Modelling of Bulk Acoustic Wave Resonators for Microwave Filters

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Abstract— **Modelling and development of *high Q* thin-film bulk acoustic wave (BAW) devices is a topic of research gaining attention due to good selectivity and steep transition band offered by these devices used for cellular applications. A preliminary survey of various modelling approaches of these devices and their validations are presented in this paper. So far two existing one dimensional (1D) models have been investigated and compared. The results obtained from the models show relatively good agreement with experimental data of the FBAR reported in the literature. The prime objective of this project is to investigate novel BAW resonators, to determine the essential physical parameters and to develop physics based model thereof suited for circuit applications**.

Index Terms— Bulk Acoustic Wave (BAW) devices, Resonator, Filters, Physics based model

I. INTRODUCTION

Thin-film bulk-acoustic-wave (BAW) devices are used for RF selectivity in mobile communication system and other wireless applications. Currently surface-acoustic-wave (SAW) is the preferred technology for RF filters. However thin-film BAW has several advantages as they are remarkably small in size, have better power handling abilities and better temperature coefficients leading to more stable operation. From a practical point of view SAW filters have considerable drawbacks beyond 2 GHz whereas BAW devices up to 16 GHz have been demonstrated [1]. BAW is expected to supersede SAW as the technology of choice in many applications over the next few years as they have now evolved in performance beyond SAW and can be manufactured in a very cost competitive way using standard IC technology.

BAW technology is commercially available for US-PCS (1.85 GHz-1.91 GHz) applications. Transmit and receive bands of the US-PCS standard are close in frequency. This demands BAW resonators which constitute the filters to be nearly loss-free. Hence one of the important goals of BAW community is to come up with high *Q* resonators for RF filters by minimizing the losses [2-5]. There is no software that will allow building good filters if your resonator performance is insufficient. Hence the optimization of resonator performance is inevitable in filter design. The simulations and theoretical analysis are essential aids to figure out issues and hence to solve it for improving the resonator performance.

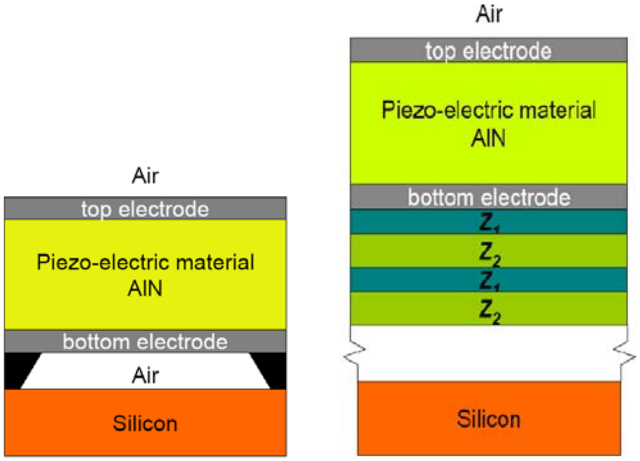
II. BAW TECHNOLOGY: BASIC PRINCIPLE

The essential building blocks of BAW filters are small sized BAW resonators which exploit the thickness extensional vibration mode of a thin piezoelectric film. The simplest configuration of a BAW resonator is a thin piezoelectric film sandwiched between two metal electrodes. When an electric field is created between these electrodes, the structure is mechanically deformed by the way of inverse piezoelectric effect and an acoustic wave is launched into the structure which propagates parallel to the electric field and which is reflected at the electrode/air interfaces. At the mechanical resonance, the half wavelength of the acoustic wave is equal to the total thickness of the stack. The resonance frequency f_r is determined approximately by the thickness t of the piezoelectric film [6]:

$$f_r \approx \frac{v}{\lambda} = \frac{v_l}{2t} \qquad (1)$$

where v_l is the longitudinal velocity of sound in the normal direction in the piezoelectric layer, t is the thickness of the piezoelectric film, and λ is the acoustic wavelength. In a real resonator device, of course, the frequency f_r is different from Eq. (1), since the acoustic properties of all other layers influence the resonator performance e.g. by the mass-loading effect of the resonator's electrodes. Albeit Eq. (1) is only a crude approximation it is important to note that as the velocity of sound is typically in the range between 3000–11000 m/s for most of the materials, the desired thickness of the piezo layer is in the order of micrometers which makes the devices relatively small.

For the device to be practical, there are two in style configurations. Fig. 1(a) shows one possible approach for an airbridge resonator often referred to as film bulk acoustic resonator (FBAR) in which substantial acoustic isolation from the substrate is achieved by micro-machining an air-gap below the structure. In FBARs, the sandwich structure is mechanically floating. Fig.1 (b) shows a more mechanically rugged solidly mounted resonator (SMR) structure that is formed by isolating the resonator from the substrate with a reflector composed of nominally quarter wavelength thick layers [7]. The number of layers depends on the reflection coefficient required and the characteristic impedance ratio between the successive layers.



