tank, if the impedance of FBAR could be taken as LC resonator, the characteristic of impedance must be as follows.

$$Z(\omega_0) = Z_s(\omega_0) = 0$$

$$\frac{d}{d\omega} Z(\omega_0) = \frac{d}{d\omega} Z_s(\omega_0) = j2L = j \frac{2}{\omega_0^2 C} \quad (2)$$

If we substitute (2) into (1), the thickness and area size of FBAR can be determined. However, the thickness calculated from simplified equation is not very exactly. The thickness of each layer should be chosen by the modified Mason model. And, the area size of FBAR can be determined by follow equation.

$$d = 2x \frac{V}{\omega_0} \quad (3)$$

$$A = \frac{x^2 + k_t^2 - 1}{k_t^2} xVC \quad x \cot x = k_t^2$$

Similarly, for shunt connected LC tank, the characteristic of impedance must be as follows.

$$Y(\omega_0) = Y_p(\omega_0) = 0$$

$$\frac{d}{d\omega} Y(\omega_0) = \frac{d}{d\omega} Y_p(\omega_0) = j2C = \frac{j2}{\omega_0^2 L} \quad (4)$$

If we substitute (4) into (1), the thickness and area size of FBAR can be determined as follows.

$$d = \pi \frac{V}{\omega_0} \quad (5)$$

$$A = \frac{8k_t^2}{\pi} \frac{VC}{\omega_0 \epsilon_{zz}^S}$$

The dimensions of a FBAW filter can be preliminarily designed by the (3) and (5).

In general, Butterworth type and Chebyshev type are usually used to filter design. The value of inductance and capacitance of ideal series and parallel LC tank can be obtained by basic filter theory [10]. Then, each FBAR thickness and area of the filter can be determined by fitting the impedance of LC tank.

III. DESIGN AND SIMULATION

During our research phase, we determined the FBAW filters should conform to 5.4-GHz wireless communication protocol. For this purpose, the desired impedance is 50 Ω , and the central frequency is 5450 MHz in the filter design. The bandwidth is 80 to 120 MHz. Stopband rejection is at least -30 dB; insertion loss is within -3 dB.

A. Design

The desired 5.4GHz FBAW filters consist of several FBAR resonators, and the layered structure is constructed from a supporting layer, a bottom electrode layer, a piezoelectric layer, a top electrode layer, and a tuning layer in sequence as shown in Fig 1. This design makes use of Butterworth function type and five-order ladder-type filter topology. The five-order FBAW filter is composed of three series FBARs and two shunt FBARs. Aluminum (Al) is applied to the bottom and top electrodes; the tuning layer material chooses aurum (Au); the piezoelectric layer material chooses aluminum nitride (AlN). Following the above design procedures, each parameter of the FBAR components constituting the desired filter is obtained. The layer thickness and area size of each FBAR component of the 5.4GHz FBAW filters are designed as listed in Table I.

B. Simulation

The authors do not consider loss effect for the moment in design phase. The above design is simulated in the ADS electronic design automation software (Agilent technologies, Santa Clara, California). The simulated S_{11} , S_{21} , S_{12} , and S_{22} parameters of the designed FBAW filter are shown in Fig. 4. The significant parameters can be obtained by the simulated scattering parameters versus frequency response curve.

Fig. 4 reveals the passband is about 5408 to 5498 MHz; return loss is smaller than -12 dB, attenuation in stopband is smaller than -35 dB, and stopband attenuation rate near the bandwidth is about 2.0 dB decay per unit MHz in the designed filter.

IV. FABRICATION

A. Layout and Consideration of Fabrication

The desired 5.4GHz FBAW filter is a five-order (three-by-two) ladder-type filter cascading with long transmission lines to demonstrate this study as shown in Fig 5. As shown in this layout, the middle series $30 \mu\text{m} \times 30 \mu\text{m}$ FBAR of the filter is replaced with two series $43 \mu\text{m} \times 43 \mu\text{m}$ FBARs, which is equivalent the middle series FBAR. The reason is (i) the symmetry of the structure can reduce high frequency parasitic effect; (ii) the FBAR unit is smaller than the other FBAR units so it is inconvenient to connecting the other FBAR and back-side etching of the below fabrication; (iii) it is in favor of the five-order filter cascading with the long transmission line. The emphasis of the FBAW filters fabrication would be the compatibility of micro-electro-mechanical systems (MEMS) process and complementary metal-oxide-semiconductor (CMOS) standard IC process. Therefore, the material and etching selectivity of each layer are considered. In the experiment, the well-oriented quality of piezoelectric layer sputtering is important.

