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Noncontact determination of thin films conductance by SH_0 plate acoustic waves

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The paper is devoted to the development of noncontact acoustic method of the determination of thin film conductance by using shear-horizontal zero order (SH_0) acoustic waves in thin piezoelectric plates. The method is based on the registration of changes in velocity and attenuation of acoustic waves in a piezoelectric plate due to placing the structure "film under study–dielectric substrate" on the certain distance from the plate. The limits of measured values by the suggested method are determined. The theoretical data are compared with the experimental results.
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I. INTRODUCTION

At present, the works concerning with synthesis of novel materials possessing by given characteristics as well as by possibility of their change under external actions (electric, magnetic and acoustic fields, temperature, illumination, pressure, etc.) are actively carried out.[1–4] They are diamond-like low-dimensional materials with developed surface, magnetic nano-structured materials, meta-materials, nanocomposite materials with nanoparticles of metals and their compounds, etc. Sometimes traditional methods of their investigation are not suitable because new materials may have an active surface and interact with a measuring instrument. Such interaction leads to the change of the properties of material under study and distorts the measurement results. In this connection, the development of noncontact methods of measuring the characteristics of aforementioned materials is relevant. This work is devoted to the development of noncontact acoustic method of the determination of conductance of thin films.

A. The structure "YX $LiNbO_3$ plate–air gap–dielectric semi-infinite media"

As is well known,[5] the properties of the piezoactive acoustic waves in a plate strongly depend on the boundary conditions on its surface. Placing a dielectric medium on some distance from a plate leads to the decrease of wave velocity in such structure.[6–8] At that the change in velocity of wave decreases with the rise of permittivity of this medium. This fact may be explained by the shielding of the electric field components of piezoactive wave.

Now we consider the shear-horizontal zero order (SH_0) wave in the structure "plate of YX lithium niobate–vacuum (air) gap–dielectric medium" (Fig. 1(a)). For the theoretical analysis, we used the standard method[9,10] based on the motion equation, Laplace's equation and the state equations for piezoelectric, air (vacuum), and dielectric media.

Due to the presence of the air gap between the plate and dielectric medium, the mechanical properties of medium may be ignored. As the boundary conditions we used the equality to zero of mechanical stresses on the piezoelectric plate surfaces and continuity of the electric potential and normal component of the electrical displacement on all interfaces

$$x_3 = -d : \Phi^{med} = \Phi^{vac}, \quad D_3^{med} = D_3^{vac}, \tag{1}$$

$$x_3 = 0, \quad h_1 : T_{i3}^{pl} = 0, \quad \Phi^{pl} = \Phi^{vac},$$
$$D_3^{pl} = D_3^{vac}, \quad i = 1 \div 3. \tag{2}$$

The indices *pl, vac*, and *med* denote that the appropriate variable refers to the piezoelectric plate, vacuum or dielectric medium, respectively.

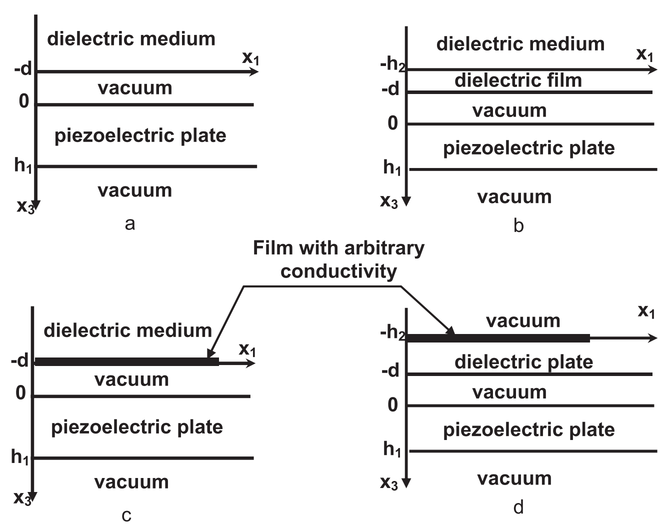

FIG. 1. Geometry of the problem.

