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Measurements of Attenuation and Electromechanic Coupling Constant of Piezoelectric Films in Microwave Resonators[1]

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Abstract—It was found that for arbitrary high overtone and thin film microwave resonators the results of the measurements of the difference between frequencies of resonance and antiresonance on any harmonic of the resonator together with the measurement of the frequency difference between the peculiarities on the frequency dependence of imagine part of the electric impedance of the resonator give a simple way of the evaluation of the losses in the materials composing resonator structures and of the evaluation of the electromechanical constant of the piezoelectric film exciting acoustic waves.

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INTRODUCTION

The frequency dependences of modulus and imagine parts of electrical impedance of bulk acoustic wave resonators (particularly high overtone bulk acoustic wave resonators HBAR's and film bulk acoustic wave resonators FBAR's) are very informative [1], It is shown that these data contain information about acoustic wave attenuation coefficient (and correspondingly about quality factor of the resonator Q) of the resonator and thin film electromechanical coupling constant. In contrast with the results of [2, 3] the results presented below are valid for arbitrary experimental conditions and are not restricted by the relation $K^2_{\text{eff}}(n)Q_n \ll 1$, where $K^2_{\text{eff}}(n)$ is the effective electromechanical coupling coefficient, and Q_n is the quality factor corresponding to the n-th resonator overtone.

In [3] it was shown that the difference Δf_n between the frequencies of "antiresonant" and "resonant" peaks of the harmonic with number n in frequency dependence of the modulus of electrical impedance of the resonator strongly depends both on electromechanical coupling coefficients K_t^2 and on acoustic wave attenuation constant in the structure. The rigorous equivalent circuit of the resonators is discussed. In case $K^2_{\text{eff}}(n)Q_n \ll 1$ it is possible to get very simple expressions describing Δf_n as a function of the attenuation losses and quality factor of the resonator supported by numerically simulated and experimentally obtained results. To find $K^2_{\text{eff}}(n)$ (and hence K_t^2) and Q_n it is suggested to measure the difference between the peculiarities on the frequency dependence of the phase of the reflection coefficient of the electromagnetic signal from the resonator at the same harmonic number (together with Δf_n). This difference also depends on $K^2_{\text{eff}}(n)$ and Q_n. So there is a system of two equations with two unknown variables. Corresponding solution gives both $K^2_{\text{eff}}(n)$ and Q_n.

This work contains two new suggestions. The first is a very simple way of the measurement of the attenuation (and quality factor Q_n). It is found, proved and experimentally confirmed that if to measure the difference Δf_n ($\text{Im}Z_e$) between the frequencies of the extremes on the frequency dependence of the imagine part of the electric input impedance of the resonator, then $Q_n = f_n/\Delta f_n$ ($\text{Im}Z_e$). Accordingly the attenuation coefficient α_n can be found from the simple formula [4] $\alpha_n = f_n/2Q_n$.

The second one is to take into account the frequency dependence of the series capacitance in the equivalent circuit (for an arbitrary value of $K^2_{\text{eff}}(n)Q_n$ product does not coincide rigorously with the transducer static capacitance C_0). It results in obtaining a more exact expression for Δf_n. It can help to find K_t^2 from the results of the measurements of Δf_n and Δf_n ($\text{Im}Z_e$). These results are applicable for arbitrary structures and frequencies.

1. EQUIVALENT CIRCUIT OF THE RESONATOR

The schematic and equivalent circuit of a typical HBAR are shown in Fig. 1. The resonator consists of a relatively thick layer with flat parallel faces *1*, a piezoelectric film *2*, and thin metallic electrodes *3*, *4*. Elec-

[1] The article is published in the original.

tric properties of this structure are characterized by input electrical impedance Z_e. It can be found using the expression for the acoustically loaded piezoelectric film [5]. After some algebraic manipulations it was transformed [2] in the form:

$$Z_e = 1/i\omega C_0' + \sum_{n=1}^{\infty} \frac{1/i\omega C_n}{\left(\frac{\omega_n}{\omega}\right)^2 - 1 + \frac{i}{Q_n}}. \quad (1)$$

Here, ω is the frequency ω_n is the frequency of the nth overtone, C_0 is the transducer static capacitance C_n is the capacitance in the equivalent circuit shown in Fig. 2. The parameters of the equivalent circuit are:

$$C_n = \frac{C_0}{K_{\text{eff}}^2(n)}, \quad L_n = \frac{K_{\text{eff}}^2(n)}{\omega_n^2 C_0}, \quad R_n = Q_n \frac{K_{\text{eff}}^2(n)}{\omega_n C_0}. \quad (2)$$

Here, $F_{\text{eff}}(n)$ is the effective electromechanical coupling constant for the excitation of the nth overtone, Q_n is the quality factor of the resonator. $Q_n = f_n/2\alpha_n$.

