ACOUSTIC HBAR SPECTROSCOPY OF METAL (W, Ti, Mo, Al) THIN FILMS

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1. ABSTRACT

Mobile telecommunication systems require development of bulk acoustic wave piezoelectric thin films filters with acoustic wave Bragg acoustic mirrors composed with pairs of layers having a big contrast in their acoustic impedance. W, Ti, Mo, Al can be used in thin-film resonators. Now there are no definite data on the acoustic losses in these materials on microwaves. To evaluate them a new high overtone bulk acoustic wave (HBAR) spectroscopy has been developed and used.

In our study HBAR's were fabricated on an YAG substrate. A ZnO piezoelectric film (with metal film electrodes) was deposited on one face of the substrate. The metallic films under investigation were deposited onto the other face of the substrate. A composite resonator is a multifrequency one. It resonates in a wide frequency band from hundreds MHz to a few GHz. Resonant frequency measurements gives the information about sound velocitiy. The width of the peaks contains the information about acoustic wave attenuation in the layers composing the structure.

In HBAR spectroscopy two steps must be made in order to evaluate the acoustic wave attenuation constant in the thin film. The first step is the experimental finding of the resonance line width that contains the information about acoustic losses in the structures with and without film under testing. The second step is a correct calculation of the attenuation coefficient in the film from the experimental data obtained.

Two different procedures of the attenuation measurements were used. Using the first method the total losses in the structure without metal film were initially measured. After it the measurements were performed when the metal film was deposited. The losses in the film were calculated from the comparison of these data.

The second procedure which in fact is preferable is based on the comparison of the attenuation data measured in the structures with and without film. Two types of the resonators with and without film in this case were prepared on the same substrate. It means that they undergo the same technological treatment before the measurements.

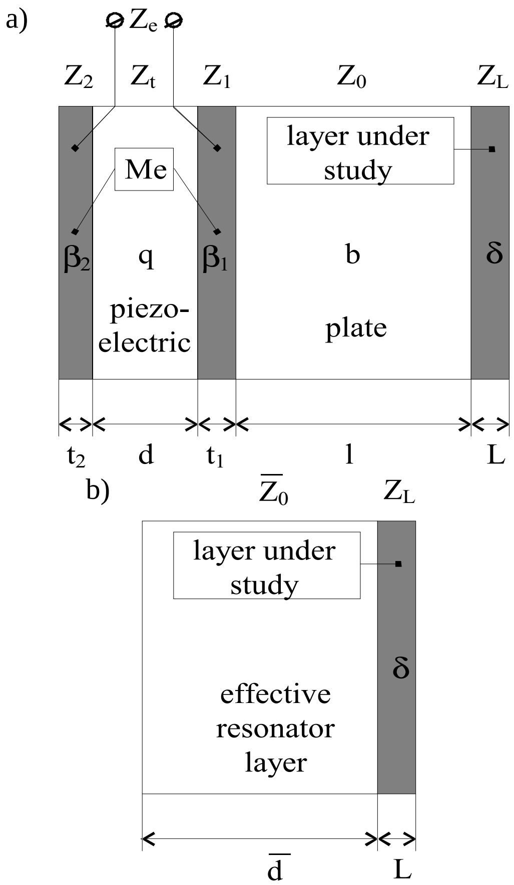

Figure 1.

a) The schematic diagram of the BAW composite resonator with the layer L under investigation.
b) The schematic diagram of the two layer model of the BAW composite resonator

2. THEORETICAL BACKGROUND

The typical high overtone BAW composite resonator structure is schematically shown in Fig. 1, a. It consists of a rather thick plate made of some acoustically transparent material with flat parallel faces (e.g. Yttrium Iron Garnet), electrode layers (aluminum or platinum films), a piezoelectric film (Zinc Oxide film).

The thin film of the material under investigation was deposited on the outer face of the plate.

The equivalent circuit of the ideal HBAR is composed of a resistance, a capacitance and a chain of parallel LCR tanks (corresponding to each particular resonance) connected in series.