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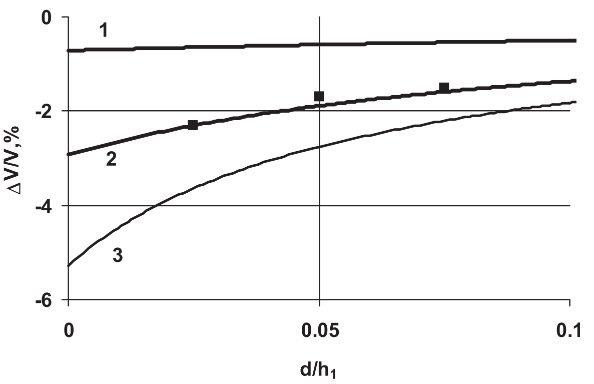

FIG. 2. The fractional change in velocity of SH_0 wave versus normalized width of the air gap between YX $LiNbO_3$ plate and dielectric medium at ε_m: 3.3 (1), 12 (2), 25 (3). Squares correspond to experimental results for structure ⟨⟨YX $LiNbO_3$ plate–air gap–Si ($\varepsilon_m = 12$)⟩⟩.

Fig. 2 shows the theoretical dependencies of the fractional change in velocity of the SH_0 wave on the normalized width of the air gap (d/h_1) between YX $LiNbO_3$ plate and dielectric medium at different values of medium permittivity ε_m. Here, d is the width of the air gap and h_1 is the plate thickness. $\Delta V/V = (V - V_0)/V$, where V and V_0 are the wave velocities in structure under study and in the free YX $LiNbO_3$ plate, respectively.

For carrying out the experimental investigations, the delay line based on the YX $LiNbO_3$ plate 1 with two interdigital transducers (IDTs) with split fingers was fabricated (Fig. 3). The distance between transducers 2 was equal 27 mm. These transducers excited and received the wave with the shear horizontal polarization (SH_0 wave), which propagated along X axis. It is known[11,12] that for such crystallographic orientation the electromechanical coupling coefficient of SH_0 wave has the significant value of ~32%. The frequency range (f) of delay line was equal 2.5–3.9 MHz. In order to prevent the reflections from the edges of the plate its opposite edges had the wavy form with the depth of $\sim\lambda/2$ (λ = wavelength). At that the wavelength was equal 1.2 mm. The delay line construction allowed to reduce the thickness of the plate from 500 μm up to 200 μm by using the lapping with the set of abrasive powders. For this purpose, the plate was fixed on the special support of acrylic glass 3 that prevented its deformation with mechanically free sides. The flatness during the lapping was ensured due to the presence along the perimeter of the support the auxiliary silicon samples 5 (Fig. 3), the hardness of which is more in comparison with lithium niobate. The dielectric plate of silicon 4 with lateral dimensions of 20×40 mm and thickness of 1 mm was placed between IDTs at the distance d from the plate of lithium niobate. The distance d was changed by using the set of foil strips 6 of various thicknesses, which were placed on the lateral edges of the lithium niobate plate outside of the acoustic beam. The theoretical analysis has shown that for the given values of the frequency and thickness of lithium niobate plate the dielectric plate with thickness of 1 mm may be considered as semi-infinite.

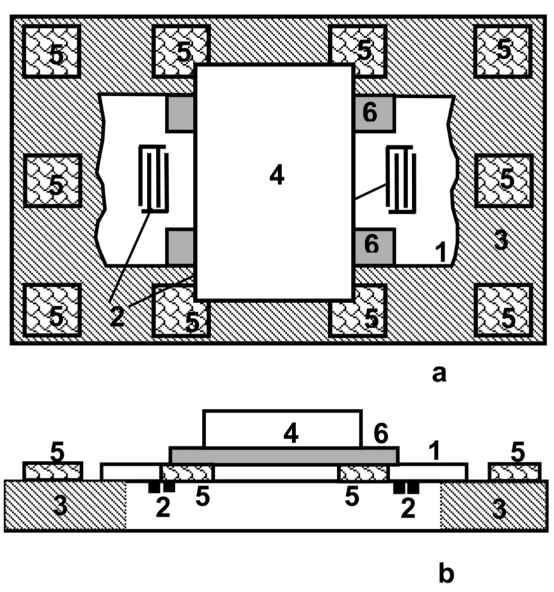

FIG. 3. (a) bottom and (b) side views of an experimental setup: 1–piezoelectric plate (Y-X $LiNbO_3$), 2–IDTs, 3–support of acrylic glass, 4–dielectric half-media Si, 5–the auxiliary silicon samples, 6–foil strips of needed thickness.

