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Air-Gap Type TFBAR Ladder Filters for Wireless Applications

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Abstract

TFBAR filters for wireless applications are simulated and fabricated. A CAD model is used to analyze the air-gap type single resonator and MBVD model is used for filter design. Aluminum nitride is used as the piezoelectric material with platinum electrodes. To verify the CAD model, simulated and measured results are compared for various top electrode thicknesses, and the agreement is within 0.5 % for the parallel resonance frequency. Various types of the ladder type band pass filters are predicted and their responses are compared with measured frequency data.

Key words : TFBAR, CAD model, MBVD model, ladder filter.

Ⅰ. Introduction

Given the inherent limitations in miniaturizing of RF systems with conventional ceramic or surface acoustic wave (SAW) devices, thin film bulk acoustic resonator (TFBAR)-based filters and duplexers are considered promising alternatives. Many researchers have focused their researches on modeling piezoelectric materials, and various models have been developed [1]~[4]. Among them, Mason's model[1] is one of the most widely used for the analysis of piezoelectric materials; however, it contains a transformer and a negative capacitance, which impose difficulties in the development of the computer-aided design (CAD). Redwood[2] and Morris[3] rearranged Mason's model to provide suitable topologies for CAD applications. Leach[4] developed previous work further and devised the SPICE models with controlled-sources to overcome the disadvantages of a transformer and a negative capacitance. Leach's circuits are modeled for both the thickness-mode and the side-electrode bar piezoelectric mode. We have considered the thickness-mode piezoelectric structure only, since the side-electrode bar mode is negligible for a small area size of the TFBAR.

TFBAR-based filters and duplexers bear numerous advantages, and some of them display low loss, good temperature stability and high dynamic range characteristics. Aluminum nitride (AlN) and zinc oxide (ZnO) are competitive materials for thin film resonators. However, aluminum nitride has been used in this work, due to several undesirable characteristics of ZnO, such as its low electrical resistance, low breakdown voltages, and high dielectric losses[5]~[7]. In this paper, four different types of TFBAR ladder filter topologies have been examined based on the modified Butterworth Van-Dyke model[8]. Two of them are conventional type 2/1 and 3/2 stage filters, while the other two types are modified from their conventional structure with additional TFBARs. The modified filters exhibit better out-of-band rejection characteristics by 3 dB per additional TFBAR.

Ⅱ. Analysis of a Single TFBAR

2-1 CAD Model for an Air-gap Type TFBAR

There are characteristic structures which form the various TFBARs, such as air-gap types, back etched types, solidly mounted types, and so on. An air-gap type TFBAR has an advantage in fabrication compared to other types, because the latter types must have the substrate material etched or several layers stacked up under the bottom electrode to form a Bragg-type reflector. Fig. 1 depicts the geometry of the air-gap type unit cell TFBAR used in this work. AlN is sandwiched between platinum electrodes, and both a SiNx membrane and air-gap are used to avoid the over-mode phenomenon due to silicon substrate loading effects. The area size of the TFBAR is 150 by 150 μm^2, and the thicknesses of the AlN, bottom electrode, membrane, air-gap and substrate are 1 μm, 0.2 μm, 0.2 μm, 1.5 μm, and 500 μm, respectively.

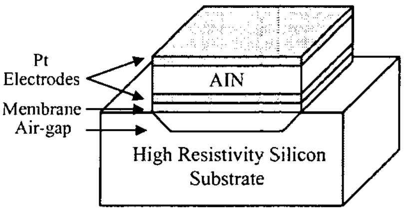

Fig. 1. Geometry of an air-gap type TFBAR.

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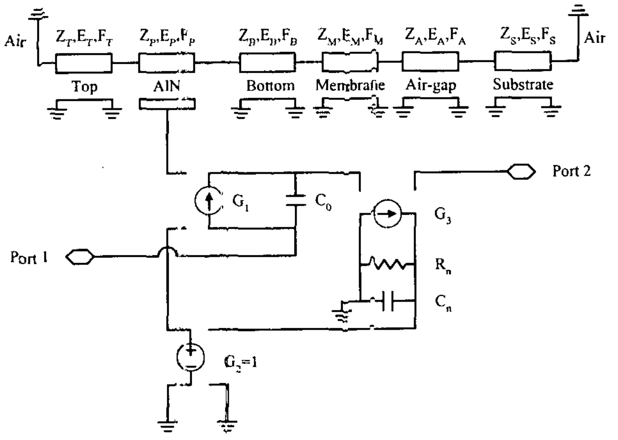


Fig. 2. CAD model for an air-gap type TFBAR.