The effective electromechanical coupling coefficient $K_{\text{eff}}^2(n)$ depends on the electromechanical coupling coefficient K_t^2 and on the thickness and the material parameters of all the layers composing the structure [3]. On high overtone frequencies a simplified expression for $K_{\text{eff}}^2(n)$ is:

$$K_{\text{eff}}^2(n) = \frac{2K_t^2(1-\cos b_0 l)(1-\cos(b_0 l + 2\psi_2))}{b_0 l \qquad \pi n}. \quad (3)$$

Here, b_0 is the wave vector in the material of the piezoelectric film, l is its thickness, ψ_2 is the phase gain in the top electrode. C_0' in (1) may be found from:

$$\frac{1}{i\omega C_0'} = \frac{1}{i\omega C_0}\left[1 + \frac{K_t^2}{2}\frac{\tan(b_0 l/2)}{b_0 l/2} \times \left(\frac{\sin b_0 l}{\pi n}[1-\cos(b_0 l + 2\psi_2)] - [1 + \cos b_0 l + \sin(b_0 l + 2\psi_2)]\right)\right]. \quad (4)$$

Figure 3 shows a typical frequency dependence of the modulus of the impedance. One can see peaks (antiresonances) and valleys (resonances) corresponding to different numbers n in the sum (1). The difference Δf_n should be measured for finding the attenuation constant and the quality factor.

2. DIFFERENCE BETWEEN ANTIRESONANT AND RESONANT FREQUENCIES

Using the equivalent circuit of the composite resonator it is possible to come to important conclusions related to its properties. Due to the existence of the series capacitor both the frequencies of the resonance and the antiresonance are not equal to ω_n. In accordance with used here definition of resonant and antiresonant frequencies they can be found as the extreme of the modulus of the impedance near the frequency ω_n

$$\left|Z_e^{(n)}\right| = \left|1/i\omega C_0' + \frac{1/i\omega C_n}{\left(\frac{\omega_n}{\omega}\right)^2 - 1 + \frac{i}{Q_n}}\right|. \quad (5)$$

The minimum corresponds to the resonant frequency $f_n^{(r)}$ and maxima corresponds to the antireso-

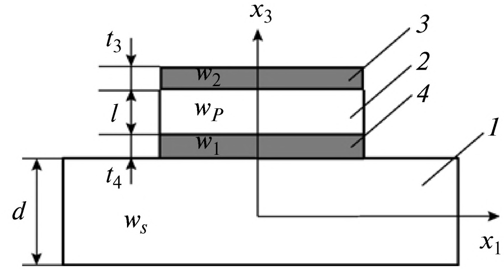

Fig. 1. The schematics of atypical HBAR.

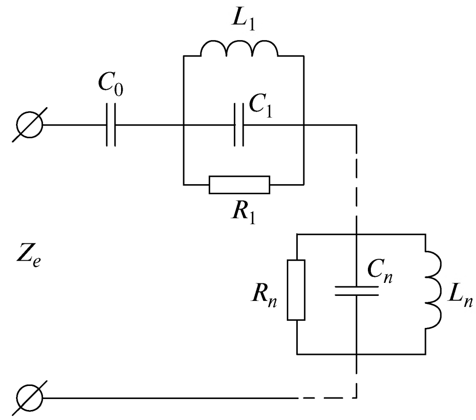

Fig. 2. The equivalent circuit of the HBAR.

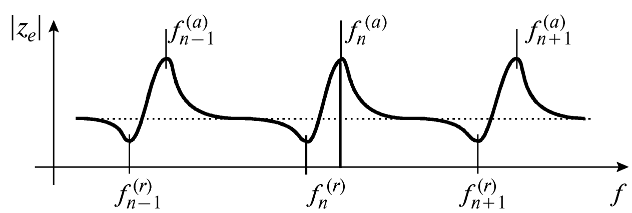

Fig. 3. Frequency dependence of the modulus of the impedance.

nant frequency $f_n^{(a)}$. It is easy to find from (5) that the difference between these frequencies is:

$$\Delta(n) = \sqrt{\frac{K_{\text{eff}}^4(n)}{4\left[1+\left(2-\frac{P}{S(n)}\right)K_{\text{eff}}^2(n)\right]}+\frac{1}{Q_n^2}}, \quad (6)$$

where $\Delta(n) = \frac{f_n^{(a)} - f_n^{(\text{r})}}{f_n}$

$$S(n) = \frac{(1-\cos b_0 l)(1-\cos(b_0 l + 2\psi_2))}{b_0 l \pi n}, \quad (6a)$$

$$P = [1 + \cos b_0 l + \sin(b_0 l + 2\psi_2)]/b_0 l. \quad (6b)$$

The difference between antiresonant and resonant frequencies is governed by the electromechanical constant and by the quality factor (or the attenuation constant) of the BAW resonator.

