Acoustoelectronic interaction in metal island films

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Abstract. The interaction of surface acoustic waves with conduction electrons of island films of various metals was investigated. Island films were formed on the surface of piezoelectric crystalline substrates: Lithium Niobate, Bismuth Germanate, and Piezoquartz. It is experimentally obtained that the surface acoustic wave attenuation as a function of film resistance has a characteristic maximum, and that the velocity changes from the velocity at the free surface of the substrate to that at the metallized surface.

Of considerable interest is the study of surface processes in planar systems of nanosized metal particles - metal island films [1], which are successfully used as cold cathodes, sensors of physical quantities and elements of microelectronics [2]. Particular attention to these systems is mainly due to the fact that their electrical properties are closer in character to those of semiconductors, despite the metallic nature of the film.

In this work, we study the interaction of surface acoustic waves (SAW) with the conduction electrons of island films of noble metals. The structure that we are investigating includes a solid half-space, a liquid or solid layer of thickness $h$ (with a dielectric constant $\varepsilon$) and a vacuum or gas (whose relative permittivity is $\varepsilon_g \approx 1$). Taking into account the Acoustoelectronic interaction in layered structures, the calculation of the parameters of surface acoustic waves is possible, but it is fraught with great mathematical difficulties. These difficulties were overcome by using electromagnetic impedance [3]. Using impedance approach, found a solution for wave fields not in the whole layer structure, but only on the flat boundary of the partition.

The dispersion equation for SAW in a layered system is written in the form [4]:

$$
-k^* = k_0 - k_m = \frac{\varepsilon_h\varepsilon_g^*\varepsilon_h + \varepsilon_g \varepsilon_h^*\varepsilon_g^*}{\varepsilon_h^*\varepsilon_g \varepsilon_h + \varepsilon_g^*\varepsilon_g^*\varepsilon_h^*\varepsilon_g^*} \text{th}(kh) + \varepsilon_g
$$

(1)

where $\varepsilon_p = (\varepsilon_{yy}^* - \varepsilon_{zz}^*)^{1/2}$ is the relative dielectric constant, relative permittivity, expressed through appropriate components of the tensor of the dielectric permeability of the piezoelectric, $k_0 = \omega/V_0$, $k_m = \omega/V_m$, $V_m$ is the velocity of the SAW on the metallized surface, $V_0$ the velocity on the "open" surface, $k^* = k + j\alpha$, $\varepsilon_a = \varepsilon' - j\varepsilon'' = \varepsilon_h(1 - j\alpha)$, $j$ is the imaginary unit, $\alpha = \tan(\delta) = \varepsilon''/\varepsilon'$, $\varepsilon' = \varepsilon_h$, $\alpha$ is the attenuation coefficient, $\omega$ is the circular frequency of the SAW.

The attenuation and dispersion coefficients of the velocity SAW are given by the relations [4]:

$$
\alpha = \text{Im}(\Delta k), \quad \Delta V/V = \text{Re}(\Delta k/k),
$$

where $\Delta k$ and $\Delta V$ – change in the wave number and velocity of surface acoustic waves as a result of acoustoelectronic interaction.
With a small layer thickness \((kh << 1)\) from equation (1) for thin semiconducting films, we obtain a shortened equation, from which we select the real and imaginary parts:

\[
\frac{k_m - k}{k_m} = K^2 \frac{1}{2} \frac{\varepsilon_p}{1 + (\varepsilon_r k_c h)^2 (\varepsilon_p + 1)},
\]

(2)

\[
\frac{\alpha}{k_m} = K^2 \frac{\varepsilon_r k_c h}{2} \frac{\varepsilon_p}{1 + (\varepsilon_r k_c h)^2 (\varepsilon_p + 1)},
\]

(3)

where \(V_s\) is the velocity of SAW, \(K^2/2 = (k_m - k_0)/k_m\), \(K\) – coefficient of electromechanical connection, \(k_c = \omega_c / V_s\), \(\omega_c = \varepsilon_e / \varepsilon_0 = 1 / \tau_M\) – the frequency of Maxwellian relaxation in the film, \(\varepsilon_0 = 8.854 \times 10^{-12} \text{ F/m}\) – dielectric constant of vacuum.