(a) (b)

Fig. 1. Schematic view of bulk acoustic wave resonators (a) Film Bulk Acoustic Resonator (FBAR) (b) Solidly Mounted Resonator (SMR).

III. BAW MODELING

Even though there were a few existing physical models [2, 8-10] for BAW, two of them were mainly under our investigation. One model [8] deals with the analytical solutions for the basic electrode-piezoelectric – sandwich structures which are obtained by solving the wave equation coupled to linear piezoelectric equations with appropriate boundary conditions. Hence, this model is specifically suited for the film bulk acoustic resonator (FBAR) in which the sandwich structure is mechanically floating. Another model [2] by K. M. Lakin which solves the acoustical equations assuming a transmission line model [11] for the subsequent layers attached to the piezoelectric film is also revisited. This model is suited for the both FBAR and full BAW resonator structure including the reflector stacks like SMR.

The analysis of a bulk acoustic wave resonator starts from a fundamental one dimensional equation defining the electrical impedance as [2]

$$Z = \frac{1}{Y} = \frac{1}{j\omega C} \cdot \left(1 - K^2 \cdot \frac{\tan\phi}{\phi} \cdot F(z_l, z_r, \phi) \right) \qquad (2)$$

$F(Z_l,Z_r,\Phi)$ is given by

$$F(Z_l, Z_r, \phi) = \frac{((Z_r + Z_l)\cos^2\phi) + j\sin 2\phi}{(Z_r + Z_l)\cos 2\phi) + j(Z_r Z_l + 1)\sin 2\phi)} \qquad (3)$$

where Φ is the half phase across the piezoelectric plate, K^2 the piezoelectric coupling, Z_l and Z_r are normalized acoustic impedances at the boundaries, and C is the high frequency capacitance.

In FBARs the boundary impedances are zero and hence eq.(2) reduces to

$$Z = \frac{1}{j\omega C} \cdot \left(1 - K^2 \cdot \frac{\tan\phi}{\phi} \right) \qquad (4)$$

This gives the impedance verses frequency characteristics of a simple acoustic resonator having thin electrodes as shown in Fig.1 (a).

All structure attached to the piezoelectric plate including the mechanical effect of the electrodes can be found by successive use of transmission line equation [11]

$$Z_{in} = Z_s \cdot \left[\frac{Z_l \cdot \cos\theta + j \cdot Z_s \cdot \sin\theta}{Z_s \cdot \cos\theta + j \cdot Z_l \cdot \sin\theta} \right] \qquad (5)$$

Here, Z_{in} is the input impedance, Z_l the load impedance, Z_s the characteristic impedance of the section, and θ the total phase across the section.

The analysis of the reflector is most conveniently done using fundamental equation of wave propagation. The mirror reflectivity R is given by

$$R = \left(\frac{Z_{RS} - Z_p}{Z_{RS} + Z_p} \right) \qquad (6)$$

where Zp is the acoustic impedance of the piezolayer and Z_{RS} is the effective acoustic impedance of the layer stack below the piezolayer, including the bottom electrode, mirror layers and the substrate. Both R and Z_{RS} are generally complex numbers.

Although the physical model described above gives useful physical insight for technology, a more compact model, based on high-order parameters, is desirable for circuit designers. Apart from the physical models, there exists a compact model which is a lumped-element electrical equivalent circuit model popularly know as *Butterworth Van Dyke* (BVD) model [13]. The BVD model consists of an inductance, capacitance and resistance, corresponding respectively to inertia, compliance and damping of the mechanical system; connected in series with a parallel capacitance, which is due to the dielectric properties of the piezoelectric crystal capacitively coupled between the electrodes.

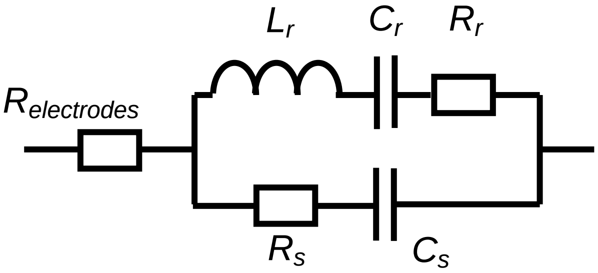


Fig.2 Modified Butterworth Van Dyke (MBVD) model

The model was further modified [14] by the addition of a parallel resistor *Rs* to incorporate the parasitic components. A *Modified Butterworth Van Dyke* (MBVD) model is illustrated in fig.2. L_r, Cr and R_r represent the motional resonance that is coupled to the voltage across the plate capacitor by the piezoelectric effect in the film. C_s represents the physical plate capacitance of the FBAR. R_s includes the dielectric loss tangent of piezofilm and models most of the losses associated with the parasitic lateral model in the FBAR. $R_{electrodes}$ represents the physical resistance of the electrodes [15]. This model is best suited for parameter extraction and design studies.