The resonant frequencies can be found from the condition $\mathrm{Re}\,\Theta = n\pi$, where:

$$\Theta = qd + \phi_1 + \phi_2 = x + iy$$

$$\phi_1 = \arctan\left(\frac{Z_1}{Z_t}\tan(\varphi_1 + w_1)\right)$$

$$\varphi_1 = \arctan\left[\frac{Z_0}{Z_1}\tan(\varphi_0 + bl)\right]$$

$$\varphi_0 = \arctan\frac{Z_L}{Z_0}\tan\delta L$$

$$\phi_2 = \arctan\frac{Z_2}{Z_t}\tan w_2$$

The total losses in the structure are calculated as $y = \mathrm{Im}\Theta$.

Quality factor of the resonator on resonant frequency ω_n is equal to $Q \approx \pi n/2y$.

The following notations here and in Fig.1 are used: q, b, β_1, β_2, δ are complex vectors (taking into account the losses in layers) for piezoelectric layer, plates, electrodes, and additional layer, d, l, t_1, t_2, L are corresponding thickness of layers, $w_1=\delta_1 t_1$, $w_2=\delta_2 t_2$.

At the first step of losses measurements the total losses in the structure without tungsten film were measured using the described above procedure. At the second step the similar measurements were performed when the tungsten film was deposited. The difference in bandwidths of the same resonance peaks was used for losses calculations in the tungsten film. For these calculations the simplified procedure based on the analysis of the dispersion equation was used.

In the simplified model the resonator is composed of two layers. The first layer with some equivalent parameters substitutes all layers except the film under investigation. In narrow frequency band such a layer may be characterized by thickness that is equal to the sum of thickness of all these layers and by some artificially introduced effective sound velocity and attenuation that correspond to the measured frequency difference between the resonant peaks and to the measured acoustic losses. When the film is absent:

$$\mathrm{Im}\Theta_0 = \alpha d = \frac{\pi f_n^{(0)}}{2Q_n^{(0)}}\frac{1}{\Delta F_n^{(0)}}$$

The second part of the simplified model is the layer under the investigation with wave vector δ and attenuation coefficient β. The imagine part of the phase in case when the film is present is described by the equation:

$$\mathrm{Im}\Theta_1 = \alpha d + \mathrm{Im}\arctan\frac{Z_L}{Z_d}\tan(\delta L + i\beta L) =$$
$$= \frac{\pi f_n^{(1)}}{2Q_n^{(1)}}\frac{1}{\Delta F_n^{(1)}}$$

Here $f_n^{(0)}$ и $f_n^{(1)}$, $Q_n^{(0)}$ и $Q_n^{(1)}$ – are the the resonant frequencies and the measured values of quality factors for the resonant peaks with the same number before and after the film deposition, v_L – acoustic wave velocity in the layer under investigation, v_d – mean acoustic velocity in the sample without layer, it is calculated as the difference between the frequencies of subsequent resonant peaks multiplied by double total measured length $\bar{v}_d$; $\gamma = Z_L/Z_0$ – the ratio of material acoustic impedances of the layer and the substrate, $\Delta F_n^{(0)}$ и $\Delta F_n^{(1)}$ – frequency differences between n and n+1 resonance before and after the film deposition. From the last two equations one can obtain:

$$\frac{\pi f_n^{(1)}}{Q_n^{(1)}\Delta F_n^{(1)}} - \frac{\pi f_n^{(0)}}{Q_n^{(0)}\Delta F_n^{(0)}} = \frac{1}{2}\ln\bigl(1 + 2\gamma\sin 2\beta L/$$
$$/\bigl((1+\gamma^2)\cosh(\beta L)^2 + (1-\gamma^2)\cos(\delta L)^2 -$$
$$-\gamma\sinh 2\beta L - 1)\bigr)$$

The simplified form of the expression may be obtained using the series expansion of this equation with small parameter βL, then

$$\frac{\pi f_n^{(1)}}{Q_n^{(1)}\Delta F_n^{(1)}} - \frac{\pi f_n^{(0)}}{Q_n^{(0)}\Delta F_n^{(0)}} = \frac{2\gamma\beta L}{\gamma^2\sin(\delta L)^2 + \cos(\delta L)^2}$$

The attenuation coefficient β may be found from the numerical solution of any of the last two equations.

