MODIFIED BVD-EQUIVALENT CIRCUIT OF FBAR BY TAKING ELECTRODES INTO ACCOUNT

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Abstract - A modified BVD-equivalent circuit model is developed when taking the thin electrodes as mass loading. It is shown that the mass of the electrodes can be directly added onto the mass of the piezoelectric film to form a series inductor and a capacitance is added to the capacitance of the film in parallel. The results implied that the traditional BVD model could be applied to the three-layer resonators with thick electrodes. Numerical simulations for three-layer FBAR consisting of AlN film with thick electrodes were carried out, and results showed that a simple $L_1 - C_1 - R_1$ and C_0 model is perfectly applicable for thick electrodes when the two electrodes have similar thickness. If the thickness of the two electrodes is very different, the simple BVD model can't be simply used.

I. Introduction

Duplexers for 1900 MHz PCS handsets based on film-bulk-acoustic-resonator (FBAR) had been realized by micro-machined thin film AlN devices [1-4]. Samples of 3.5 GHz, even 6.0 to 8.0 GHz were reported more recently [5-8]. Before entering real applications, a few key technologies had been solved. Firstly, the boundary "free" condition was realized on both sides [9-12], either by real empty or by mechanical supported but acoustically free. Then suppressing the lateral modes was realized by using non-parallel edges, for example, pentagon shape [12]. Another key issue in engineering research and development of FBAR is the electrode. Many requirements and restrictions [5] posed on this issue: (1) low acoustic attenuation, (2) high electric conductivity, (3) coupling coefficient enhancement [14], (4) process compatibility and (5) temperature compensation [4]. To those demands, thickness of the electrodes is not thin usually.

For properly analyzing the FBAR, it is necessary to have reasonable models. Mason's equivalent circuit (transmission line) model is accurate, and always valid for any one-dimensional multi-layer resonators and transducers. But the parameters involved are "distributed values", rather than constants. It is time-consuming to analyze FBAR by using Mason's model. Contrarily, BVD equivalent circuit model, which is simpler and lumped-elements model, is only valid near the resonance frequencies of the one-dimensional modes. This model is based on "all parameters are constant" and so it is fast and convenient. It had been used to wafer mapping of FBAR devices in in-line production monitoring with fair accuracy [1].

Strictly speaking, BVD-model can't be simply used to analyze the FBAR samples developed at Agilent [1], Ceramic Lab [7,14], TFR [6] and Marconi Materials Technology [15] because all they are multi-layer structures and each layer is neither near resonance nor very thin. In [1], however, a BVD equivalent circuit model, where the thick electrodes and the piezo-layer were considered as a "whole piezoelectric plate", was used to simulate the resonator behaviors. The R_0 added in series with the clamped capacitance C_0 is the dielectric loss of the film, rather than the "material loss". The material losses related with wave propagation should be included in R_1, we believe. Actually, there was not any modification in the model used in [1] for the motional branch, i.e., it is still a simple $L_1 - C_1 - R_1$. It seems unreasonable but the results demonstrated good agreement with the measured data [1]. Why there is such discrepancy? We are interested in knowing whether the simple model can be used for any piezoelectric film-electrode combinations or only for some special combinations. In this paper, we will study the validity of using the simple BVD model in a three-layer structure. In section 2, we will investigate the effects of the thin electrodes on the BVD equivalent circuit and qualitatively obtain some insights on this topic. In section 3, we will investigate the validity of the simple BVD circuit to FBAR with thick electrodes by numerical simulation.

II. Modified BVD equivalent circuit of FBAR with thin electrodes

The basic idea of this section is: from the input electric impedance of a three-layer resonator, which is from Sittig's model of equivalent circuits, we obtain two formulae for its parallel and series resonance frequencies. In those formulae, the effects of the material parameters and thickness of the electrodes on the resonance frequencies are explicitly expressed. On the other hand, we use a capacitor C_1' and an inductor L_1' to express the effects of the thin electrodes, and then we use the BVD model to show the roles of the capacitor C_1' and inductor L_1' in BVD circuit. Comparing the parallel and series resonance frequency formulae obtained by above two ways, we can obtain some useful information. If the capacitor C_1' is in parallel with the motional capacitor C_1 of the film and the inductor L_1' is in series with the motional inductor L_1 of the film, then we can obtain a qualitative conclusion that the simple BVD model can be used in for a multi-layer FBAR.