B. Fabricated Procedure

The FBAW filter structure are used for air-via-hole suspended formations and located on Si_3N_4 membrane above silicon substrate. Therefore, the bulk micromachining MEMS process is applied to this fabrication. The fabrication flow is shown in Fig. 6.

TABLE I. THE DIMENSIONS OF EACH FBAR IN DESIGNED 5.4GHz FILM BULK ACOUSTIC WAVE FILTER

Filter Topology	 five-order filter (3×2 discrete)		
FBAR Component	Series A1	Shunt A2	Series A3
Area Size (μm^2)	55×55	97×97	30×30
Supporting layer Si_3N_4 (nm)	104	104	104
Bottom electrode Al (nm)	120	120	120
Piezoelectric layer AlN (nm)	570	570	570
Top electrode Al (nm)	120	120	120
Tuning layer Au (nm)	0	3.6	0

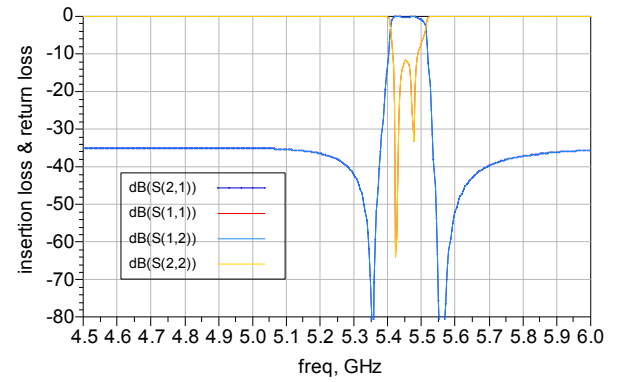


Figure 4. Simulated result of the designed film bulk acoustic wave filter.

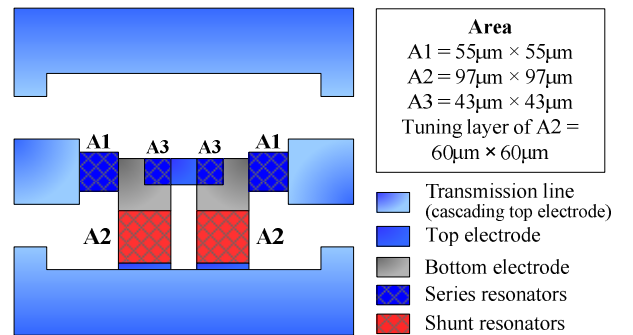


Figure 5. The layout schematic of film bulk acoustic wave filter structure.