Fig. 2 shows the CAD model proposed in this paper. Transmission line models are used to characterize the top and bottom electrodes, membrane, air-gap and silicon substrate. Transmission line model parameters are acoustic impedance *Z*, electrical length *E* in degree and resonance frequency of piezoelectric material *F*, which decide the electrical length *E*. They are given as:

$$Z = \rho v_a A, \qquad E = \frac{360 dF}{v_a}, \qquad F = \frac{v_a\sqrt{\pi^2 - 8k_t^2}}{2\pi d_p} \tag{1}$$

where ρ is the density of the material, v_a is the acoustic velocity of the material, *A* is the area, *d* is the thickness of the material, k_t^2 is the electromechanical coupling constant and d_p is the thickness of the piezoelectric material. One voltage controlled voltage source (VCVS) and two current controlled current sources (CCCS) are used to substitute for a transformer and a negative capacitance in Mason's model. Each CCCS has the Gain of $G_1 = hC_0$ and $G_2 = h$, where *h* is obtained from material stiffness constant. C_0 is the electrical capacitance between two electrodes and depends on three parameters: the dielectric constant of piezoelectric material, area of the TFBAR and distance between the electrodes d_p. R_n and C_n are included to prevent the node from being a floating node. Transmission line model parameters can be obtained from the material parameters summarized in Table 1.

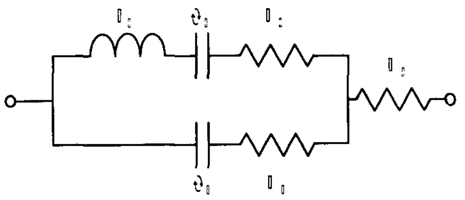
Table 1. Material parameters used in the CAD model.

Property(Unit)	Pt.	AlN	Air	SiNx	Si
Acoustic impedance(Mrayls)	69.8	37	4e-3	20.8	19.7
Acoustic velocity(m/s)	3250	6350	330	6700	8430
Density(kg/m^3)	21500	11350	12	3100	2332

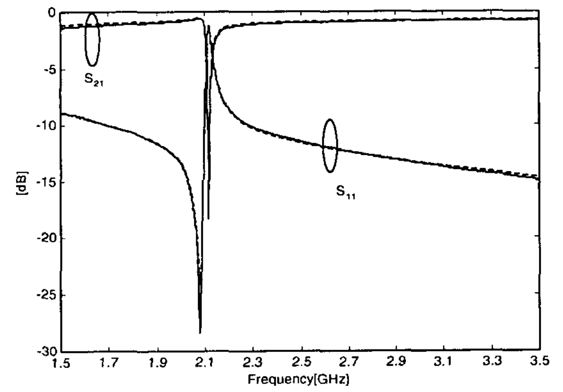
2-2 Modified Butterworth-Van Dyke Model

A Single TFBAR can be analyzed by the above mentioned 3-port Mason's model [1] or Leach's Model[4]. However, Since TFBARs have very thin electrodes, which are negligible, the Mason's model or Leach's model may be simplified to the six lumped elements model. The Modified Butterworth-Van Dyke model(MBVD), as shown in Fig. 3a, consists of the electrical and motional arms in parallel. In the electrical arm, there are parallel plate electric capacitance C_0 and material losses R_0; while in the motional arm, there is an acoustic resonance circuit with series R_m-L_m-C_m. Parameter extraction of the MBVD model has been directly performed from measured data, as given in reference[8]. For the acquisition of the experimental data, a microwave probe station and vector network analyzer combination has been used with the Line/Reflect/Line calibration procedure for accuracy. Fig. 3b shows good agreement between the comparison of the modeled and measured S-parameter results of the unit cell TFBAR.

The modeled parameters have low resistance values, and C_0 is about 2.4 pF. The electromechanical coupling constant k_t^2 and quality factor Q_s can be derived from the measured as well as modeled data with the equation;



(a) Six element Modified BVD model



(b) Single TFBAR frequency response

——— Simulation

··········· Measurement

Fig. 3. MBVD model and frequency response.

