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Effect of the conductivity of a thin film located near the acoustic delay line on the characteristics of propagating SH_0 wave

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ABSTRACT

The results of the study of the influence of the conductivity of a thin film located with a certain gap above the acoustic delay line on the characteristics of propagating acoustic wave with a quasi-shear-horizontal polarization (SH_0) are presented. The delay line was made of Y-X lithium niobate plate with a thickness of 200 μm containing two interdigital transducers for exciting and receiving SH_0 wave. The operating frequency range of the delay line was equal to 2.6–3.8 MHz. The 1 mm thick glass plate with a film of the given conductivity applied on one plate's side was placed above this delay line with the some air gap. The change in the phase of output signal of the delay line was measured at the various values of the width of this gap. As films with the various values of the conductivity, tin dioxide films deposited on a glass plate by high-frequency reactive magnetron sputtering in the oxygen-argon mixture were used. It has been shown that the velocity of SH_0 wave propagating in the delay line under investigation depends on the film conductivity and the width of the gap between the delay line and conductive film. The dependences of the change in the SH_0 wave velocity on a width of the gap between the surface of the delay line and conductive film were constructed, as well as on the film conductivity. The comparison of the experimental results with the theoretical data showed their good agreement.

1. Introduction

At present, the characteristics of acoustic waves in piezoelectric plates that are thin compared with the wavelength are quite thoroughly investigated [1–11]. It has been shown that zero-order quasi-shear-horizontal waves (SH_0) are characterized by the highest value of the square of electromechanical coupling coefficient in comparison with antisymmetric and symmetric Lamb waves, as well as surface acoustic waves, in the same material [6–9]. Besides, it is of a great practical interest to investigate the possibility of controlling the properties of acoustic waves in piezoelectric plates by changing the electrical boundary conditions. As is known [12], the piezoactive acoustic waves are accompanied not only by the mechanical deformation during propagation, but also by the electric field. When an acoustic wave propagates in a piezoelectric plate, this electric field penetrates into the vacuum and by influencing this field one can change the wave characteristics. It is obvious that the influence of the electrical boundary conditions on the acoustic wave increases with increasing the value of the electromechanical coupling coefficient. Therefore, the use of SH_0 waves instead of surface acoustic waves can significantly improve the performance of the existing signal processing devices and increase the sensitivity of the different acoustic sensors. There are many papers [13–19], in which the influence of the electrical boundary conditions on the properties of SH_0 waves propagating in piezoelectric plates has been theoretically studied. Thus, in [19], by solving a homogeneous problem, the analysis of the influence of the film conductivity on the phase velocity of an acoustic wave with the quasi-shear-horizontal polarization propagating in the structure "piezoelectric plate of the lithium niobate Y-X cut – vacuum gap – conductive film on a silicon substrate" was carried out. It has been shown that a significant change in the velocity occurs when the conductivity of the film varies within the limits of 0.1–1 μS. However, there is no detailed experimental study of the effect of the film conductivity on the characteristics of a wave with shear-horizontal polarization in the literature.

The present work is devoted to the experimental and theoretical study of a structure consisting of a delay line based on the Y-X lithium niobate plate with a propagating quasi-shear-horizontal wave of zero-order (SH_0) and a conductive film located with the some gap above the plate. The influence of the film conductivity, as well as the width of the gap between the film and delay line on the SH_0 wave characteristics, was investigated.

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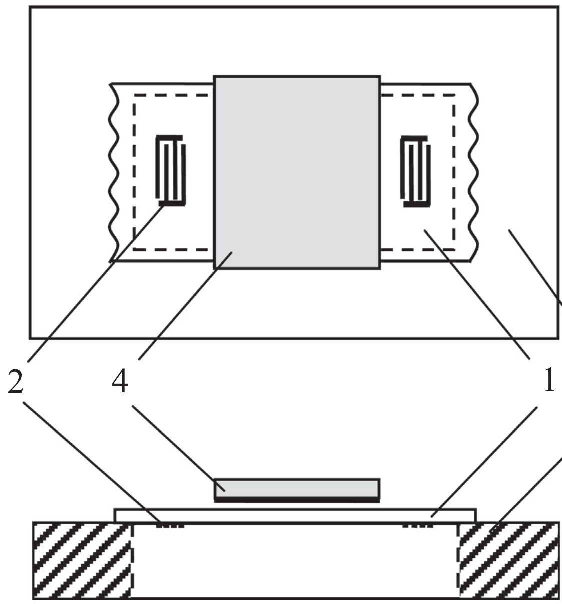

Fig. 1. The scheme of the experimental device: 1 – the plate of Y-X $LiNbO_3$, 2 – the IDTs, 3 – the holder of plexiglass, 4 – the glass substrate with the conducting film.