Fig. 2 shows also the experimental dependence of the change in SH_0 wave velocity in the structure "plate YX lithium niobate–air gap–plate of Si ($\varepsilon_m = 12$)" as function of the normalized gap width. One can see a good agreement between theoretical and experimental data.

B. Structure "YX $LiNbO_3$ plate–air gap–thin dielectric film–dielectric substrate"

Now we consider the influence of the dielectric properties of thin non-conducting film deposited on the surface of dielectric substrate on the velocity of SH_0 wave in a piezoelectric plate separated by the distance d from the aforementioned structure (Fig. 1(b)). The conducted analysis has shown that the mechanical properties of the film also may be ignored.

In this case, in addition to the boundary conditions (1), (2) we used the next ones

$$x_3 = -h_2 : \Phi^{med} = \Phi^f, \quad D_3^{med} = D_3^f, \tag{3}$$

$$x_3 = -d : \Phi^f = \Phi^{vac}, \quad D_3^f = D_3^{vac}. \tag{4}$$

Here, index *f* denotes that the appropriate variable refers to the film under study.

Fig. 4 demonstrates the theoretical dependencies of the fractional change in velocity of SH_0 wave on the normalized width of the vacuum (air) gap between the plate of lithium niobate and structure "film-substrate" at the different values of film (ε_f) and substrate (ε_m) permittivity. The value of the normalized film thickness was equal $(h_2 - d)/h_1 = 0.025$. One can see that the difference between curves 1 and 2 decreases with the rise of substrate permittivity. It means that the value of $\Delta V/V$ practically does not depend on film permittivity for the case $\varepsilon_m > 10$. We also obtained the experimental dependence of the change in the wave velocity as function of the normalized width of the gap for the structure "lithium niobate plate–vacuum (air) gap-diamond–like film on the substrate of silicon." The film thickness was

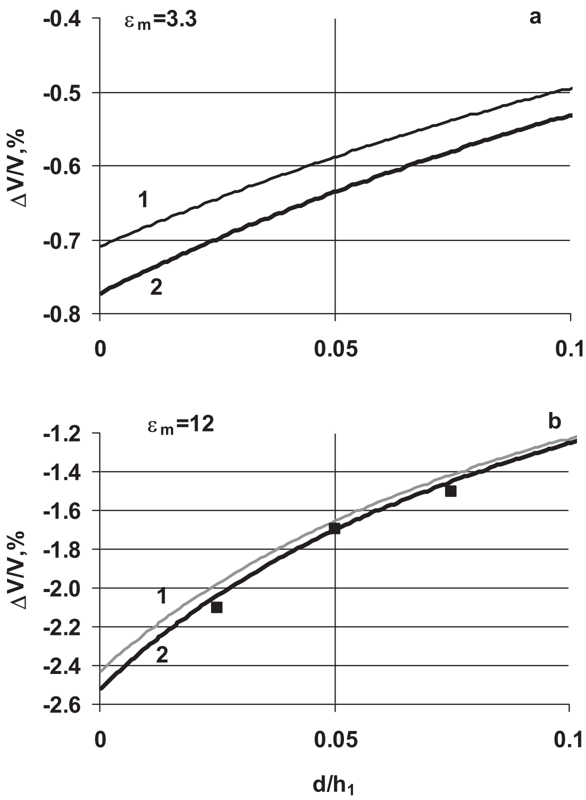

FIG. 4. The fractional change in velocity of SH_0 wave versus normalized value of the air gap between YX $LiNbO_3$ plate and structure "dielectric film-dielectric semi-infinite medium" at $\varepsilon_f = 2$ (1), and 50 (2). As the substrate quartz glass $\varepsilon_{m=} = 3.3$ (a) and silicon $\varepsilon_{m\ =} = 12$ (b) are used. Squares correspond to experimental results for the structure ⟨⟨YX $LiNbO_3$ plate–air gap–diamond-like film on Si substrate ($\varepsilon_m = 12$)⟩⟩.

equal ~5 μm. The substrate of silicon with the film was placed above the lithium niobate plate on the aforementioned foil strips (Fig. 3). Fig. 4 demonstrates the experimental results by the points.