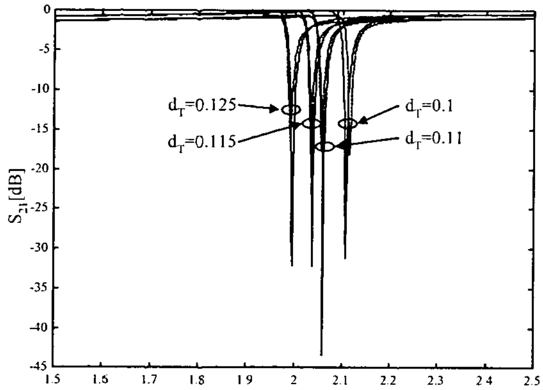
$$k_t^2 = \frac{\pi^2}{4}\left(\frac{f_p - f_s}{f_p}\right), \quad Q_s = \frac{2\pi f_s L_m}{R_m} \tag{2}$$

where f_p and f_s are the parallel and series resonance frequencies, respectively. For a unit cell TFBAR, k_t^2 is 4.2 %, and quality factor Q_s at series resonance is 577.2.

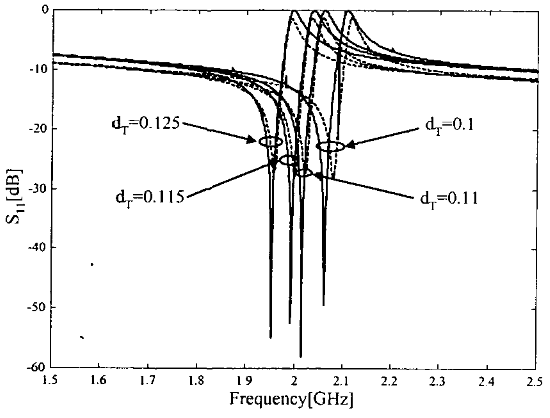
Ⅲ. Simulation and Results

3-1 CAD Model Simulation and Experimental Results

The modeled circuits analyzed in 2-1 have been simulated using a commercial design suite, and the frequency responses of the fabricated TFBARs are measured with a probe station and vector network analyzer. The thicknesses of top electrode d_T are 0.1 μm, 0.11 μm, 0.115 μm and 0.125 μm, and the area size of the TFBAR is 150 by 150 μm^2. Fig. 4 shows the simulated and measured S parameters for four different electrode thicknesses.



(a) S_{21} response



(b) S_{11} response

——— Simulation
·········· Measurement

Fig. 4. Simulated and measured results with respect to top electrode thickness change. (d_T : Top electrode thickness)

Table 2. Results of the CAD simulation and measurement.

Top electrode thickness(μ m)	Parallel resonance frequency (GHz)		Error (%)
	Simulation	Measurement	
0.125	1.996	1.991	0.25
0.115	2.038	2.034	0.19
0.11	2.060	2.056	0.19
0.1	2.107	2.115	0.37

It is apparent that the resonance frequency shifts to a lower frequency region as the top electrode becomes thicker. A parallel resonance frequency peak is adapted for comparison with the measured data, because its values are easier to find than the series resonance frequency. Table 2 summarizes the parallel resonance frequencies and their percentage errors. It reveals that the simulations and measurements are in good agreement within an error rate of 0.5 %.

3-2 Ladder Type Filter Design and Results

Ladder type filters are commonly used in the design of TFBAR filters due to their good power handling capability, low insertion loss and high stop-band attenuation characteristics. In this paper, four types of ladder filters, 2/1 stage, 3/2 stage, 4/1 stage and 4/2 stage are considered. The top electrode thickness of shunt TFBARs is adjusted to have about a 2 % lower resonance frequency than series TFBARs. Fig. 5 shows the S_{21} frequency response of the modeled and measured results for 2/1 and 4/1 stage ladder filters. Both filters reveal a good insertion loss of less than 3 dB, and it is interesting to observe that the 4/1 stage filter has an improvement of about 6 dB in the stop-band. Any additional TFBARs cause a negligible amount of