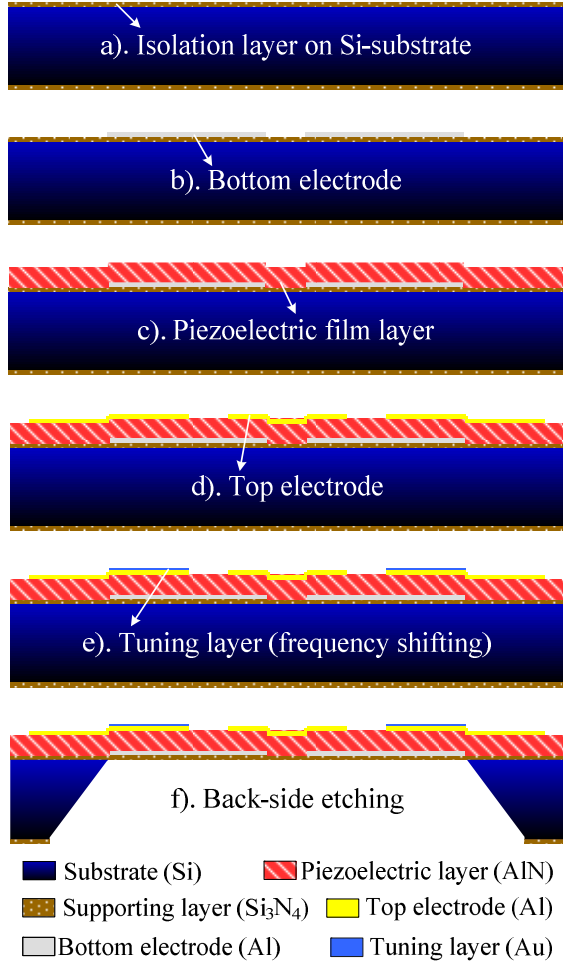


Figure 6. The fabricated procedure of film bulk acoustic wave filter.

First, the supporting layer (Si_3N_4) is developed on a silicon (Si) substrate, which will reduce substrate loss of electrodes connecting with ground-signal-ground (G-S-G) pads and enhance the filter strength.

Second, the bottom electrode (Al) is deposited on the supporting layer, and it is patterned by lift-off approach. A uniform bottom would be helpful for excellent piezoelectric deposition.

Third, a well-oriented piezoelectric layer (AlN) is sputtered on the patterned bottom electrode. The temperature is limited to approximately 300°C .

Fourth, the top electrode layer (Al) and the thin film of tuning layer (Au) are deposited successively on the piezoelectric layer. The top electrode layer is patterned by wet etching approach; furthermore, the tuning layer is preferred to pattern by lift-off approach.

Last, after depositing each layer of the FBAW filter, the Si substrate of the structure will be backside patterned and etched by potassium hydroxide (KOH). Then, the structure is successfully suspended and accomplished.

V. RESULT AND DISSCUSSION

A. Structure and Piezoelectric Film Analysis

The 5.4GHz FBAW filter has been accomplished as shown in Fig. 7. The top view of the FBAW filter structure is shown in Fig. 7(a). By the Fig. 7(a) illustration, we can confirm that the whole size of the structure is $0.74\text{ mm} \times 0.42\text{ mm}$. The fabricated FBAW filter is cascading with a long transmission line, and the part of filter is only size of $0.35\text{ mm} \times 0.15\text{ mm}$. The crystalline of a piezoelectric material has a particularly strong influence the FBAR performance. The piezoelectric layer consists of C-axis-oriented AlN, which is deposited by pulsed reactor DC magnetron sputtering. The cross-sectional structure of AlN film between Al electrodes is shown in Fig. 7(b). Fig. 7(b) reveals that the AlN film exhibits a c-axis-oriented columnar structure and a columnar grain structure in the vicinity of the bottom electrode Al.

B. Measured Result

The measured FBAW filter is an accomplished five-order filter and the I/O pads are located on transmission lines connecting top electrodes of the filter as shown in Fig. 8. The measurement is used of HP8510C Vector Network Analyzer (VNA) and probes using Cascade Microtech's standard Air CoplanarTM G-S-G 150 pitch probe tips. The Measured result is shown in Fig. 9.

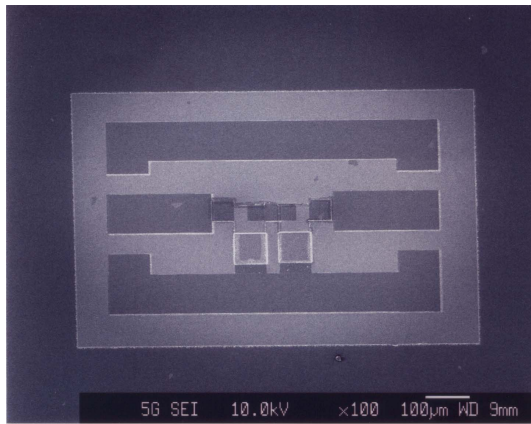
Fig. 9 reveals the measured S_{11} , S_{21} , S_{12} , and S_{22} parameters of the FBAW filter. The performance of the FBAW filter can be obtained by the measured scattering parameters versus frequency response. The central frequency is 5406 MHz, and the bandwidth is approximately 70 MHz. Return loss in the passband is smaller than -18 dB . Insertion loss in passband is approximately -10 dB . Attenuation in stopband is approximately -36 dB . The practical stopband rejection (i.e., the difference between attenuation in stopband and insertion loss in passband) is smaller than -26 dB . The stopband attenuation rate near the bandwidth is approximately 0.6 dB decay per unit MHz. The measurement compared with design of the 5.4GHz FBAW filter is listed in Table II.