It is important to point out that the frequency f_n, (corresponding to ω_n (1)) coincides neither with $f_n^{(r)}$ nor with $f_n^{(a)}$ and the resonant peculiarities are not observed on this frequency. The overtone frequency f_n lying between the frequencies $f_n^{(r)}$ and $f_n^{(a)}$ is closer to the antiresonance frequency. The frequency f_n corresponds to the resonant frequency of the parallel L_nC_n tank shown in the equivalent circuit.

The quality factor Q_n of this tank depends on the acoustic and other losses in the resonator. It practically coincides with the unloaded Q factor.

3. QUALITY FACTOR AND ATTENUATION CONSTANT

In order to find $K_{\text{eff}}^2(n)$ using (6) it is necessary to eliminate $1/Q_n$. It is possible to find $1/Q_n$ if to measure the frequency dependence of the imagine part of the input electric impedance of the resonator that contains the information about the attenuation of the acoustic waves in the structure. The frequency dependence of $\text{Im}Z_e$ also has extremes. The typical dependence of $\text{Im}Z_e$ is shown in Fig. 4. The analysis is based on finding the frequencies of the extremes of $\text{Im}Z_e$:

$$\text{Im}Z_e^n = \text{Im}\left(1/iC_0' + \frac{1/i\omega C_n}{\left(\frac{\omega_n}{\omega}\right)^2 - 1 + \frac{i}{Q_n}}\right). \quad (7)$$

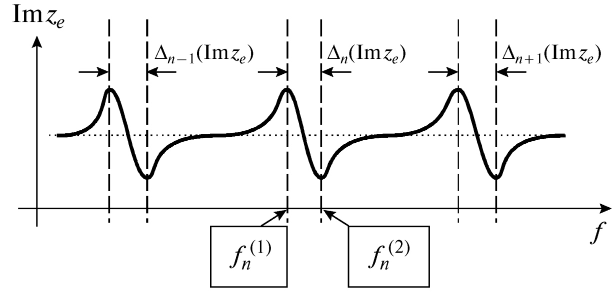

Fig. 4. Frequency dependence of the imagine part of the impedance.

If to find the difference between the frequencies of maxima and minima one can obtain a very simple and useful expression:

$$\Delta_1(n) = \frac{f_n^{(2)} - f_n^{(1)}}{f_n} = \frac{1}{Q_n}, \quad (8)$$

$$\alpha_n = \pi \Delta f_n(\text{Im}Z_e^{(n)}). \quad (9)$$

This expression gives a very simple method of the evaluation of quality factor of any BAW resonator using the results of the measurements of $\text{Im}Z_e$ as a function of frequency (by a vector network analyzer).

It means that this method is fruitful for the evaluation of the quality factor and hence the attenuation coefficient for acoustic waves in the structure.

Expression (8) together with formulae (6) is a set of two equations with two unknown variables—the effective electromechanical coupling constant and the quality factor of the structure. Then one can obtain the equation for electromechanical coupling constant:

$$K_t^2 = \frac{\cot\left(\frac{bl}{2}\right)}{2S(n)\left(1 + \frac{1}{4\sqrt{\Delta^2(n) - \Delta_1^2(n)}}\right) + P}. \quad (10)$$

This expression is used below for the calculations of the electromechanical coupling constant from the results of the measurements.

EXPERIMENT

In accordance with (10) the electromechanical coupling constant of the BAW resonator was found using the results of the measurements of the frequency dependences of the modulus of Z_e and $\text{Im}Z_e$ by a vector network analyzer. Also the thickness of the layers composing the resonator structure and sound velocities in these layers must be known in order to calculate $S(n)$ and P in accordance with (6a) and (6b).

We used an experimental setup that provided getting the necessary data of the frequency differences in