The analysis of the last equation shows that the accuracy of attenuation measurement is strongly depends on the film thickness. With the micrometer thickness of the film in GHz band the parameter δL is not small. If one knows the value of sound velocity in a film the thickness of the film can be easily found from the acoustic experiments. If the thickness of the film is known the HBAR spectroscopy is convenient for the estimation of sound velocity in films. The sound velocity may be found from the numerical solution of the equation:

$$\left[\frac{f_{n+1}^0}{\left(\cos\left(2\pi f_{n+1}^0 L/v_L\right)\right)^2} - \frac{f_n^0}{\left(\cos\left(2\pi f_n^0 L/v_L\right)\right)^2}\right]\cdot L +$$
$$+\left[\frac{f_{n+1}}{\left(\cos\left(2\pi f_{n+1} L/v_L\right)\right)^2} - \frac{f_n}{\left(\cos\left(2\pi f_n L/v_L\right)\right)^2}\right]\cdot\frac{v_d}{v_L} +$$
$$+ d\cdot\delta f\cdot\frac{\rho_d}{\rho_L} = 0$$

here $\delta f = f_{n+1} - f_{n+1}^0 - f_n + f_n^0$

f_{n+1} and f_{n+1}^0 frequencies of (n+1)-th resonance after and before the film deposition, f_n and f_n^0 the same for n – th resonance.

3. EXPERIMENTAL PROCEDURE

The standard High Overtone Bulk Acoustic Wave Resonator (HBAR) spectroscopy [1] is based on frequency dependence measurements of the positions of the peculiarities of the resonance points of the phase of the electromagnetic wave reflection coefficient from the composite resonator structure.

New modified version of HBAR spectroscopy [2] used here is based on the measurements of only parallel resonance bandwidth of composite resonator structures at each resonance frequency. Series resistance and the capacitance near each resonance point (including parasitic contact wire resistance and inductance) were measured independently and subtracted from the measured total electric impedance. These measurements of series resistance and the capacitance were taken on the frequencies between the resonances. The removal of the series reactance resulted in disappearance of all series resonance points in frequency dependences of experimentally measured impedance. Only series of simple parallel resonance maximums remained and the width of each resonant peak and corresponding Q-factor could be measured easily using a traditional way.

Samples: In our experiments the high overtone bulk acoustic wave resonator (HBAR) was fabricated on a YAG substrate with a ZnO piezoelectric film (with metal film electrodes) deposited on one face of the substrate. The films of tungsten, molybdenum and titanium under study were prepared using r.f. magnetron sputtering in vacuum in Ar atmosphere. The substrates were heated. The thickness of these films was between 1.35 and

2 µm. The films obtained were not mechanically stressed. The Al films were prepared using two methods. The first one was also magnetron sputtering and the

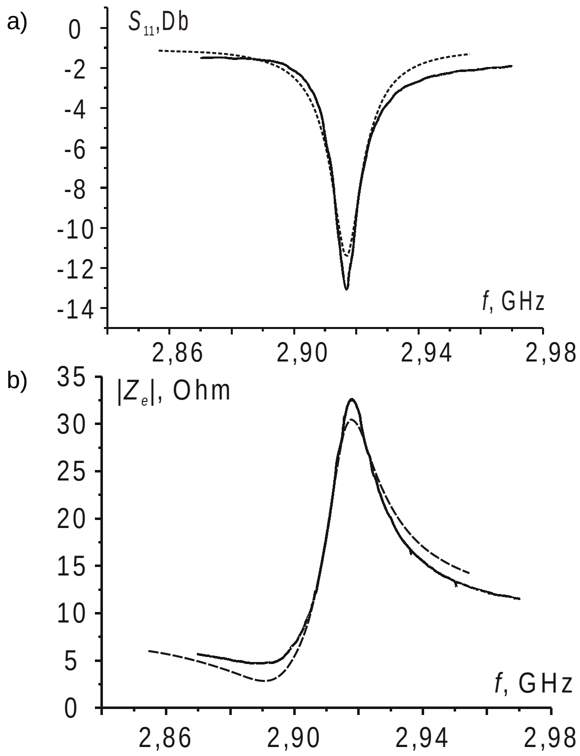

Figure 2.
a) EMW reflection coefficient
b) Modulus of the electric impedance

second one was thermal evaporation. The Al films were deposited by r.f. sputtering.

4. MEASUREMENT RESULTS

The data on longitudinal and transverse acoustic waves velocity measurements obtained in our study for W, Ti, Mo, and Al are in a good agreement with the data of other authors.

Attenuation coefficients and sound velocities in thin films were measured in a wide frequency band (0.6 – 5.0 GHz). Numerical data obtained for 1 GHz are listed in the Table given below. Most of the data were obtained just at the frequency of 1 GHz. The frequency dependence of the attenuation did not obey f^2 law rigorously.

