TFBAR Filters for 2 GHz Wireless Applications

K.W. Kim, J.G. Yook, M. G. Gu+, W.Y. Song*, Y. J. Yoon, and H. K. Park

Dept. of Electrical and Electric Eng., Yonsei Univ., Seoul, Korea
+ MEMS Solutions Inc., Seoul, Korea
* College of Sci. and Eng., Chongju University, Chongju, Korea

***Abstract*—Thin film bulk acoustic resonators (TFBAR) using AlN with two electrodes have been used in the design of band pass filters at 2 GHz frequency bands. Both membrane and air-gap are used to suppress the over-mode phenomenon. Resonator modeling was performed based on measured frequency response of a single resonator with modified Butterworth-Van Dyke (MBVD) model. Electric coupling coefficient, k, is 0.2075 (4.3%) and Q is 577.18 for a single TFBAR. Additional TFBAR is used to improve out of band rejection in the conventional ladder topology and each contributes −3 dB suppression improvement at stop-band. Four different types of ladder filters were fabricated and modelled and revealed only −2 to −3 dB insertion loss for all the cases with bandwidth of around 52 MHz.**

I. INTRODUCTION

Rapid growth in wireless communications handset market is remarkable and there is a great demand for miniaturized devices. Improvements in the miniaturization of the conventional ceramic and Surface Acoustic Wave (SAW) devices enable small sized front-end RF and IF filters. However, they have difficulties in on-chip implementation and also have poor electrical power handling capability and limited range characteristics [1]-[2]. TFBAR technology is considered as an alternative in miniaturization of those filters. The advantages of TFBAR are low loss, good temperature stability and high dynamic range [1]. Aluminum nitride is used as a piezoelectric material instead of Zinc oxide (ZnO) because ZnO has some defects of low electrical resistance, low breakdown voltages, and high dielectric losses. There are some structures to form TFBAR such as air-gap type, back etched type, solidly mounted type and so on. An air-gap type TFBAR has an advantage in fabrication compared to back etched type or solidly mounted type. The latter two types have complex fabrication procedures, because they have to etch the substrate and stack up several layer under the substrate to form a reflector [1]. The previous work has been concentrated on the piezoelectric materials, the resonator characteristics with respect to electrode thickness, and the modeling of a resonator [1]-[5]. In this paper, various types of TFBAR ladder filter topologies have been examined and their measured as well as modeled results are presented.

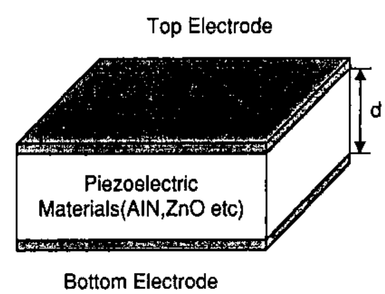
II. MODIFIED BUTTERWORTH-VAN DYKE MODEL

Thin film bulk acoustic resonator is conveniently fabricated by micromachining processing techniques. Fig. 1 shows (a) perspective view, (b) conventional BVD model and (c) modified BVD model of TFBAR. Single TFBAR can be modeled by one dimensional model called the 3-port Mason model [3]-[4]. TFBAR has very thin electrodes, which are negligible, and 3-port Mason model may be simplified to the five lumped elements model. Butterworth-Van Dyke model as shown in Fig. 1(b) consists of the electrical arm (plate electric capacitance C_0 and material losses R_0) and the motional arm (acoustic resonance circuit with series L_m-C_m-R_m) in parallel. Larson [5] added a series resistor outside of the resonance block and thus the conventional BVD model has been modified. With approximations, the impedance of the equivalent circuit with respect to frequency can be defined as; [5]

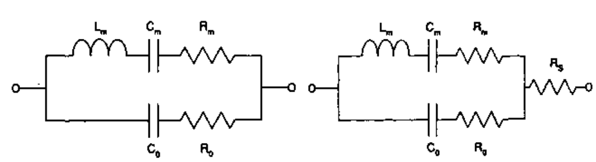
$$Z(\omega) = \frac{X_p}{j\left(\frac{\omega}{\omega_p}\right)} \frac{\left[1-\left(\frac{\omega}{\omega_s}\right)^2 + j\left(\frac{\omega}{\omega_s}\right)\frac{1}{Q_{so}}\right]}{\left[1-\left(\frac{\omega}{\omega_p}\right)^2 + j\left(\frac{\omega}{\omega_p}\right)\frac{1}{Q_{po}}\right]} \qquad (1)$$

where,

$$r = \frac{C_0}{C_m}, \omega_s = \frac{1}{\sqrt{L_m C_m}}, \left(\frac{\omega_p}{\omega_s}\right)^2 = 1 + \frac{1}{r}$$