2. Description of the experimental setup and method of the measurement

For the experimental study, a delay line based on the plate of Y-X lithium niobate (Y-X $LiNbO_3$) with the shear dimensions of $20 \times 50\,mm^2$ and thickness of 200 µm containing two interdigital transducers (IDTs) with the split fingers (Fig. 1) was used. Each transducer contained 5 pairs of the fingers with an aperture of 8 mm and a period of 1.25 mm. The distance between the IDTs was equal to 27 mm. These transducers excited and received SH_0 wave propagating along the X axis. The operating frequency range of the delay line was 2.6–3.8 MHz. To prevent the reflections from the edges of the plate, its opposite edges had the wavy form with a depth of $\lambda/2$ (where the wavelength $\lambda = 1.25$ mm). The plate was fixed on a special holder of plexiglass, which eliminated its deformation while keeping the sides mechanically free.

To carry out the measurements, the investigated delay line was connected to the meter of S-parameters E5071C ("Agilent", USA) in the regime of measuring the parameter S_{12}. First, the frequency dependences of the insertion loss and phase of the output signal of delay line were measured at the absence of a conducting film. These dependencies are presented in Fig. 2a, and b, respectively. One can see that the maximum value of the insertion loss of delay line is equal to 26 dB, and the frequency dependence of the phase is linear.

Then, a glass plate with a deposited conductive film was placed above the delay line with a certain air gap, and the frequency dependences of the insertion loss and phase of the output signal of the delay line were measured. The width of the air gap varied from 0 to 300 µm with the step of 10–20 µm. The width of the gap was changed and checked by the special micrometric device with the accuracy of 1 µm. As conductive films we used the tin dioxide films with the following values of the surface conductivity: 0.0072; 1.48; 46.1; 550, and 87,000 µS. The films were deposited on the glass substrates 1 mm thick by the high-frequency reactive magnetron sputtering 99.99% tin (iTASCO, Korea) into an oxygen-argon mixture [20]. By selecting the ratio of the components of this mixture, it was possible to change the stoichiometry of the resulting film and, accordingly, to change the film conductivity. To monitor the film conductivity, tin contacts were first deposited on a glass substrate by electron-beam evaporation. The distance between the contacts was exactly equal to the width of the substrate and, correspondingly, to the width of the conductive film (25 mm). In this case the surface conductivity of the film was exactly equal to its total conductance and was measured by a digital multimeter GDM-78251 (GW Instek, Taiwan) directly during the deposition of the film. In the course of the experiment, a glass substrate without a conducting film (as a film with "zero" conductivity) and a glass substrate with an aluminum film (as a film with "infinitely large" conductivity) were also investigated.

3. Obtained experimental results

As a result, the frequency dependencies of the phase of the output signal of delay line was obtained for the aforementioned films with the different values of the film conductivity and width of the gap between the surface of the delay line and glass plate with the deposited film. These dependencies had the same linear nature as the dependence presented in Fig. 2b.

On the basis of these dependences, the phase change ($\Delta\Phi$) of the output signal of delay line at a frequency of 3.25 MHz (the frequency of the minimum insertion loss) as function of the gap width at the different values of the film conductivity was constructed. These dependencies, normalized to zero for a gap width of 300 µm, are shown in Fig. 3 (left ordinate axis).

One can see from the Fig. 3 that with increasing the gap width, the phase of the output signal of delay line increases and reaches the saturation at a width of 250–300 µm for all the films under study. It is also seen that the phase change due to increasing the gap width is the stronger the higher the conductivity of the film. The greatest phase change is observed for the aluminum film ("infinite" conductivity), and also for the films with the values of the conductivity of 87,000 and 550 µS. For these cases (curves 1–3 in Fig. 3) the maximum change in phase is equal to 203, 187 and 160 degrees, respectively. For all the conductivity values of the films, the largest phase change in the output signal of delay line occurs in the range of the gap width of 10–100 µm.