A. Input impedance of a resonator with thin electrodes

The input impedance of a resonator with two electrodes can be obtained from the two-port expression of the piezoelectric layer, and of the electrodes [16]

$$Z_{in} = \frac{V}{I} = \frac{1}{j\omega C_0} \cdot \left[1 - \frac{k_t^2}{\gamma} \cdot \frac{(z_1 + z_2)\cdot \sin\gamma + j \cdot 2 \cdot (1 - \cos\gamma)}{(z_1 + z_2)\cdot \cos\gamma + j \cdot (1 + z_1 \cdot z_2)\cdot \sin\gamma} \right], \quad (1)$$

Where, $z_1 = Z_1 / Z_0$, $z_2 = Z_2 / Z_0$, $Z_0 = A \cdot \rho \cdot V_l^D, C_0 = A / (\beta_{33}^S \cdot l)$, Z_0 is the acoustic impedance of the piezoelectric layer. k_t^2 is the electro-mechanical coupling coefficient, and $\gamma = \varpi \cdot l V_L^D$;

$V_l^D = \sqrt{C_{33}^D / \hat{\rho}}$; Z_1, Z_2 are the impedances of the electrodes, presented to the up and down faces of the piezoelectric layer.

$$Z_1 = F_1 / u_1 = j \cdot Z_{E1} \cdot \tan\gamma_{E1} \; Z_2 = F_2 / u_2 = j \cdot Z_{E2} \cdot \tan\gamma_{E2} \qquad (2)$$

Where $\gamma_{E1} = \omega d_{E1} / V_{E1}$, $\gamma_{E2} = \omega d_{E2} / V_{E2}$; $Z_{E1} = A \cdot \rho_{E1} \cdot V_{E1}$; $Z_{E2} = A \cdot \rho_{E2} \cdot V_{E2}$; . A is the area of the electrodes; ρ_{E1}, ρ_{E2} are the densities of the top and bottom electrodes; V_{E1}, V_{E2} are the velocities of the top and bottom electrodes; d_{E1}, d_{E2} are the thicknesses of the top and bottom electrodes.

B. Parallel and series resonance frequency formulae

For simplicity, the two electrodes are assumed to be the same, and then the parallel and series resonant frequencies are given by

$$1/\tan(\gamma/2) - z_E \cdot \tan(\gamma_E) = 0 \qquad (3)$$

and $1/\tan(\gamma/2) - z_E \cdot \tan(\gamma_E) = k_t^2 / (\gamma/2)$ (4)

The parallel resonance frequency of the fundamental mode is nearby $\gamma = \pi$, and if the electrodes are thin, we can expand Eq. (3), using $\tan(\gamma_b) \cong \gamma_b, \gamma = \pi + \varepsilon$. Then the parallel resonance frequency is

$$f_p = \frac{\hat{V}_L}{2l} \cdot \frac{1}{1 + 2\rho_{El} d / \hat{\rho} l} = f_{p0} \cdot (1 + 2 \cdot \rho_E d / \hat{\rho} l)^{-1}; \qquad (5)$$

Where, $f_{p0} = \hat{V}_L / 2l$ is the parallel resonance frequency of the resonator by ignoring the electrodes. Comparing with the resonator where the electrodes are ignored, the parallel resonance frequency decreases by a factor of $(1 + 2\rho_E \cdot d / \hat{\rho} \cdot l)$, which is just the unit area mass ratio of the bare film to the film coated by two electrodes.

C. Approximate formulae of the effective electro- mechanical coupling coefficient for thin electrodes case

From (4), we can obtain an approximate formula

$$k_{eff}^2 = \frac{\pi^2}{4} \cdot \frac{f_s}{f_p} \cdot \left(1 - \frac{f_s}{f_p}\right) = k_t^2 \cdot \left(1 + \frac{2\rho_E \cdot d}{\hat{\rho} \cdot l}\right). \qquad (6)$$

Where k_{eff}^2 is the effective coupling factor when the electrodes are taken into account. It is shown in Eq. (6) that the effective coupling factor is increased by a factor of $(1 + 2\rho_{El} \cdot d / \hat{\rho} l)$ compared with the material coupling factor, operating at the same mode.

D. A supposed modified BVD equivalent-circuit

Suppose an inductor L_1' is in series with L₁ of the film, and a capacitor C_1' is in parallel with C_1. The new resonance frequencies and their BVD parameters will be

$$\omega_S^2 = \frac{1}{(C_1 + C_1')(L_1 + L_1')} = \omega_{S0}^2 \cdot \frac{1}{(1 + R_C + R_L + R_C \cdot R_L)}; \qquad (7)$$

$$\omega_p^2 = \omega_{p0}^2 \cdot \frac{(1 + r + R_C)}{(1 + r) \cdot (1 + R_C + R_L + R_C \cdot R_L)}; \qquad (8)$$

Where, $\omega_{S0}^2 = 1 / C_1 L_1; \quad \omega_{p0}^2 = \omega_{S0}^2 \cdot (1 + C_1 / C_0)$