In order to increase the sensitivity of the structure to the change in the film permittivity one can suggest use the piezoelectric plate with stronger piezoelectric effect. This is confirmed by Fig. 5 which presents the analogous theoretical dependencies for the SH_0 wave in plate of Y–X potassium niobate ($KNbO_3$). In this material, the electromechanical coupling coefficient for SH_0 wave is equal 96% for parameter $h_1 f = 900$ m/s.[13] One can see that the use of more piezoactive wave may lead to increasing the sensitivity of method and enhance the accuracy of the determination of the film permittivity. In this case, the value of the normalized film thickness was equal $(h_2 - d)/h_1 = 0.025$.

C. Structure "YX $LiNbO_3$ plate–air gap–film with arbitrary conductivity–dielectric substrate"

Now we consider the possibility of the determination of the electrical conductance of thin films by using the structure presented in Fig. 1(c). Thin film with arbitrary conductance the thickness of which is significantly less than wavelength was placed in plane $x_3 = -d$. In this case, the mechanical properties of the film may be ignored and the electrical boundary conditions have the following form:[5]

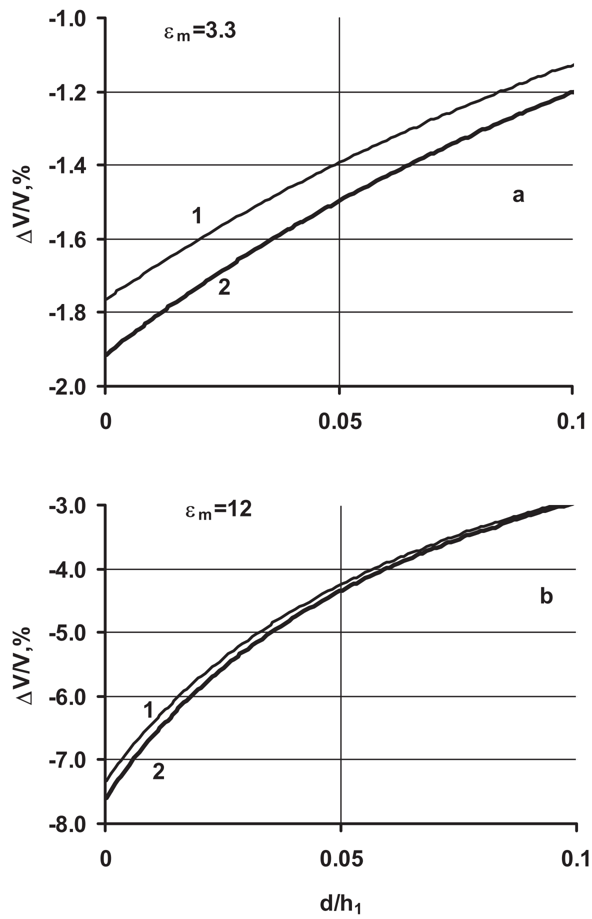

FIG. 5. The fractional change in velocity of SH_0 wave versus normalized value of air gap between YX $KNbO_3$ plate and structure "dielectric film-dielectric semi-infinite medium of quartz glass" at $\varepsilon_f = 2$ (1) and 50 (2). As the substrate quartz glass $\varepsilon_{m=} = 3.3$ (a) and silicon $\varepsilon_{m\ =} = 12$ (b) are used.

$$x_3 = -d : \Phi^{med} = \Phi^{vac}, \quad D_3^{med} - D_3^{vac} = -\delta. \qquad (5)$$

Here, $\delta = -i\sigma_s \Phi^{med} \omega / V^2$ is the density of surface charge, σ_s, ω, and V are surface conductance of film, circular wave frequency, and wave velocity, respectively.

Fig. 6 presents the theoretical dependencies of the fractional change in velocity (a) and attenuation (b) of SH_0 wave on the normalized width of air gap between plate of lithium niobate and structure "film with arbitrary conductivity–substrate Si" at different values of the surface conductance of film σ_s.