The dependences shown in Fig. 3 (left ordinate axis) lead to the

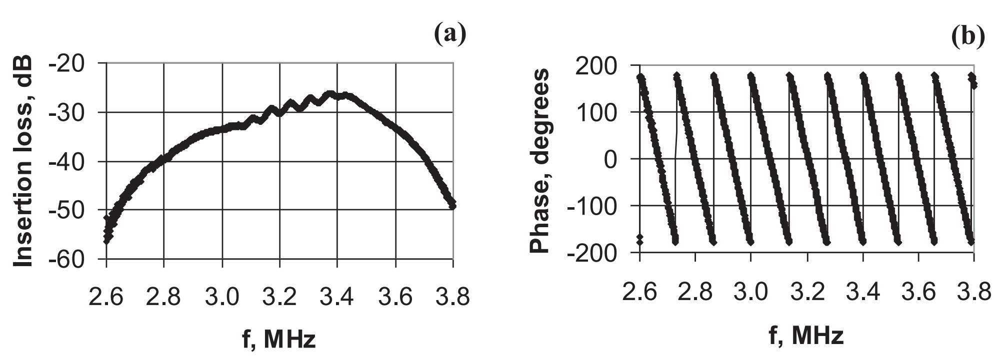

Fig. 2. Frequency dependences of the insertion loss (a) and phase (b) of the output signal of acoustic delay line based on the Y-X $LiNbO_3$ plate.

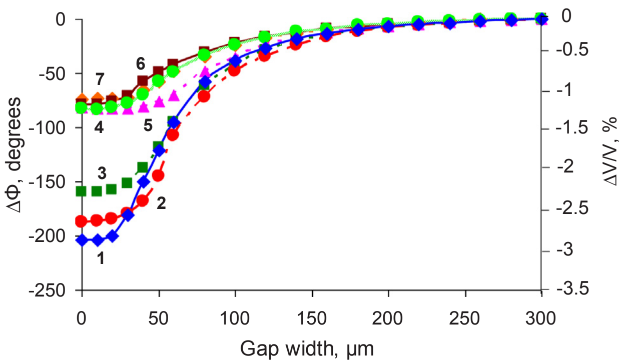

Fig. 3. Experimental dependences of the change in phase (ΔΦ) of the output signal (left ordinate axis) and of the relative change in the SH_0 wave velocity (ΔV/V) (right ordinate axis) of delay line on the gap width at 3.25 MHz for the following values of the film conductivity: (2) – 87000, (3) – 550, (4) – 46, (5) – 1.481, (6) – 0.072 μS, (1) refers to the aluminum film, (7) refers to the glass substrate without a film.

conclusion that the presence of a conducting film near the surface of delay line causes the change in the velocity of acoustic wave in the piezoelectric plate of lithium niobate.

The normalized phase of the output signal of delay line was converted into a relative change in the acoustic wave velocity as follows. It is known that for a fixed frequency of an acoustic wave the relative phase change (Φ) of the output signal of delay line is exactly equal to the relative velocity change (ΔV/V) [21], i.e.: $\Delta\Phi/\Phi = -\Delta V/V$. Here ΔΦ is the normalized phase change of the output signal of delay line, found in the experiment, and Φ is the total phase incursion in delay line at a length which is equal to the width of the conducting film (L).

Thus, in order to find the relative change in the velocity, one should know the value of the total phase incursion Φ, which is expressed by the following formula: $\Phi = -360 \times L/\lambda$, where λ is the acoustic wavelength. In our case, L = 25 mm, λ = 1.25 mm (the period of the IDT). Therefore, Φ = 7200 deg. It should be noted that the "−" sign in the formula for Φ is due to the tunings of the meter of S-parameters (E5071C), in which the phase of the output signal decreases with increasing the frequency (see Fig. 2b).

The dependences of the relative change in the velocity (ΔV/V) of acoustic SH_0 wave, which propagates in delay line on the gap width for the different values of the film conductivity are presented in Fig. 3 (right ordinate axis). These dependencies are also normalized to zero at the gap width of 300 μm.

One can see from Fig. 3 that the greatest change in the velocity corresponds to the aluminum film ("infinite" conductivity), and also to the films with the values of the conductivity of 87,000 and 550 μS. For these cases (curves 1–3 in Fig. 3) the maximum change in the velocity is equal to 2.8%, 2.6% and 2.2%, respectively, for a gap width of 0–30 μm. For all values of the film conductivity, the greatest change in the velocity of the acoustic wave occurs in the range of the gap width of 10–100 μm.

