Performance of Polygonal-Shaped TFBARs and On-Wafer Tuning Inductors

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***Abstract* — In this paper, two different shapes of thin film bulk acoustic resonators (TFBARs) are characterized with respect to electrode thickness and overall area, and gold plated on-wafer inductors are employed to tune the TFBAR filter performance. Air-gap type TFBARs are fabricated with aluminum nitride (AlN) as a piezoelectric material and platinum as top and bottom electrodes. Equivalent inductor model is employed for the tuning of fabricated TFBAR bandpass filters designed based on the modified Butterworth-Van Dyke (MBVD) equivalent circuit. Fabricated inductor revealed inductance of 3 nH and Q factor of about 8 at 2 GHz. It is clearly shown that tuning inductor can enlarge the bandwidth of the TFBAR ladder filters about 10 MHz and suppress the out-of-band rejection around 10 dB further.**

I. INTRODUCTION

Recent developments in surface micromachining technology made it possible to miniaturize and integrate various microwave circuit components. As a result, bandpass filters that are one of the critical elements in RF handheld transceivers could also become smaller to be integrated on silicon wafer. Most of RF front-end systems for mobile station have used ceramic or SAW (Surface Acoustic Wave) filters. These filters are relatively large in size, reveal poor power handling capability and pose limitation of operating frequency range[1]-[2]. TFBAR filters, however, are developed to overcome some of the drawbacks in conventional filters. TFBAR technology could also yield extremely compact filters bearing high Q characteristic, excellent power handing capacity and moderate temperature coefficients implemented on the semiconductor substrates. Thus, they can be an achievable integrated solution for RF system-on-chip transceiver paradigm.

TFBAR is formed by thin film piezoelectric material, such as AlN, ZnO, PZT, sandwiched between top and bottom electrodes. TFBAR with these piezoelectric materials could be employed into low-GHz regime RF front-end filters for global positioning system (GPS) receivers or personal communications system (PCS) handsets[3]. It is observed that ZnO and PZT TFBAR filters have poor insertion loss, low Q value and quite wide bandwidth to be used for mobile phones in 1~2 GHz region. The resonant frequency of TFBAR is determined by various structural and material parameters, and among them the thickness of piezoelectric film and electrodes play a dominant role. The thickness of the piezoelectric material and electrodes can be controlled by various conditions, such as ambient temperature, pressure, sputtering velocity, as well as DC bias in fabrication process.

In the early 90's, C. Vale[4] reported the possibility of developing TFBAR filters in GHz region and tuning methodology with external inductors and capacitors. In the late 90's, the exquisite MEMS process enabled the easy fabrication of TFBAR, and extensive researches have been published regarding the selection of appropriate piezoelectric material, thickness control and various filter design topologies. While most tuning has been accomplished with chip devices and transmission lines on test fixture, on-wafer inductor tuning technique has been implemented in this work and two types of duplexer TFBAR filters are presented.

II. MODELING AND ANALYSIS OF SINGLE TFBAR

For accurate and effective modeling of TFBARs, various approaches have been presented in the literature[5]. Among them, Mason's model has been accepted most widely used in analyzing vertical structure of TFBAR. However, it is difficult to incorporate the model into CAD system due to the ideal transformer and negative capacitance. For accurate analysis, some researchers have tried full wave simulation technique like FDTD (Finite Difference Time Domain) or FEM (Finite Element Method). Although numerical analysis is very accurate, it is very time consuming process. The modified Butterworth-Van Dyke (MBVD) model[5] composed of six lumped el-

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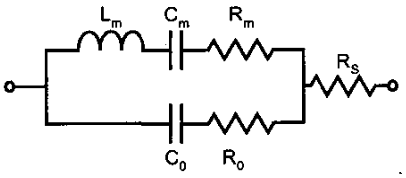