It is interesting to compare the obtained results with the ones existing in literature. For Al the known data for the attenuation of longitudinal acoustic waves on 1 GHz are 7.5×10^{-2} [4] and 2×10^{-2} dB/µm [5]. The data obtained by thermal evaporation in vacuum agree with the data in the references. In the films obtained by magnetron sputtering in our case the losses are much higher.

The data for tungsten obtained directly near the frequency of 1 GHz are relatively high. The value 1.1×10^{-3} dB/µm was were obtained using the extrapolation from the data obtained in 2 – 4 GHz frequency region in accordance with f^2 law. These data are in better agreement with [3] (1.3×10^{-3} dB/µm). The fact of the disagreement between our experimental data means that at 1 GHz frequency some additional mechanism of losses (additional to Akhieser one) exists. The data for titanium are in agreement with that from [5] (10^{-3} dB/µm). In fact W, Mo, and Ti have much less losses than that in Al. The quality of the metallic films under investigation in our experiments probably are not absolutely perfect. So, the obtained numerical data may probably be exceeded in the future study of other films. The data obtained may be used for the evaluation of the order of magnitude of the losses in the metallic film.

5. METALLIC BRAGG MIRROR

Among the other possible applications for metallic thin films is a resonator with Bragg mirror. It seems that

Table

Material	Sound velocity (km/s)	Attenuation on 1 GHz (dB/µm)
Aluminum 1.Magnetron sputtering 2. Thermal evaporation	v_l=6.40±0.01 v_t=3.05±0.01	$\alpha_L=(23\pm5.0)10^{-2}$ $\alpha_L=(7.1\pm1.0)10^{-2}$ $\alpha_T=(5.3\pm1.0)10^{-2}$
Tungsten	5.23±0.01	$(2.9\pm0.5)\ 10^{-3}$ direct measurement on 1 GHz $(1.1\pm0.2)\ 10^{-3}$ extrapolated from 2.5–4 GHz
Molybdenum	v_l=6.43±0.01 v_t=3.42±0.01	$\alpha_L=(1.6\pm0.4)10^{-3}$ $\alpha_T=(2.4\pm0.6)10^{-2}$
Titanium	v_l=6.30±0.01	$(7.0\pm2.0)10^{-3}$

metallic layers are very useful for this application because of the bottom electrode formed from one of the reflecting layers. Pair W-Ti with acoustic contrast ~3.75 meets the requirements for the reflecting layers.

The working prototype of the thin film acoustic resonator with Bragg mirror was made using data obtained in the previous investigations. Piezoelectric layer (ZnO, d=0.52 µm) is deposited on the reflecting structure of six quarter-wavelength layers made of Ti and W. The lowest layer is the film of Ti (d=0.54 µm) deposited on the polished surface of the silicon substrate. The highest layer made of W (d=0.41 µm) is simultaneously a bottom electrode of the resonator. Upper electrode of the resonator is made of thin film of Al (d=900Å). Resonant frequency of the structure is 2.9 GHz. As the acoustic impedance of W (bottom electrode) is higher then the acoustic impedance of ZnO (piezoelectric) the thickness of the piezoelectric film was made equal the quarter of the wavelength. The single resonance peak at the frequency of 2.9 GHz was seen in the experiment. Measured frequency dependencies of the reflection coefficient of the electromagnetic waves (EMW) from the structure (S_{11}) and modulus of the acoustic impedance of the structure ($|Z_e|$) are shown at Fig. 2 a) and b) respectively. One can see strict resonant and anti-resonant peaks. By the distance between these peaks one can obtain a value of the electromagnetic coupling constant of piezoelectric film. In our experiments this value was found to be equal to 0.16, which is smaller than known value of 0.28. The difference can be explained by the presence of the defects in the structure of the piezoelectric. Using this value calculation of EMW reflection coefficient and electric impedance of the structure was made.

Calculated values are presented with dashed lines on the Fig. 2 a) and b) respectively. One can observe good accordance between measured value and calculated one.

The Q factor of our resonator is 245. This value can be increased in the future structures by two ways. The first is the improving the acoustic quality of the piezoelectric layer. The second is the increasing the number of layers of the isolating structure.

6. AKNOWLEDGMENTS

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