Equation (2) describes the dispersion of the velocity SAW in a layered system. Equation (3) makes it possible to estimate the absorption of surfactants as a result of acoustoelectronic interaction with charge carriers in a semiconducting film or layer. It should be noted that expressions (2) and (3) were obtained without taking into account diffusion fluxes smoothing the distribution of free charge carriers along the wave.

In the case of an island film, the determination of the thickness is problematic. To avoid measuring effective thickness \(h\) we will use surface conductivity \(\sigma_s\) or surface resistance \(R_s\) \((\sigma_s = h \sigma_e = 1 / R_s)\), where \(R_s\) resistance of a film section with the same length and width in the plane of the substrate. It can be shown that the SAW attenuation due to acoustoelectronic interaction \(\alpha\) (dB/cm) is determined by the expression

\[
\alpha = 4.34 \frac{\omega}{V_s} \frac{K^2}{1 + \left(V_s (\varepsilon_p + 1) \varepsilon_0 R_s\right)^2} R_s,
\]

(4)

and reaches the maximum value \(\alpha_{\text{max}}\) at \(R = R_{\text{max}}\) and under the condition \(V_s R_{\text{max}} (\varepsilon_p + 1) \varepsilon_0 = 1\).

Metals with a purity of 99.9% were used for spraying. The metal deposition rate was about 0.5 nm/s. During the deposition, the vacuum was maintained at \(\sim 2 \times 10^{-6} - 6 \times 10^{-5}\) mm Hg. The substrate was placed at a distance of \(\sim 18\) cm from the evaporation boat. Evaporation was carried out from a tungsten or tantalum boat coated with Al2O3 to prevent the metal from the boat from reacting with the evaporated substance. To obtain reproducible results, the evaporation boat must be loaded with a fresh sample. After each spraying to clean the boat, the metal of the old sample must be completely evaporated.

Standard methods and equipment were used to excite and record changes in the SAW attenuation and velocity. Surface waves were excited by an emitting transducer, to which a continuous or pulsed (duration \(\sim 5\) μs) high-frequency (fundamental frequency \(\sim 43.5\) MHz) signal from an HF generator was applied. The signal amplitude was controlled by an attenuator. Spreading over the surface of the crystal, the SAW interact with the sprayed film and are converted by the receiving transducer into an electrical HF signal delayed relative to the input signal for the duration of propagation. The change in SAW attenuation was recorded in dB on the \(Y\) axis, and the change in the film resistance was recorded in a logarithmic scale on the \(X\) axis. The \(Y\) and \(X\) axes (attenuation and surface resistance values) were calibrated using an attenuator and resistance box after completion of each deposition.

It has been experimentally obtained that the SAW attenuation, depending on the resistance of metal films deposited on the surface of piezoelectric substrates, has a characteristic maximum, and the SAW velocity changes from the velocity on the “free” surface \(V_0\) to \(V_m\) – the velocity on the metallized surface. The features of the change in the attenuation and velocity of SAW indicate that the acoustoelectronic interaction in the studied layered structure is of a relaxation nature. Physically, this is explained by some inertia of charge carriers (electrons) in the film. The accumulation and resorption
of excess electrons in the minima of the electric field potential of SAW does not occur instantaneously. For the space charge in the film to change by a factor of \(\varepsilon\varepsilon_0\), a finite time \(\tau_M = \varepsilon/\varepsilon_c\) is required, which is called the Maxwell relaxation time. The SAW frequency \(\omega\) should not be less than the conduction frequency \(\omega_c = \sigma_c/\varepsilon\), so that the space charge in the film does not have time to completely screen the electric field of the elastic surface wave.

Analysis of electron microscopic images showed that the film has an island structure. The size of the island in the region of maximum attenuation of SAW is of the order of 50-100 nm. The discreteness of the structure of the film allows us to assert that the diffusion effects in it are insignificant and, therefore, diffusion frequency \(\omega_D >> \omega_c\), \(\omega\). Therefore, to analyze the interaction of surfactants with conduction electrons in an island metal film, one can use equations (2), (3), and (4) obtained without taking into account the diffusion smoothing of the electron distribution along the wave.