One can see that the film conductance leads to the attenuation of SH_0 wave and the value of the fractional change in velocity $\Delta V/V$ strongly depends on the surface conductance of film in the range $5 \times 10^{-8} \div 10^{-5}\,\mathrm{Ohm}^{-1}$. Fig. 7 shows the analogous dependencies for SH_0 wave in structure "YX $KNbO_3$ plate–conducting film–quartz glass ($\varepsilon = 3.3$)." It is possible to see that the use of stronger piezoactive wave allows to increase the accuracy of the measurement of the film conductance and to widen the range of measured values of conductance to $10^{-8} \div 10^{-4}\,\mathrm{Ohm}^{-1}$.

The analysis has also shown that the range of the measurable conductance may be increased by using the structure presented in Fig. 1(d). In this case, the film under study is

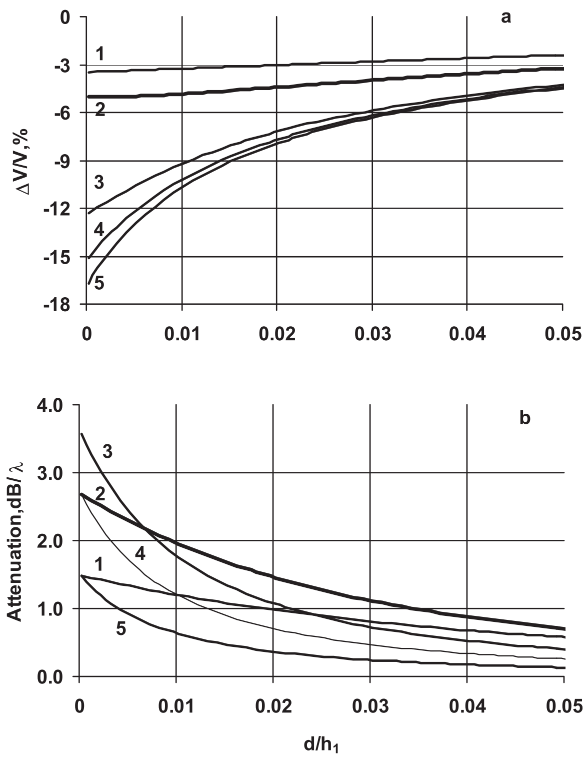

FIG. 6. Dependencies of the fractional change in velocity (a) and attenuation per wavelength (b) of SH_0 wave versus normalized width of air gap between YX $LiNbO_3$ plate and structure “conducting film—substrate of Si” at $\sigma_s = 5\times10^{-7}\,\mathrm{Ohm}^{-1}$ (1), $10^{-6}\,\mathrm{Ohm}^{-1}$ (2), $3\times10^{-6}\,\mathrm{Ohm}^{-1}$ (3), $5\times10^{-6}\,\mathrm{Ohm}^{-1}$ (4), and $10^{-5}\,\mathrm{Ohm}^{-1}$ (5).