$r = C_0 / C_1; \quad R_C = C_1' / C_1; \quad R_L = L_1' / L_1$

On the other hand, from (5) and from (6)

$$\omega_p = 2\pi \cdot \frac{\hat{V}_L}{2l} \cdot \frac{1}{1 + 2\rho_{El} d / \hat{\rho} l} = \omega_{p0} \cdot \frac{1}{1 + 2\rho_{El} d / \hat{\rho} l}; \qquad (9)$$

$$\omega_S^2 = \frac{\omega_{S0}^2}{\left[1 - \frac{8}{\pi^2} \cdot k_t^2\right]} \cdot \left(1 + \frac{2\rho_E d}{\hat{\rho} l}\right)^{-2} \cdot \left[1 - \frac{8k_t^2}{\pi^2} \cdot \left(1 + \frac{2\rho_E d}{\hat{\rho} l}\right)\right]; \qquad (10)$$

Comparing (8) and (9), one can obtain a formula, and comparing (7) and (10), one has another formula. There are two unknowns, R_C and R_L, and they can be determined by the two formulas.

Taking the first order approximation, one can find

$$R_C = \frac{C_1'}{C_1} = \frac{2\rho_E d}{\hat{\rho} l} \cdot \left[\frac{1 + \frac{8k_t^2}{\pi^2}}{1 - \frac{8k_t^2}{\pi^2} \cdot \left(1 + \frac{2\rho_E d}{\hat{\rho} l}\right)}\right] \approx \frac{2\rho_E d}{\hat{\rho} l} \cdot \left[1 + \frac{16 \cdot k_t^2}{\pi^2}\right]; \qquad (11)$$

$$R_L = \frac{L_1'}{L_1} = \frac{2\rho_E d}{\hat{\rho} l} \cdot \left[\frac{1 + \frac{2\rho_E d}{\hat{\rho} l} - \frac{\pi^2}{8k_t^2}\left(2 + \frac{2\rho_E d}{\hat{\rho} l}\right)}{1 - \frac{\pi^2}{8k_t^2} + \frac{2\rho_E d}{\hat{\rho} l}}\right] \approx \frac{2\rho_E d}{\hat{\rho} l}; \qquad (12)$$

Where

$$L_1 = \frac{1}{8}\left(1 + \frac{8}{\pi^2} \cdot k_t^2\right) \frac{M}{(h_{33} / \beta_{33}^S)^2} \cdot \left(\frac{l}{A}\right)^2; \quad M = \hat{\rho} l A; \qquad (13)$$

This is a mass essentially and

$$C_1 \approx \frac{8}{\pi^2}\cdot\frac{\left(h_{33}/\beta_{33}^S\right)^2}{\hat{C}_{33}^D}\cdot\frac{A}{l}; \qquad (14)$$

This is a "spring".

E. Parameters of the modified BVD equivalent circuit

It is clearly shown that both R_C and R_L are positive and this means our assumptions are correct- adding a capacitor with C_1 in parallel and adding an inductor with L_1 in series. The total motional inductor L_m, and capacitor C_m, of the resonator can be given by

$$L_m = L_1 + L_1' = L_1\cdot\left[1+R_L\right] = L_1\cdot\left(1+\frac{2\rho_E d}{\hat{\rho} l}\right); \qquad (15)$$

$$\begin{aligned} C_m &= C_1 + C_1' = C_1\cdot\left[1+R_C\right] \\ &= C_1\cdot\left(1+\frac{2\rho_E d}{\hat{\rho} l}\cdot\left[1+\frac{16\cdot k_t^2}{\pi^2}\right]\right) \end{aligned} \qquad (16)$$

It can be seen that the total inductance is the summation of the masses of the film and of the electrodes, and the total capacitance is the parallel addition of two "springs"- one is the "spring" of the film, but another is not simply the "spring" of the electrodes (the elastic constant of the electrodes doesn't appear). The capacitor of C_1' is a kind of mass-loading related variation.

The above analysis results qualitatively indicate that the inductance of the three layers can be combined into one inductor and the capacitance can be combined into one capacitor by a relationship as shown in Fig. 1. This insight implied that if the electric resistance of the electrodes and the dielectric loss of the AlN film are ignored, the traditional 4-parameter model might be used to describe the resonance characteristics of the general three-layer FBAR.