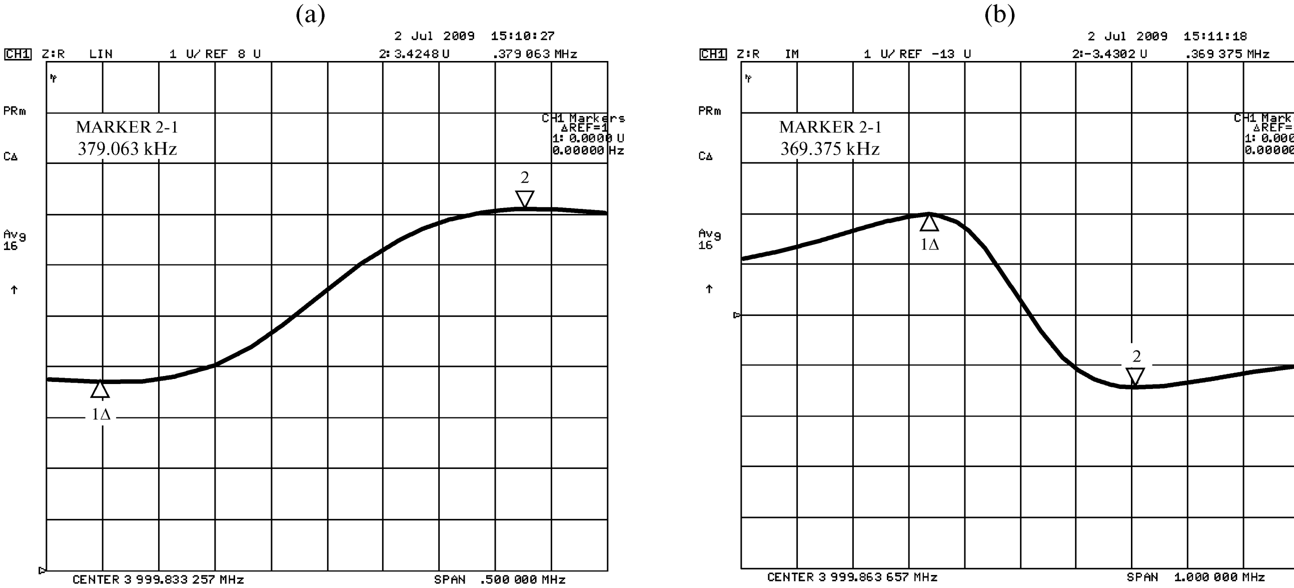

Fig. 5. The results of the measurements of the frequency dependences of the modulus of Z_e (a) and ImZ_e (b).

a wide frequency band from 500 up to 6000 MHz. The samples under study were BAW composite resonators operating on longitudinal and shear acoustic waves. The substrates were flat parallel face plates of langatate, langasite and sapphire. ZnO films (1–8 μm) deposited between thin Al electrodes onto the surface of the plate were used as transducers.

The example of the results of the measurements of the frequency dependences of the modulus of Z_e and ImZ_e of the resonator operating on longitudinal acoustic waves is shown in Fig. 5. The structure under study was: the substrate (a plate of X-cut LGT, the thickness is 745 μm), the bottom electrode (Al, the thickness is 0.15 μm), the ZnO film (the thickness is 0,82 μm), the top electrode (Al, the thickness is 0.15 μm), $N = 1034$.

The results of the experiment and calculations are: $Q = 10839$, $K^2 = 0.069$.

The results of measurements with the same structure on other frequencies are:

$$f = 4.5\text{ GHz},\quad Q = 10698,\quad K_t^2 = 0.068;$$

$$f = 3.421\text{ GHz},\quad Q = 8945,\quad K_t^2 = 0.076;$$

$$f = 2.499\text{ GHz},\quad Q = 15623,\quad K_t^2 = 0.063.$$

These measurements showed almost the same values close to the table value $K_t^2 = 0.08$.

It is interesting to point out that the values of the quality factor of the composite resonator measured using this method and the method based on the subtracting of the active and reactive components from the measured impedance of the structure [5] are the same.

The method can be usefully applied to the study of FBAR's. The experimental results obtained for the FBAR made of the ZnO and AlN films (the thickness is 0.45–1.0 μm) with Al electrodes (the thickness is 0.1 μm), acoustically isolated from the (100)—oriented Si substrate by 4 pairs of the AlN-SiOx quarter wavelength layers were described by (8), (9) and gave the values of K_t^2 close to the known table data 0.038.

CONCLUSIONS

1. The difference between antiresonant and resonant frequencies is not only governed by the electromechanical constant but also by the attenuation constant of the bulk acoustic wave resonator.

2. Expression (9) gives a very simple method of the evaluation of the quality factor of any BAW resonator using the results of the measurements of the frequency dependence of ImZ_e by a vector network analyzer. Only the frequencies of the extremes must be measured.

3. Expression (10) offers the method of the evaluation of the electromechanical coupling constant of a BAW resonator using the results of the measurements of the frequency dependences of the modulus of Z_e and ImZ_e by a vector network analyzer. It is necessary to measure the frequencies of the extremes on these dependences and the thickness of the layers composing the resonator structure.

4. When $K_{\mathrm{eff}}^2(n)Q_n \ll 1$ the result of this work coincides with the results of our previous works [2, 3].

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