(a) Physical piezoelectric resonator



(b) BVD model (c) Modified BVD model

Fig. 1. Thin Film Bulk Acoustic Resonator structure and their models

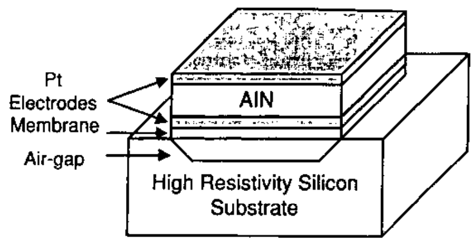


Fig. 2. The unit cell TFBAR structure

$$X_p = \frac{1}{\omega_p C_0}, \frac{1}{Q_s} = \omega_s \cdot R_m \cdot C_m, \frac{1}{Q_e} = \frac{\omega_s \cdot R_m \cdot C_m}{r}$$

$$\frac{1}{Q_{so}} = \frac{1}{Q_s} \cdot \left(1 + \frac{R_s}{R_0}\right), \frac{1}{Q_{po}} = \left(\frac{\omega_p}{\omega_s}\right)\left(\frac{1}{Q_s} + \frac{1}{Q_e}\right)$$

where, r is a capacitance ratio of the motional arm and electrical arm, ω_s is a series resonance frequency and ω_p is a parallel resonance frequency. Single stage unit structure consisting of series impedance and parallel admittance can be used for a multi-stage filter design and 2-port ABCD parameters are derived from the impedance equation (1);

$$\begin{bmatrix} a & b \\ c & d \end{bmatrix} = \begin{bmatrix} 1 & Z_a \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ Y_b & 1 \end{bmatrix} = \begin{bmatrix} 1 + Z_a Y_b & Z_a \\ Y_b & 1 \end{bmatrix} \tag{2}$$

where Z_a is a series impedance and Y_b is a parallel admittance. Using multiplicative property of ABCD parameters, multi-stage ABCD parameters are easily obtained. In terms of ABCD parameters, the 2-port S-parameter filter response is given by;

$$\begin{aligned} S_{21} &= \frac{2}{a + b/Z_0 + cZ_0 + d} \\ S_{11} &= \frac{a + b/Z_0 - cZ_0 - d}{a + b/Z_0 + cZ_0 + d} \end{aligned} \tag{3}$$

where Z_0 is the characteristic impedance of the port. Fig. 2 shows an air-gap type TFBAR used in this paper. High Resistivity Silicon (HRS) is used as a substrate and there is an air-gap between membrane and substrate. Typical fabrication involves deposition of a piezoelectric film on a substrate followed by removal of a $1.5\mu m$ of the substrate to form the air-gap. Conventional structure uses the air-gap as a membrane, however both membrane and air-gap are fabricated for the over-mode suppression in this study. Basically, membrane supports the piezoelectric material block and piezoelectric material is sandwiched in between top and bottom platinum electrodes.

III. The Unit Cell TFBAR

The MBVD parameters can be extracted from the measured S-parameters using well-known equations. For the experimental data acquisition microwave probe station and vector network analyzer combination have been used. The Line/Reflect/Line calibration is adapted for accuracy. Calibration procedure is very important to obtain accurate experimental results. Fig. 3 shows measurement and modeling results of the unit cell TFBAR S-parameters and reveals sharp skirt characteristics and low insertion loss. Modeled parameters have low resistance values and C_0 is about $2.4pF$. Table. I summarizes the unit cell TFBAR characteristics. From TFBAR characteristics of Table.I, electric coupling coefficient,k, is 0.2075(4.3%) and Q is 577.18 at series resonance. The unit cell TFBAR characteristics are very important, because the ladder or lattice type filter responses highly depend on their unit cell characteristics.

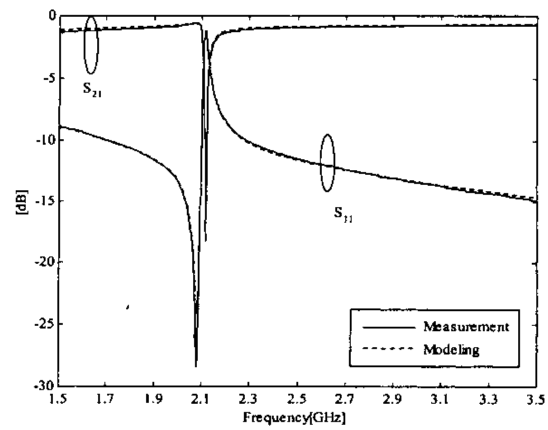


Fig. 3. Frequency response of the unit cell TFBAR

TABLE I
THE UNIT CELL TFBAR CHARACTERISTICS

Series Resonance			Parallel resonance			Offset
Freq. (GHz)	S_{11} (dB)	S_{21} (dB)	Freq. (GHz)	S_{21} (dB)	S_{11} (dB)	(MHz)
2.0787	-28.39	-0.6	2.115	-18.32	-1.3	36.3