Fig. 1. MBVD model

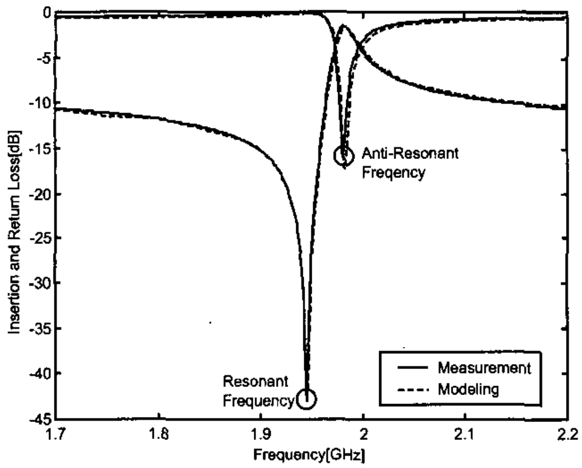

Fig. 2. Frequency response of single TFBAR

ements as shown in Fig. 1 provides an appropriate method with simplicity and accuracy for characterizing TFBAR and designing bandpass/bandstop filters. Fig. 2 shows good agreement between the MBVD model and measured data from fabricated unit TFBAR. The relations between the modeling and material parameters can be defined as[1];

$$C_0 = \frac{\varepsilon_r \varepsilon_0 A}{d} = \frac{\varepsilon_r \varepsilon_0 A \omega_r}{\pi \upsilon_a},\ R_m = \frac{\pi \eta\ \xi \varepsilon_0}{8k_t^2 \rho A \omega\ \upsilon_a} \tag{1}$$

$$C_m = \frac{8}{\pi^2} k_t^2 C_0,\ L_m = \frac{\pi^3 \upsilon_a}{8\varepsilon_r \varepsilon_0 A \omega_r^3 k_t^2},\ \omega_r = \frac{1}{\sqrt{L_m C_m}}$$

where ε_r is relative permittivity of material, ε_0 is permittivity of free space, η is acoustic viscosity, ρ is density, v_a is acoustic velocity and A is resonator area size. From the equation (1), it is clear that the thickness 'd' and the resonant frequency are inversely proportional. Moreover, as the area size of resonator becomes larger, the insertion and return loss of the resonator exhibit better performance while maintaining the same resonant frequency. This is due to the fact that C_m increases in proportion to area 'A', but L_m varies inversely. The resonator shape could be a critical factor, however it is revealed that resonator shape do not affect overall TFABR performance. The measured data for various TFBAR thickness is shown in Fig. 3. The