The experimental studies also allowed to construct the dependence of the phase change of the output signal of delay line on the film conductivity for the various values of the width of the gap between the delay line and substrate with a conducting film. These dependences are shown in Fig. 4 (left ordinate axis). One can see from the figure that with increasing the film conductivity the phase of the output signal of the delay line initially practically does not change, then decreases sharply in the interval of 10–1000 μS, and then increases insignificantly. At that, the smaller width of the gap between the delay line and conductive film, the more the phase of the output signal of delay line changes in the entire range of the film conductivity. The most significant phase changes are observed for the values of the gap width in the range of 10–100 μm. When the conductive film is removed for a distance greater than 200 μm, the phase practically ceases to change.

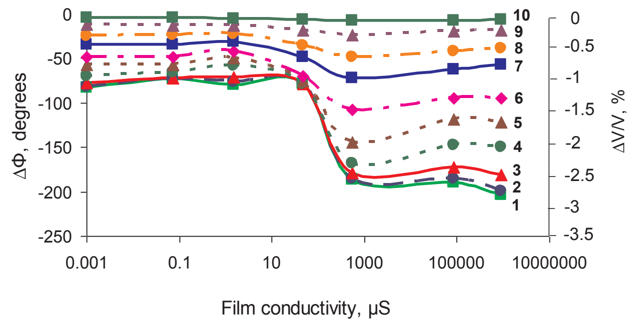

Fig. 4. Experimental dependences of the change in phase (ΔΦ) of the output signal (left ordinate axis) and of the relative change in the SH_0 wave velocity (right ordinate axis) of delay line on the film conductivity for the following values of the gap width: (1) – 10, (2) –20, (3) – 30, (4) – 40, (5) – 50, (6) – 60, (7) – 80, (8) – 100, (9) – 140, (10) – 200 μm.

Dependencies of the relative change in the SH_0 wave velocity propagating in delay line on the film conductivity for the various values of the gap width were also plotted. These dependencies are shown in Fig. 4 (right ordinate axis).

The behavior of these dependences for ΔV/V is naturally the same as for ΔΦ (see Fig. 4 left ordinate axis).

4. Theoretical results

In order to compare the experimental results obtained with the theoretical data, we calculated the relative change in the SH_0 wave velocity in the structure "Y-X lithium niobate plate – vacuum gap – conductive layer on a glass substrate" for the different values of the gap width and film conductivity. In the theory, the same values of the film conductivity were used as in the experiment, i.e.: 0.0001, 0.0072, 1.48, 46.1, 550, 87000, and 900,000 μS. The first and last conductivity values correspond to the situations when the film is absent and when the film is perfectly conductive, respectively.

To solve this problem, we used the technique described in [19]. The propagation of an acoustic wave along the x_1 axis in a piezoelectric plate of the thickness h was considered. The dielectric substrate of the thickness h_2 with the infinitely thin layer with the surface conductivity of σ_s was located at a distance d from the piezoelectric plate. The geometry of the problem is shown in Fig. 5.

To solve the problem, we used the standard equation of the motion of an elastic medium:

$$\rho\frac{\partial^2 u_i}{\partial t^2} = \frac{\partial T_{ij}}{\partial x_j} \tag{1}$$

Laplace's equation for the plates and vacuum:

$$\frac{\partial D_j}{\partial x_j} = 0 \tag{2}$$

and the equation of the state of the piezoelectric crystal:

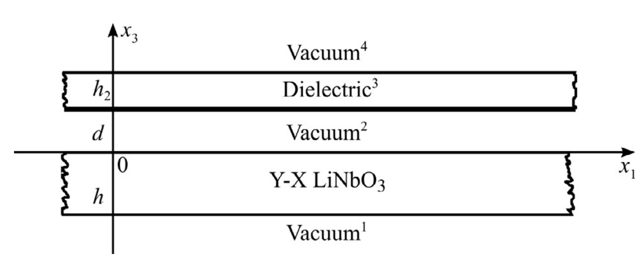

Fig. 5. Geometry of the problem.