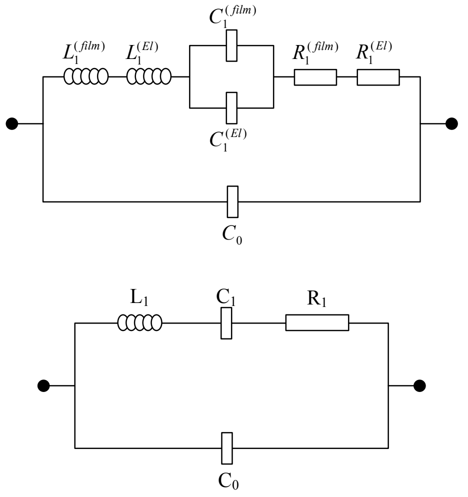

Fig. 1 Modified BVD model with thin electrodes

III. Verifying the validity of simple BVD circuit to FBAR with thick electrodes

In this section we will verify the validity of simple BVD equivalent circuit model to FBAR with thick electrodes by numerical simulations. The piezoelectric film is AlN, and the electrode materials, as given in Table I, cover a wide range of different acoustic impedances. Thickness of the electrodes changes from zero to more than the thickness of the AlN film. Comprehensive combinations of same or different materials and same or different thicknesses for the two electrodes are simulated.

A. Simulation procedure

Taking the parameters of AlN and a group of electrode materials and thickness, substituting these data into Eq. (1), one can find its input impedance distribution. The series and parallel resonance frequencies, f_S, f_p, and the Q_S (or Q_p) can be deduced from data of input impedance. Reasonably keeping C_0 as a constant unchanged, the three parameters, L_1, C_1 and R_1 can be deduced from

$$\omega_S^2 = 1/C_1L_1; \quad \omega_p^2 = \omega_S^2\cdot\left(1+C_1/C_0\right); \quad Q = \omega L_1/R_1 \qquad (17)$$

Using the extracted L_1, C_1 and R_1 values and the value of C_0, one can calculate the impedance curve of the 4-elements BVD model given in Fig. 1(b). Comparing the two impedance curves calculated by using the two methods, we can identify if the simple BVD model is valid or not.

Table I: Data of the electrode materials used in simulations:

Material	Density, ρ_E	Velocity, V_E	Acoustic Impedance
Tungsten	18.71	5.231	97.87
Pt	21.5	4.017	86.37
Au	19.49	3.361	65.5
Mo	10.0	6.30	63.0
Nickel	8.97	5.894	52.87
Steel	7.9	5.9	46.6
Cu	8.93	5.01	44.7
Silver	10.6	3.6	38.2
Al	2.7	6.295	17.0

AlN-film, $\hat{\rho} = 3.260$; $\hat{V} = 11.350$; $k_t^2 = 5.0\,\%$

B. Simulation results and conclusions:

(1). Taking same material and same thickness for the two electrodes and taking mass ratio of the electrode to film, i.e., $(\rho_{E1} \cdot d_1 + \rho_{E2} \cdot d_2)/(\hat{\rho} \cdot l)$, as a parameter, from zero to 2.0, we calculated the impedance and the curves on Smith Chart. It was found that for all the different electrodes, there was no visible difference, except Al electrode case.

(2). Taking molybdenum electrode on both sides but with different thickness. For example, on one side thickness is equal to that of the film (thickness ratio equal to 1.0), and on another side the thickness ratio changes from 1.0 to zero. It was found that the difference of the two curves is getting more and more significant.

(3). The two electrode materials are different but with the same thickness. As an example, one side is Al ($\rho_{E2} = 2.7$) and another side is Pt ($\rho_{E2} = 21.5$). Thickness ratio of the electrodes is changed from zero to 1.0. There was no visible difference under thickness ratio of 0.5, and the difference is not significant up to the ratio of 0.8.

(4). Different electrode materials and different thickness. For example, the two electrode materials are the same as in item 3, but choose different thickness for different side. By keeping one side thickness ratio 0.01 and changing another side's thickness from 0.01 to 1.0, it was found that when another side's thickness reaches to 0.2, visible difference appears and when the ratio reaches 0.4 the difference becomes significant. By keeping one side's thickness ratio being 0.2, when another side's thickness reaches 0.8 or more the difference becomes significant. Similar results were obtained for Tungsten and Aluminum electrodes.

It can be concluded from the simulation results: (1) for a thick electrode FBAR, if the two electrodes have similar thickness (same or different materials), the simple BVD model can be used to describe the FBAR behaviors accurately. The valid range could be that the thickness of the electrodes is the same as that of the piezoelectric film. (2) If the two electrodes have very different thickness, for example, one is less than 0.1 and another is thicker than 0.8, the simple BVD model can not be used to describe the thick electrode FBAR's resonance behaviors.

IV. Conclusion

In this paper, the validity of the simple BVD equivalent circuit to describe a three-layer FBAR structure is studied. When the electrodes are thin enough to allow to be taken as mass loading, analytical results showed that the inductance of the three layers can be combined as one inductor and the capacitance of the electrodes is added in parallel. Those results imply that the simple BVD model could be used to describe the resonance behaviors of a three-layer FBAR with thick electrodes. Comprehensive numerical simulation results for different electrode materials and thickness ratios indicated that if the thickness of the two electrodes is similar, above prediction is correct. If the thickness of the two electrodes is very different, the simple BVD model can't be simply used.

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