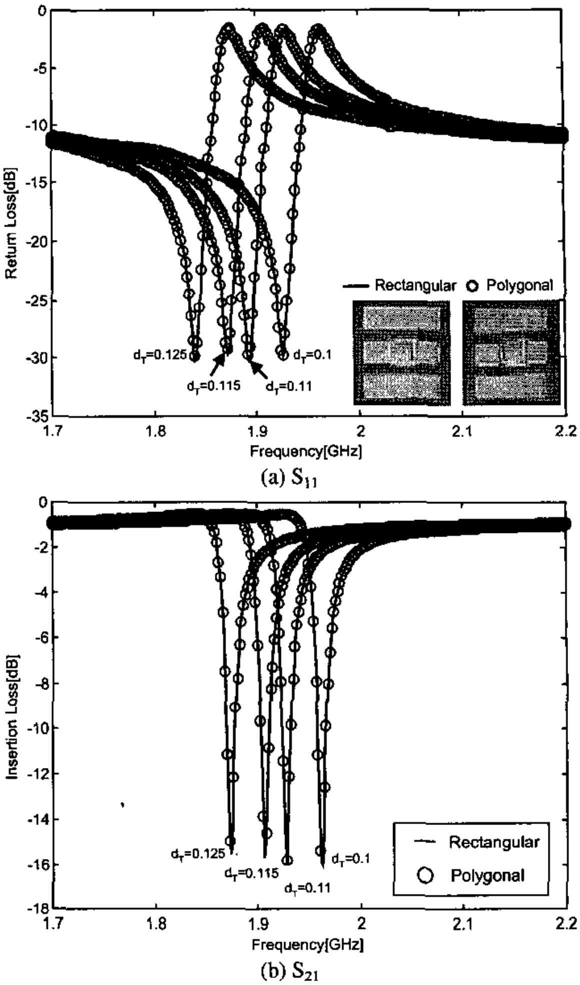

Fig. 3. Frequency response of TFBAR with different shape respect to top electrode thickness

top electrode thickness of the fabricated TFBAR in Fig. 3 is chosen as 0.1, 0.11, 0.115 and 0.125 μm. It is important to mention that the resonator shape does not play an important role in the TFBAR performance and as a result, optimal sized-filter design for miniaturization could be possible.

III. LADDER FILTER DESIGN

There are three types of commonly used TFBAR filter designs, such as ladder, lattice and balanced type. Among them, the ladder type is the most popular approach due to its apparent advantages over other topologies in terms of number of resonators, insertion and return loss. Single stage of ladder filter is a pair of series and shunt resonators. The resonant frequency of the shunt TFBARs must

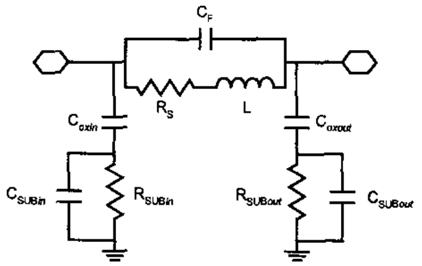

Fig. 4. Inductor equivalent model

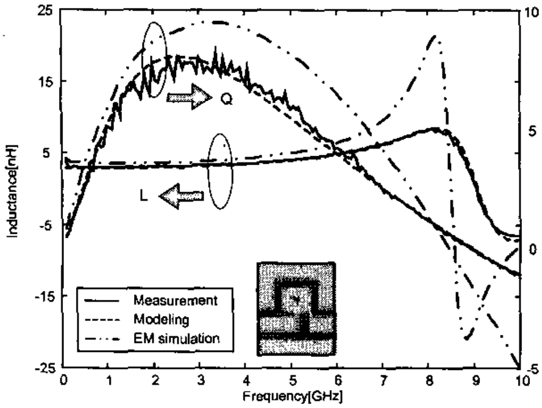

Fig. 5. Inductance and Q value of fabricated inductor

be designed to have 2~3% lower than series TFBARs, which can be accomplished by adjusting the thickness of top electrode as mentioned in the previous section. The number of stages is determined to comply with a given specification and it is worth to mention that the increase in the number of stages leads to better out-of-band rejection characteristic, though insertion loss is degraded[6]. In this work, two types of TFBAR ladder filters are fabricated to compile the on-wafer inductor tuning effects. Tx filters in a duplexer, which usually have steeper skirt characteristic in the right side of passband, are designed with four series and two shunt resonators, namely, 4/2 stage, while Rx filter is devised with 2/2 stage to have mirrored image of Tx filter. Ladder filters with only TFBARs could hardly satisfy the commercial duplexer specifications for mobile communication systems. Therefore, on-wafer inductor tuning methodology is presented to control isolation characteristics between Tx and Rx filters in duplexer design.