IV. Filter Design and Experimental Results

The ladder type filter is commonly used in design of TFBAR filters. They have advantages in better power handling capabil-

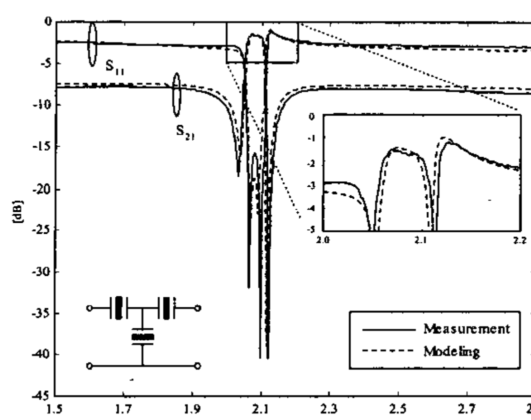


Fig. 4. 1.5 stage filter frequency response

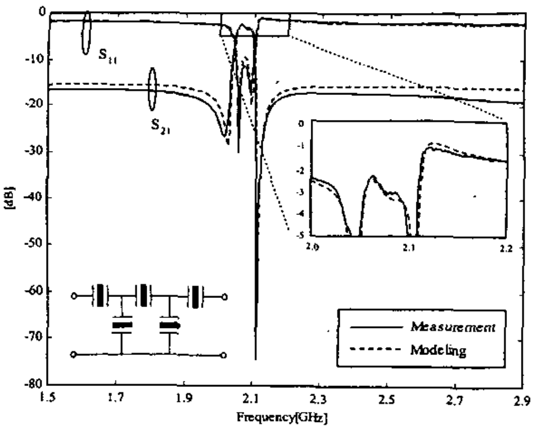


Fig. 5. 2.5 stage filter frequency response

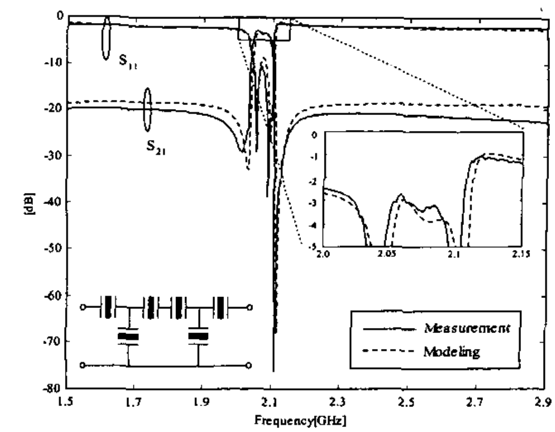


Fig. 7. 2.5 stage filter with additional TFBAR frequency response

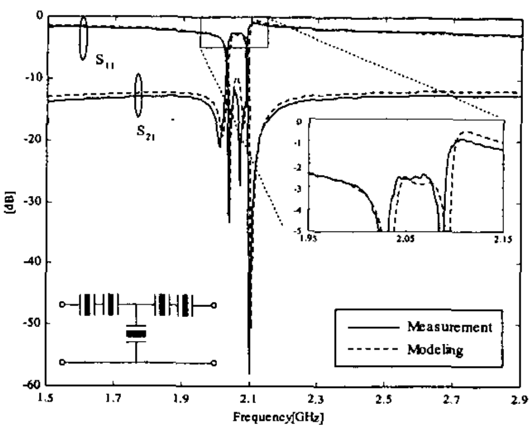


Fig. 6. Double series arm 1.5 stage filter response

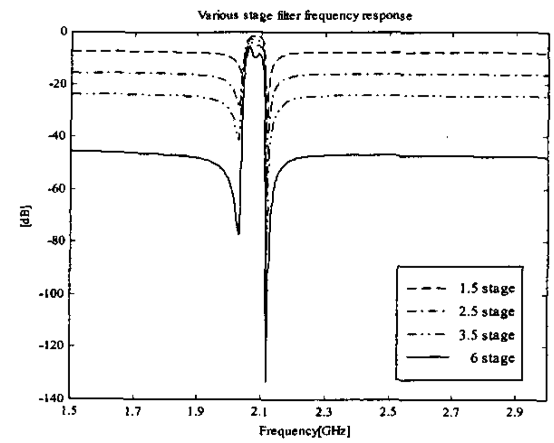


Fig. 8. Various stage filters simulation results

ity, low insertion loss, high stop-band attenuation, better reflection coefficient at stop-band and good 3rd order intercept point characteristics. The ladder type filter exhibits loss characteristics such that more stages are used poorer insertion loss but better return loss at stop-band are obtained. The number of the filter stage is decided by the specification of the applications. *Fig. 4 and Fig. 5 show the results of 1.5 stage and 2.5 stage fil*ter responses, respectively. Both filters have good insertion loss characteristics less than -3 dB and sharp skirt characteristics. Fig. 6 shows the results of double series arm 1.5 stage ladder topology. Double series arm means that there are two TFBAR pair in the series arm. Double series arm makes additional attenuation in the filter skirts by 6 dB and it is reported that the double series arm topology can support high power handling tolerance up to 1 W [6]. Additional stage could lead to the same phenomena, but the total size of the filter can be reduced with only additional TFBAR structure. Fig. 7 shows the results of 2.5 stage filter response with additional TFBAR in the middle of the topology and reveals additional 3 dB suppression at stop-band compared to the previous 2.5 stage ladder filter. Additional TFBAR cause a negligible shift in center frequency but it can be adjusted if necessary. Various types of ladder structures are also under investigation for better performance. Four types of filter have almost same frequency bandwidth of about 52 MHz, and which is suitable for RF filter in most 2 GHz wireless applications such as PCS, IMT-2000 etc. In addition, simulation results of various stage filters are presented in Fig. 8 and observed that additional stages ensure about 5 dB return loss suppression improvement at stop-band. Table.II summarizes the results of the four types of filter characteristics.

V. Conclusion