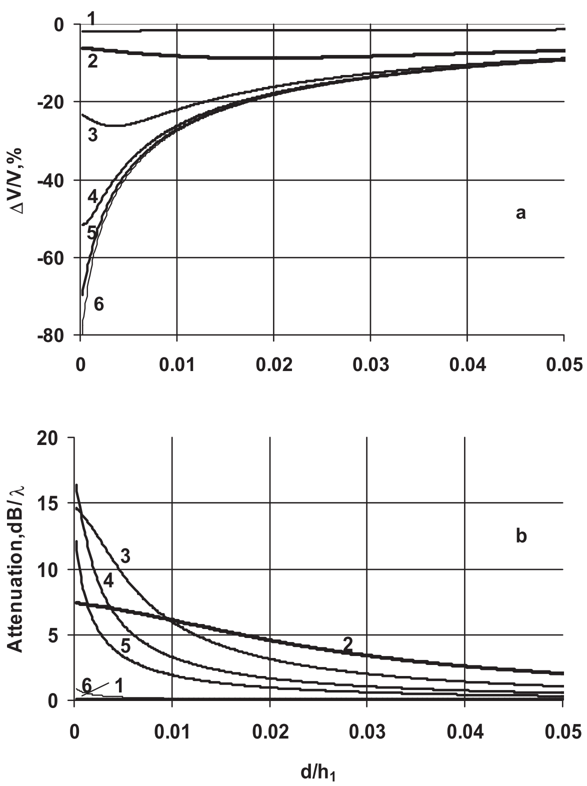

FIG. 7. The fractional change in velocity (a) and attenuation per wavelength (b) of SH_0 wave versus normalized width of air gap between YX $KNbO_3$ plate and structure “conducting film—substrate of quartz glass” at $\sigma_s = 10^{-8}\,\mathrm{Ohm}^{-1}$ (1), $8\times10^{-7}\,\mathrm{Ohm}^{-1}$ (2), $2\times10^{-6}\,\mathrm{Ohm}^{-1}$ (3), $4\times10^{-6}\,\mathrm{Ohm}^{-1}$ (4), $7\times10^{-6}\,\mathrm{Ohm}^{-1}$ (5), and $10^{-4}\,\mathrm{Ohm}^{-1}$ (6).

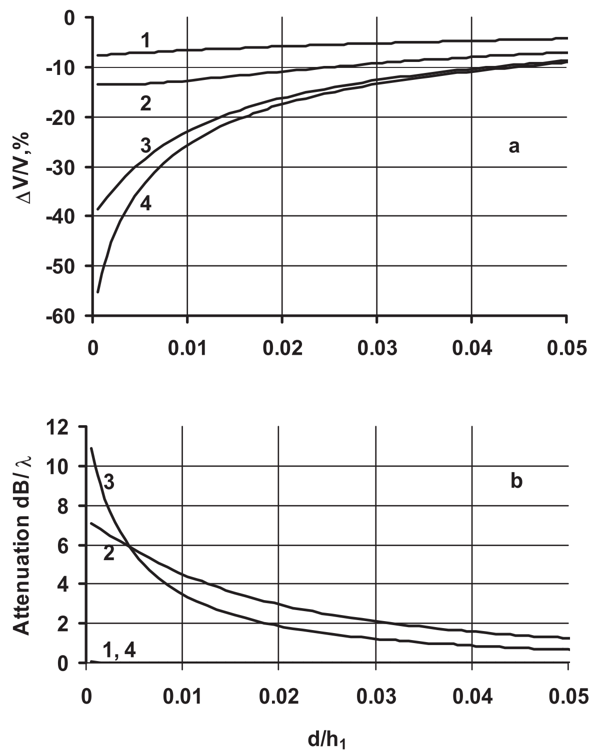

FIG. 8. The fractional change in velocity (a) and attenuation per wavelength (b) of SH_0 wave versus normalized width of air gap between YX $KNbO_3$ plate and structure “dielectric plate with $\varepsilon = 80$, $h_2 f = 100$ m/s—film with arbitrary conductivity” at $\sigma_s = 10^{-9}\,\mathrm{Ohm}^{-1}$ (1), $10^{-6}\,\mathrm{Ohm}^{-1}$ (2), $3\times10^{-6}\,\mathrm{Ohm}^{-1}$ (3), $10^{-3}\,\mathrm{Ohm}^{-1}$ (4).

placed in a plane $x_3 = -h_2$. Electric field of SH_0 wave penetrating through dielectric plate weakens due to its permittivity. Thus, the influence of the film conductance on the wave velocity and attenuation also weakens. This effect leads to the expansion of the range of measurable film conductance from 10^{-9} up to $10^{-3}\,\mathrm{Ohm}^{-1}$ (Fig. 8).

As a whole the obtained results allows to make the conclusion about the possibility of the described method for the determination of conductance of thin films deposited on the surface of dielectric substrate.

II. CONCLUSION

The paper is devoted to the development of noncontact acoustic method of the determination of thin film conductance. Theoretical results show that the accuracy of the determination of the conductance increases with increase of the electromechanical coupling coefficient of the propagating wave. The limits of the measured values by the suggested method are determined ($10^{-9} \div 10^{-3}\,\mathrm{Ohm}^{-1}$).

ACKNOWLEDGMENTS

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