$$T_{ij} = c_{ijkl}\frac{\partial u_l}{\partial x_k} + e_{kij}\frac{\partial \varphi}{\partial x_k} \quad (3)$$

$$D_j = e_{jkl}\frac{\partial u_l}{\partial x_k} - \varepsilon_{jk}\frac{\partial \varphi}{\partial x_k} \quad (4)$$

where x_k is the coordinate, t is the time, u_l is the component of the mechanical displacement, φ is the electrical potential, c_{ijkl}, e_{jkl}, ε_{jk} are the elastic, piezoelectric, and dielectric constants, respectively, T_{ij} is the component of the mechanical stress, D_j is the electrical displacement. The variables without an upper index refer to a piezoelectric plate, and ones with an upper index of 1, 2, 3, 4 refer to the vacuum under the piezoelectric plate, the vacuum between the plates, the dielectric plate and the vacuum above it, respectively (see Fig. 5).

The boundary conditions in the planes $x_3 = 0$, $x_3 = -h$ corresponded to the mechanically free and electrically open surfaces of the piezoelectric plate:

$$T_{j3} = 0|_{x_3=0},\ T_{j3} = 0|_{x_3=-h} \quad (5)$$

$$\varphi = \varphi^1,\ D_3 = D_3^1|_{x_3=-h},\ \varphi = \varphi^2,\ D_3 = D_3^2|_{x_3=0} \quad (6)$$

The effect of a dielectric plate with a conducting layer in the $x_3 = d$ plane was taken into account through a jump in the normal component of the electrical displacement due to the surface charge in the conducting layer [22], and also the field penetration into the vacuum above the plate:

$$\varphi^2 = \varphi^3,\ D_3^2 - D_3^3 = -\delta|_{x_3=d} \quad (7)$$

$$\varphi^3 = \varphi^4,\ D_3^3 = D_3^4|_{x_3=d+h_2} \quad (8)$$

Here, δ is the density of the surface charge, which is expressed in terms of the density of the surface current J_1 in the layer through the conservation of the charge condition [22]:

$$\frac{\partial J_1}{\partial x_1} = -\frac{\partial \delta}{\partial t} \quad (9)$$

By using the expression for the density of the surface current [22]:

$$J_1 = -\sigma_s\frac{\partial \varphi}{\partial x_1}, \quad (10)$$

and considering the dependence of all variables on the coordinate x_1 and time t as $\exp(I\omega(t - x_1/V))$, where I is the imaginary unit, ω is the angular frequency of the wave, V is the phase wave velocity, one can obtain the expression (11) for δ:

$$\delta = -\sigma_s\varphi\frac{\omega}{V^2}. \quad (11)$$

By solving the Eqs. (1)–(4) and using the boundary conditions (5)–(8) and expression (11), the phase velocity V of the acoustic wave was determined in accordance with [19] as a function of the distance d between the piezoelectric plate and conductive layer and on the layer conductivity σ_s.

The dependencies of the relative change in the SH_0 wave velocity propagating in the lithium niobate plate on the width of the vacuum gap between the piezoelectric plate and conductive film is shown in Fig. 6. One can see that with increasing the gap width, the acoustic wave velocity at first practically does not change, then, in the range 0.1–100 μm increases, and further reaches the saturation. Thus, these dependences are in the qualitative agreement with the obtained experimental dependences presented in Fig. 3. However, the theoretically found initial saturation region does not coincide with the experimental one. This is due to the fact that in the experiment it was not possible to provide an ideal plane-parallelism of the gap between the surface of the delay line and substrate with a conducting film. Therefore, at the minimum approach of these surfaces, one edge of the piezoelectric plate obviously touched the substrate with the film, and the other one had a nonzero gap. Therefore, the experimentally found initial saturation region shifted to the region of the higher values of the gap width.

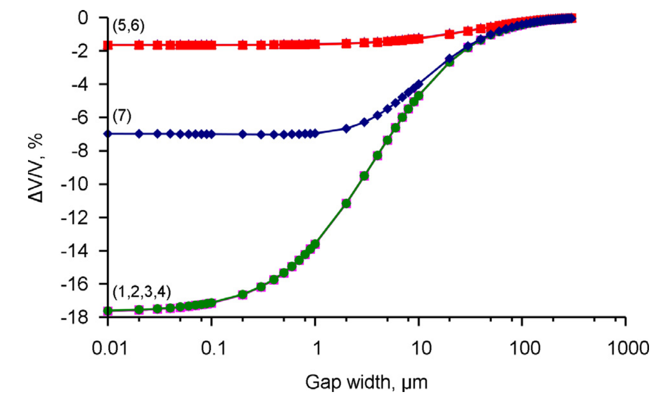

Fig. 6. Theoretical dependencies of the relative change in the SH_0 wave velocity (ΔV/V) on the gap width for the following values of the layer conductivity: (1) – 900000, (2) – 550, (3) – 87000, (4) – 46.1, (5) – 0.0001, (6) – 0.072, (7) – 1.48 μS.