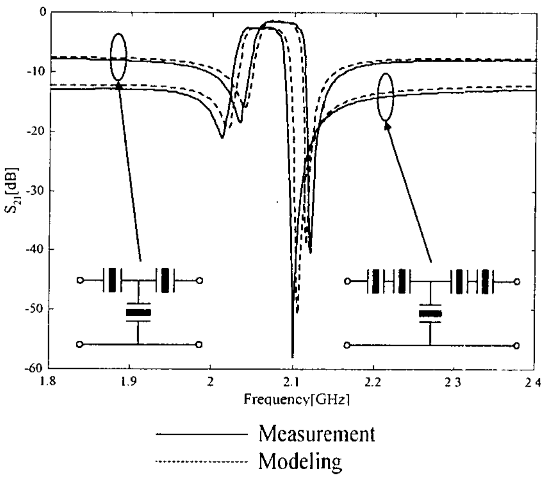


Fig. 5. 2/1 stage and 4/1 stage ladder filter response.

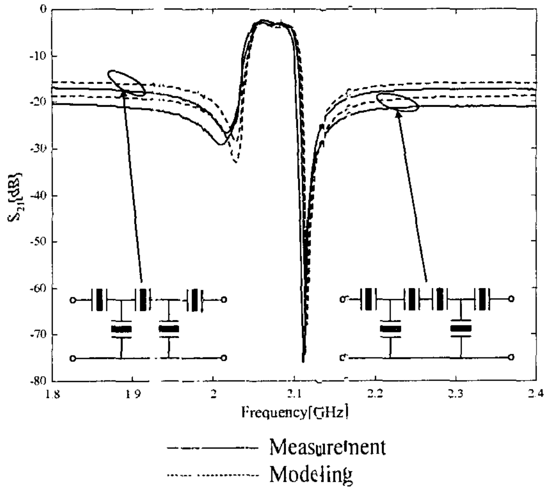


Fig. 6. 3/2 stage and 4/2 stage ladder filter response.

Table 3. Summary of filters characteristics.

Types of Filter	Insertion loss(dB)	S_{11} in pass band(dB)	Out-of-band rejection(dB)	Bandwidth (MHz)
2/1 stage	−1.50	− 7 to −40	− 8.2	57.5
3/2 stage	−2.36	−11 to −30	−17.2	51
4/1 stage	−2.45	−11 to −32	−14.1	52.5
4/2 stage	−2.75	−11 to −39	−20.4	52.4

shift in center frequency, which can be adjusted if necessary. Fig. 6 shows the S_{21} of the 3/2 and 4/2 stage filters, and it is observed that the 4/2 stage filter has a about 3 dB suppression improvement in the stop-band, while maintaining an equal insertion loss in the pass-band. A summary of the four different types of filter characteristics is presented in Table 3.

Ⅳ. Conclusion

In this paper, we present a CAD model for an air-gap type TFBAR, and its validity has been proved with measured data and four types of ladder filters are fabricated based on the CAD model. The presence of an air-gap prevents the over-mode phenomenon by separating the bottom electrode from the silicon substrate.

The disadvantages of Mason's model have been modified with controlled sources, and a transmission line model is used to model the non-piezoelectric materials. For verification of the CAD model, TFBARs with four different top electrode thickness have been fabricated, and the measured and modeled data agree very well (with a 0.5 % discrepancy) at the parallel resonance frequency.

Various TFBAR-based filter topologies are also presented, and their characteristics are predicted with measured TFBAR frequency responses. AlN is used as a piezoelectric material, and the electric coupling coefficient k_t^2 is 4.2 %, and the quality Q_s factor is 577.2 for a unit cell TFBAR. It is shown that suppression in the stop-band can be improved by 3 dB per additional TFBAR. The CAD model presented in this paper predicts the behavior of TFBAR filter responses with respect to various geometrical as well as material parameters. Fabricated TFBAR filters in this paper have a low insertion loss of 2 to 3 dB and a bandwidth around 52 MHz. They can be used as highly selective RF filter devices with minor tuning.

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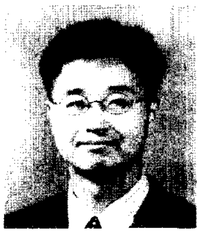

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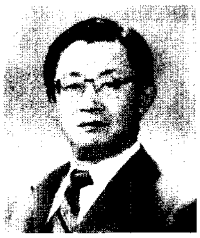

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