From the adopted model of Acoustoelectronic interaction, it follows that the surface conductivity of an island film at the maximum value of the electron damping coefficient of surface acoustic waves is a constant value for a given piezoelectric substrate. The surface resistance \(R_{\text{max}}\) does not depend on the type and chemical purity of the metal from which the film is obtained.

Figure 1 illustrates the constancy of \(R_{\text{max}}\) regardless of the specific resistance of a particular metal. The experimental values of the electronic damping coefficient of surfactants in layered structures (island films of different metals on three different piezoelectric substrates) in Figure 1 are compared with theoretical dependences, which are represented by solid curves. It follows from the foregoing that only the values of the electronic damping normalized for each substrate with respect to \(\alpha_{\text{max}}\) can be compared.
Table 1. Data for evaluating the electronic attenuation of surface acoustic waves in the "piezoelectric - metal island film" system.

| Material substrate | Orientation | $V_s$, m/s | $\lambda_s$, μm | $K^2$, % | $\varepsilon$ | $R_{\text{max}}$, Ohm/sq | $\alpha_{\text{max}}$, dB/cm |
|--------------------|-------------|-------------|-----------------|--------|---------|-----------------|-----------------|
| LiNbO$_3$          | Y, Z        | 3485        | 80              | 4.59   | 50.2    | 6.48-10$^5$     | 78.26           |
| Bi$_{12}$GeO$_{20}$| (111), [110]| 1708        | 80              | 1.69   | 43.6    | 1.50-10$^6$     | 28.14           |
| Quartz             | Y, X        | 3159        | 100             | 0.225  | 4.52    | 6.33-10$^6$     | 2.51            |

The results of measuring the surface conductivity depend both on the conditions for the formation of an island film (deposition rate, substrate temperature), on its structural homogeneity, and on the procedure for measuring the surface resistance. Preliminary experiments have shown that even for noble metals, it is not possible to obtain the same resistance values by sputtering island films of the same weight thickness, for example, on three pairs of film electrodes with a standard gap between them. The deposition of Ag and Au was carried out under the same conditions from the same evaporator located at a sufficiently large distance from the substrate. In some cases, the resistance of the films differed by an order of magnitude, which cannot be explained, for example, by the difference in the geometric dimensions of the films.

Thus, an island metal film on a flat polished surface of a piezoelectric substrate is an object with a significant contribution of surface forces. Depending on the thickness and morphological structure of the metal island film, its conductivity changes. The electric field, which accompanies SAW in a piezoelectric, interacts with charge carriers of the island metal film. It was experimentally found that the velocity of SAW varies from the velocity on the free surface of the substrate to the velocity on the metallized surface. The attenuation of SAW, depending on the conductivity of the island metal film, has a characteristic maximum. At surface conductivity corresponding to the maximum attenuation of SAW, the size of the islands is ~ 50–100 nm.

The discreteness of the structure of the film allows us to assert that diffusion effects in it are insignificant. It is found that the interaction of SAW with conduction electrons in island films has a relaxation nature. The relaxation frequency depends on the surface resistance of the films. The surface resistance at the maximum attenuation of surface acoustic waves has a constant value for a given piezoelectric substrate and does not depend on the type of sprayed metal. In addition, it was revealed that the results of measuring the surface conductivity depend on the conditions for the formation of an island metal film, its structural homogeneity, and the method for measuring the surface resistance.

References
[1] Boltaev A P, Penin N A, Pogosov A O and Pudonin F A 2003 Journal of Experimental and Theoretical Physics 96 5 940–4
[2] Fedorovich R D, Naumovets F G and Tomchuk P M 2000 Physics Reports 328 73–179
[3] Biryukov S V, Gulyaev Yu V, Krylov V V and Plesskij V P 1991 Surface acoustic waves in inhomogeneous media (Moscow, Nauka)
[4] Simakov I.G, Gulgenov Ch Zh and Bazarova S B 2019 Vestnik Buryatskogo gosudarstvennogo universiteta. Matematika. Informatika 2 95–103