Therefore, a quantitative comparison of the theoretical and experimental dependences of the relative change in the SH_0 wave velocity (ΔV/V) on the gap width was carried out in the range of 10–300 μm. The theoretical dependencies for this range of the gap width are shown in Fig. 7.

Comparison of Figs. 3 and 7 shows that the maximum changes of the velocity in the theory and experiment are 4.7% and 2.7%, respectively, for the films which conductivity changes in the range of 46.1–900,000 μS. This discrepancy, apparently, is also due to the fact that the films under investigation were most likely inhomogeneous in the shear directions.

The obtained results can be explained from the physical point of view as follows. It is known that a piezoactive acoustic wave propagating in a piezoelectric plate is accompanied by an electric field penetrating in the vacuum [12]. It is obvious that the conductive film located near the delay line with zero gap, shunts the electric field in a vacuum and have the greatest influence on the velocity of acoustic wave. This shunting leads to a decrease in the velocity of acoustic wave. When the conductive film is moved away from the piezoelectric plate, the degree of the shunting decreases and at the some distance the conductivity of this film will no longer affect the characteristics of the acoustic wave. The indicated distance corresponds to the depth of the penetration of the electric field of the wave into the vacuum and is equal to ~300 μm.

The theoretical dependences of the relative change in the SH_0 wave velocity in the structure "piezoelectric lithium niobate plate – vacuum

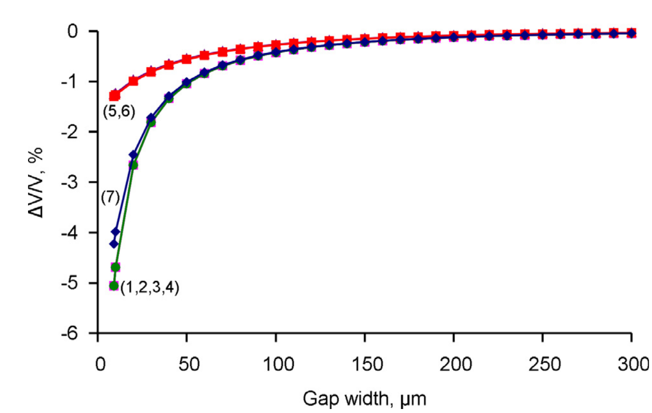

Fig. 7. Theoretical dependences of the relative change in the SH_0 wave velocity (ΔV/V) on the gap width in the range 10–300 μm for the following values of the layer conductivity: (1) – 900000, (2) – 550, (3) – 87000, (4) – 46.1, (5) – 0.0001, (6) – 0.072, (7) – 1.48 μS.

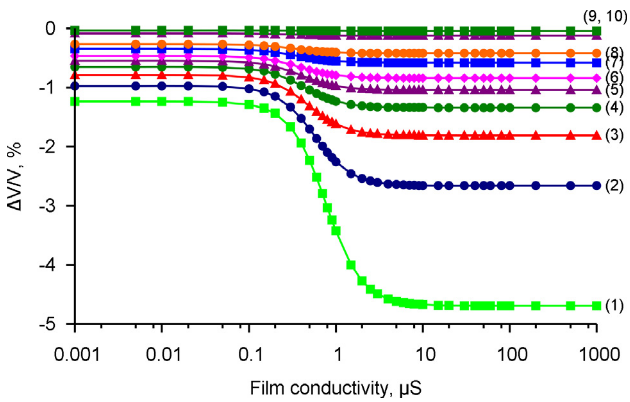

Fig. 8. Theoretical dependences of the relative change in the SH_0 wave velocity ($\Delta V/V$) on the layer conductivity for the following values of the gap width: (1) – 10 μm, (2) – 20 μm, (3) – 30 μm, (4) – 40 μm, (5) – 50 μm, (6) – 60 μm, (7) – 80 μm, (8) – 100 μm, (9) – 200 μm, (10) – 300 μm.

gap – conducting layer on a glass substrate" on the layer conductivity were also constructed. These dependencies are shown in Fig. 8. One can see from the figure that with increasing the layer conductivity, the acoustic SH_0 wave velocity initially practically does not change, then in the interval 0.1–10 μS sharply decreases and then remains constant.