VI. CONCLUSION

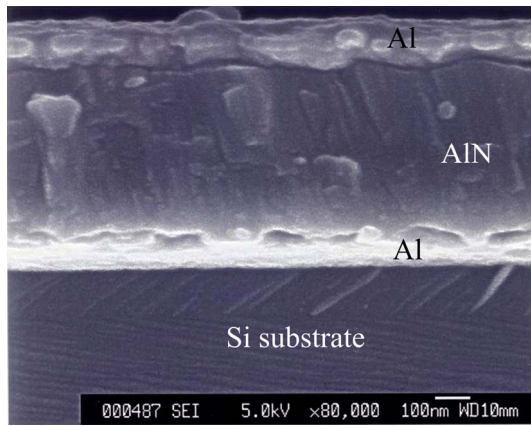
A complete solution to design and fabricate an FBAW filter is revealed in this paper. FBAW filters could be more easily designed, simulated and fabricated by using the above method. The 5.4GHz FBAW filter has been demonstrated, which is an air-via-hole suspended formation by bulk micromachining MEMS process. The fabricated FBAW filter has central frequency of 5406 MHz, bandwidth of 70 MHz, return loss of -17 dB , insertion loss of -10 dB , stopband attenuation of -36 dB , and size of $0.74\text{ mm} \times 0.42\text{ mm}$.

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(a)



(b)

Figure 7. Scanning electron microscopy images of the fabricated film bulk acoustic wave filter. (a) Top view of the structure. (b) Cross-sectional view of the structure.

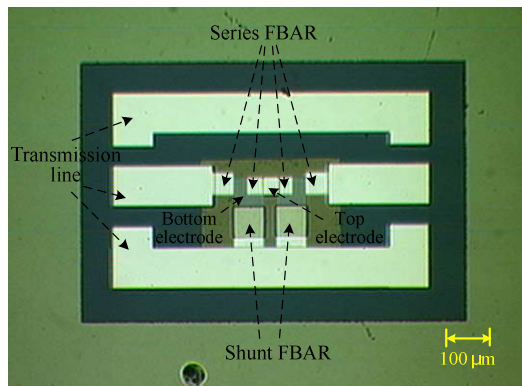


Figure 8. Photograph of the accomplished film bulk acoustic wave filter.

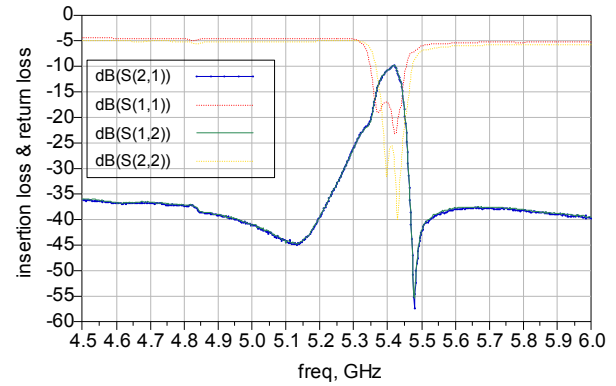


Figure 9. Measured results of the accomplished film bulk acoustic wave filters. The measured S-parameter vs. frequency diagram.

TABLE II. PERFORMANCE LIST OF THE DESIGNED AND MEASURED 5.4GHZ FILM BULK ACOUSTIC WAVE FILTER.

Performance	Design	Measurement
Central frequency	5453 MHz	5406 MHz
Bandwidth	90 MHz	70 MHz
Return loss	< -12 dB	< -7 dB
Insertion loss	-1 dB	-10 dB
Attenuation in stopband	< -35 dB	< -36 dB
Stopband attenuation rate near passband	-2.0 dB/MHz	-0.6 dB/MHz

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