IV. Inductor Modeling

The behavior of spiral inductor is predicted with 3-dimensional electromagnetic simulator and lumped elements of the equivalent circuit model in Fig. 4 are extracted

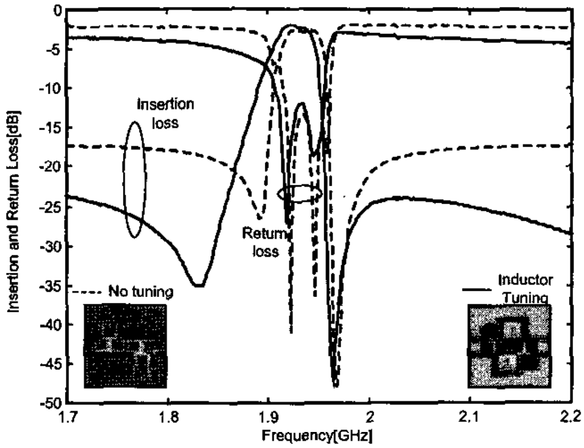

Fig. 6. Tuning results of Tx type filter

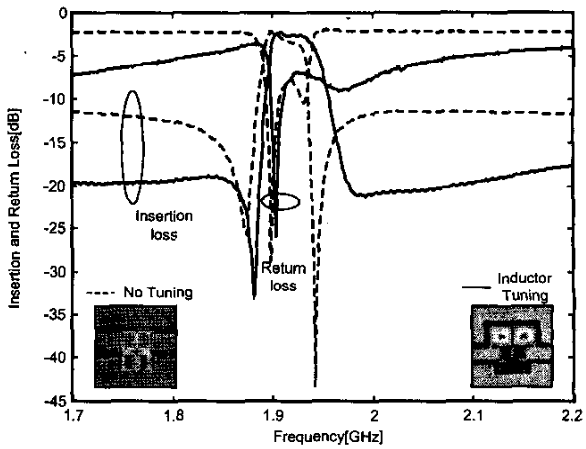

Fig. 7. Tuning results of Rx type filter

from the measured Y parameters of fabricated inductor. Gold plated platinum is used as inductor metal and the overall spiral inductor size is 300×300 μm^2. Fig. 5 shows the electromagnetic simulated, equivalent circuit modeled and measured inductance and Q values with good agreement between equivalent model and measured data. Inductance and Q values are calculated from the real and imaginary terms of Y_{11};

$$L = \frac{\mathrm{Im}[1/Y_{11}]}{2\pi f},\ Q = -\frac{\mathrm{Im}[Y_{11}]}{\mathrm{Re}[Y_{11}]} \tag{2}$$

V. On-Wafer Inductor Tuning

In ladder filter topology, the difference in resonant frequencies between series and shunt TFBARs affects passband shape, bandwidth and roll-off characteristics. Particularly, the resonant frequency of shunt TFBARs and anti-resonant frequency of series TFBARs determine the left and right pole location of passband, respectively. For Tx filter with 4/2 stage, inductors are added in series to two shunt TFBARs. As shown in Fig. 6, the pole in the left side is shifted downward to provide 10 dB better out-of-band rejection without degradation in insertion loss or variation in the location of right pole. For Rx filter with 2/2 stage, inductors are connected in parallel to two series TFBARs. The inductor tuned filter reveals about 8 dB out-of-band rejection improvement compared to the un-tuned filter, while it has about 10 MHz wider bandwidth as shown in Fig. 7.

VI. Conclusion

In this paper, TFBARs and inductors are designed and fabricated on silicon substrate, and the characteristics of single TFBAR and on-wafer tuned TFBAR ladder filters are presented. Aluminum nitride is used as piezoelectric material and platinum is used for electrodes. Fabricated TFBAR has k_t^2 of 4.5 % and Q value of 1280 at resonant frequency. For the single TFBAR, the resonant frequency is shifted to lower frequency region as the top electrode becomes thicker, and better insertion and return loss characteristics are obtained for bigger area. It is worth to mention that resonator shape do not affect the overall performances if resonator thickness and size remain the same. Tuning spiral inductors are made of gold plated platinum, which shows inductance of 3 nH and Q value of about 8 at 2 GHz. Inductor tuned Tx and Rx TFBAR ladder filters show improved out-of-band rejection performance. These results demonstrate that filters with internal inductors on silicon wafer can be regarded as a good candidate for on-chip high performance RF filters.

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