At that, as the width of the gap between the piezoelectric plate and conductive layer decreases, the degree of the change in the SH_0 wave velocity increases over the entire layer conductivity range. The most significant changes in the wave velocity are observed for the values of layer conductivity in the range of 0.1–10 μS, which does not coincide with the experimentally determined range of 10–1000 μS. When the conductive layer is moved away for a distance greater than 200 μm, the acoustic wave velocity practically ceases to change and this completely corresponds to the experiment. Comparison of Figs. 4 and 8 shows that the maximum velocity changes in the theory and experiment are equal to 4.7% and 2.7%, respectively.

Apparently, these discrepancies between the theory and experiment are due to the fact that in the experiment, as pointed above, it was not possible to ensure the plane-parallelity of the gap between the delay line and plate with a conducting film. At that, the films under the investigation were probably inhomogeneous in the shear directions.

Thus, for a fixed width of the gap with increasing the layer conductivity, the acoustic wave velocity at first practically does not change, then in the certain range of the conductivity decreases sharply and after that, again remains unchanged. This dependence can be explained from the physical point of view as follows. At the small values of the conductivity, the degree of the shunting of the electric field of an acoustic wave is negligible and the wave velocity is maximum. At the high values of the conductivity, the electric field of the acoustic wave is completely shunted and its velocity has a minimum value. Obviously, when passing from the small values of the conductivity to higher ones, there is some transition that corresponds to the condition $2\pi f\tau \approx 1$, where f is the wave frequency and $\tau = \varepsilon_{eff}/\sigma_s$ is the Maxwell time of the relaxation (σ_s = layer conductivity, ε_{eff} = effective surface permittivity) [23,24]. In our case for the value of the frequency f = 3.25 MHz the Maxwell time of the relaxation $\tau \approx 5 \times 10^{-8}$ s. In accordance with the theory and experiment $\sigma_s \approx 1$ μS and $\sigma_s \approx 100$ μS, respectively. It means that in these cases the effective surface permittivity $\varepsilon_{eff} = 5 \times 10^{-14}$ F and $\varepsilon_{eff} = 5 \times 10^{-12}$ F from theory and experiment. Such discrepancy may be explained by the inhomogeneity of the film in the shear directions.

5. Conclusions

Thus, an experimental and theoretical study of the effect of the film conductivity and the air gap between the surface of the delay line and plate with a conducting film on the phase change of the output signal of the delay line and the velocity of the acoustic wave propagating in piezoelectric plate was carried out. The dependences of the relative change in the velocity ($\Delta V/V$) of the acoustic SH_0 wave in the lithium niobate plate on the width of the gap between the surface of the delay line and substrate with a conducting film are obtained for different film conductivities. It is shown that the relative change in the SH_0 wave velocity depends both on the width of the gap between the surface of the delay line and substrate with the conductive film, and on its conductivity. It is shown that with increasing the gap width, the velocity increases and reaches the saturation in the interval of 250–300 μm for all the films under study. The change in the velocity with increasing the gap width is the stronger the higher the conductivity of the film.

The dependences of the relative change in the SH_0 wave velocity in the lithium niobate plate on the film conductivity are constructed for the different values of the width of the gap between the surface of the delay line and substrate with a conducting film. It is shown that with an increase in the film conductivity, the acoustic SH_0 wave velocity initially practically does not change, then sharply decreases and then increases insignificantly. At that, as the width of the gap between the delay line and conductive film decreases, the degree of the change in the SH_0 wave velocity increases over the entire film conductivity range. The most significant changes in the wave velocity are observed for the values of the gap width in the range of 10–100 μm. When the conductive film is moved away for a distance greater than 200 μm, the acoustic wave velocity practically ceases to change. The comparison of the experimental and theoretical data showed their good agreement. The obtained results can be used, for example, for the contactless measurement of the conductivity of thin films, for the gas sensors, when the conductivity of the film changes in the presence of the different gases, etc.

Acknowledgments

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