IV. MODEL VALIATIONS

Models explained in section 3 were implemented using MathCAD [16]. The impedance versus frequency characteristics of a simple FBAR having thin electrodes was plotted using eq. (4).This was compared with Ren's model [8]. Both models show good agreement with each other for various (anti)resonance frequencies. Fig. 3 shows the comparison of results from the two models.

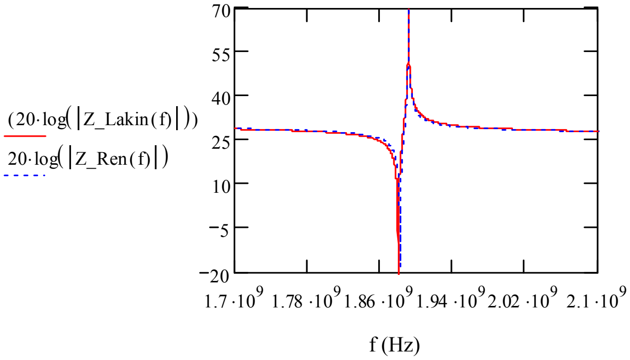


Fig.3 Comparsion of Lakin's and Ren's model

The results obtained from the model show relatively good agreement for the resonant frequencies with experimental data of the FBAR reported in the literature [16].

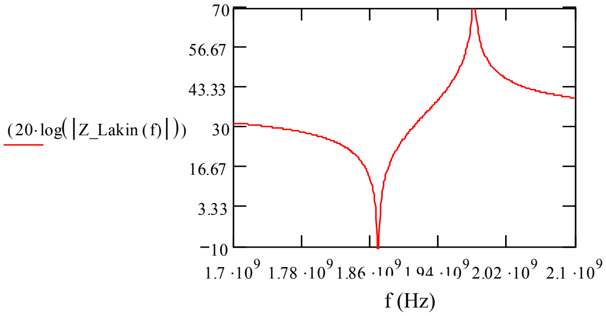


Fig.4 The impedance of the resonator with 9 layers with alternate quarter wavelength stacks of SiO2 and Ta2O5.

Lakin's model was further extended for SMR using successive use of transmission line equation, eq. (5) and a model was implemented using the material parameter data base of NXP. The layers used in the Bragg Reflector are silicon dioxide and tantalum pentoxide. The results are shown in fig. 4.

A reflectivity analysis of the Bragg reflector of SMR was carried out using eq. (6). A study was performed varying the number of layers in the reflector stack and the results are compared. This is shown in fig. 5. As the number of layers increases the reflectivity also improves due to reflections at additional interfaces.

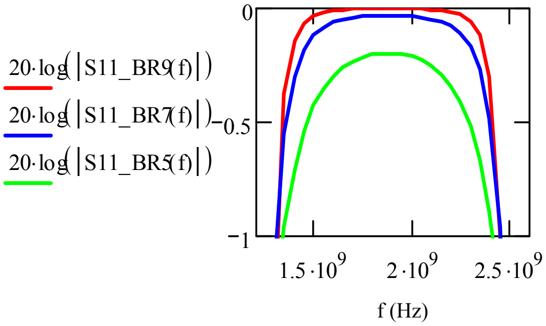


Fig.5.Variation of reflection coefficient with number of layers of the reflector stack. Green-5 layers, Blue-7layers and Red-9 layers.

The validation of the compact BVD model is also carried out for an FBAR using the reported values from experiments in literature [16]. This is also in agreement with the results obtained from the physical models. Fig. 6 shows the BVD validation.

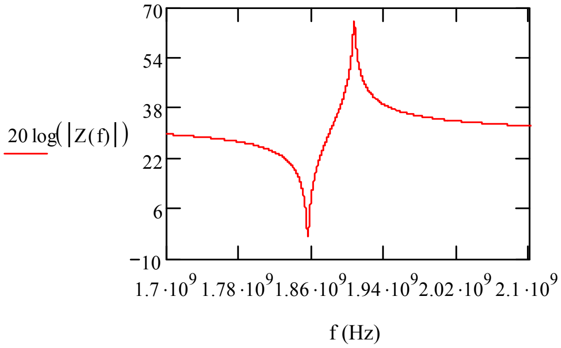


Fig.6. Input impedance using MBVD model

V. SUMMARY

This article presents an overview of modeling of bulk acoustic wave resonators which are the building blocks of inter-stage filters and duplexers in mobile communication. The existing models have been revisited and their validations have been successfully carried out with reported literatures. Design and modeling of microwave acoustic devices involve some complications primarily because though the devices are acoustic in nature they are measured and used in electronics environment. The diverse domains involved in modeling like acoustic, electric, piezoelectric and electromagnetic domains make the task cumbersome. We aim to come up with a physics based model suited for circuit applications incorporating essential parameters from various domains.

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