This paper presents TFBAR ladder filter topologies and their excellent characteristics. AlN is used as a piezoelectric material and electric coupling coefficient k is 0.2075(4.3%) and Q is 577.18 for a single TFBAR. MBVD model is proved to be appropriate in the TFBAR ladder type filter design and its parameter extraction is directly performed from measured S-parameters. It is shown that suppression at stop-band can be improved by 3 dB per additional TFBAR and additional stage could provide about 5 dB return loss improvement at stop-band. Fabricated TFBAR filters in this paper have low insertion loss of 2 to 3 dB and have bandwidth around 52 MHz. They can be

TABLE II
SUMMARY OF FILTER CHARACTERISTICS

	Insertion Loss(dB)	Return Loss In Pass Band(dB)	Out of Band Rejection(dB)	Bandwidth(MHz)
1.5 stage	−1.50	−7 to −40	−8.2	57.5
2.5 stage	−2.36	−11 to −30	−17.2	51
1.5 stage with double series arm	−2.45	−11 to −32	−14.1	52.5
2.5 stage with added TFBAR	−2.75	−11 to −39	−20.4	52.4

used as RF filters with highly selective devices and also can be applied to VCO for the better phase noise performance due to TFBAR's high Q characteristics.

ACKNOWLEDGEMENT

The authors wish to acknowledge the assistance of J.M. Jhung on the fabrication of TFBAR devices. This work was supported in part by grant No.R01-2000-00270 from the Korea Science & Engineering Foundation.

REFERENCES

[1] Q. X. Su, P. Kirby, E. Komuro, A. Imura, Q Zhang, and R. Whatmore, "Thin-film bulk acoustic resonators and filters using ZnO and Lead-Zirconium-Titanate thin films," *IEEE Trans. Microwave Theory and Techniques*, vol. 49, no. 4, pp. 769-778, April 2001.

[2] R. S. Naik, J. J. Lutsky, R. Reif and C. G. Sodini, "Electromechanical coupling constant extraction of thin-film piezoelectric materials using a bulk acoustic wave resonator," *IEEE Trans. Ultrasonics, Ferroelectrics, and Frequency Control*, vol. 45, no. 1, pp. 257-263, Jan. 1998.

[3] K. M. Lakin, "Modeling of thin film resonators and filters," *1992 IEEE MTT-S Digest.*, vol. 1, p.149-152, 1992.

[4] K. M. Lakin, G. R. Kline, and K. T. McCarron, "Thin film bulk acoustic wave filters for GPS," *1992 Ultrasonics Symposium Digest*, vol. 1, pp. 471-476, 1992.

[5] J. D. Larson III, P. D. Bradley, S. Wartenberg, and R. C.Ruby, "Modified Butterworth-Van Dyke circuit for FBAR resonators and automated measurement system," *2000 IEEE Ultrasonics Symposium Digest*, vol. 1, pp. 863-868, 2000.

[6] P. D. Bradley, R. C. Ruby, J. D. Larson III, Y. Oshmyansky and D. Figueredo, "A Film Bulk Acoustic Resonator (FBAR) Duplexers for US-PCS Handset Applications," *2001 IEEE MTT-S Digest*, vol. 1, pp.367-370, 2001.