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Creation and research of the SAW transducer with a single-phase grid and a piezoelectric zinc oxide film

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A method for obtaining a new type of surface acoustic wave (SAW) transducer operating at double frequency with a single-phase closed-loop lattice and a piezoelectric zinc oxide film is developed and experimentally investigated. A method for calculating such a transducer has been developed, its equivalent circuit has been compiled, taking into account propagation losses, losses in the metal film and the inductance of the connecting wires. When the frequency is doubled, the SAW attenuation per unit length increases.

Keywords: Surface acoustic wave (SAW); interdigital transducer (IDT); zinc oxide (ZnO) film.

1. Introduction

The acousto-electronic surface acoustic wave (SAW) attenuation is determined by the formula[1]

$$\Gamma = k_{\text{ef}}^2 \left(\frac{2\pi}{\lambda}\right) \frac{\sigma_{\text{sh}}/\sigma_M}{1+\sigma_{\text{sh}}{}^2/\sigma_M^2}, \tag{1}$$

where k is the coefficient of electromechanical coupling, $\sigma_{\text{sh}} = \sigma \cdot h$ is the surface conductivity, h is the thickness of the film with a specific conductivity σ, $\sigma_M = V_{\text{SAW}}(\varepsilon_s \cdot \varepsilon_0)$, V_{SAW} is the SAW velocity, ε_s is the dielectric constant of the substrate and λ is the SAW length. It follows from (1) that the shorter the SAW length, the stronger the acousto-electronic interaction will be per unit length. Therefore, it is advisable to increase the SAW operating frequencies to increase the acousto-electronic attenuation. In the microwave range, the width of the IDT electrodes will be less than 0.5 μm, which significantly complicates the process of manufacturing IDT. But if one uses a single-phase transducer (Fig. 1),[2] then it is possible to increase the operating frequency of the transducer by two times with the same width of the electrodes, thereby increasing the acousto-electronic attenuation by two times per unit length.

As can be seen from Fig. 1, there is a piezoelectric zinc oxide film between the solid electrode and the short-circuited grid. Then the spaces between the solid electrode and each electrode of the single-phase grid form a transducer, that excites the acoustic waves both into the volume of the substrate and along its surface. At the same time, the waves emitted along the surface add up if the SAW length is equal to the distance between the electrodes, which leads to an increase in the amplitude of SAW at the output of the converter. In this case, such a converter effectively converts the electrical signal supplied to it into SAW, and the waves emitted into the volume from each electrode do not add up in phase, mutually suppressing each other. If the SAW length does not correspond to the distance between the electrodes, the emitted SAWs do not add up and their amplitude at the output of the transducer differs slightly from the amplitude of the SAW emitted by one electrode of a single-phase grid. In addition, in a single-phase transducer, the voltage between the electrodes is two times greater than that between the IDT electrodes (Fig. 2), which should lead to a certain decrease in the introduced attenuation.[3]

From the comparison of Figs. 1 and 2, it can be seen that the manufactured transducer differs from the one given in our patent[2] in that the short-circuited grid is on the film, and the solid electrode is on top of the film, while in the patent there is first a solid electrode, then a film and then a short-circuited grid. But this should not affect the operation of the transducer, since in both cases the film is located between a short-closed grid and a solid electrode.

This transducer was manufactured based on the IDT located on a substrate of the YX/128°-cut lithium niobate. The IDT had a period of 40 μm. The number of pairs of electrodes was equal to 260. For creating short-circuited grid, the IDT was closed by spraying a metal film along its edges. Then, a film of zinc oxide with a thickness of about 3 μm was sprayed onto its surface by laser spraying. In this case, there is a small maximum of the electromechanical

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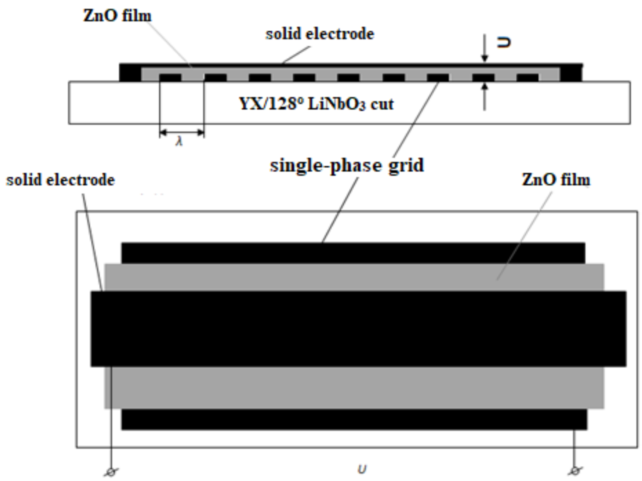

Fig. 1. A new type of SAW transducer with a single-phase grid and a piezoelectric zinc oxide film on YX/128°-cut $LiNbO_3$.

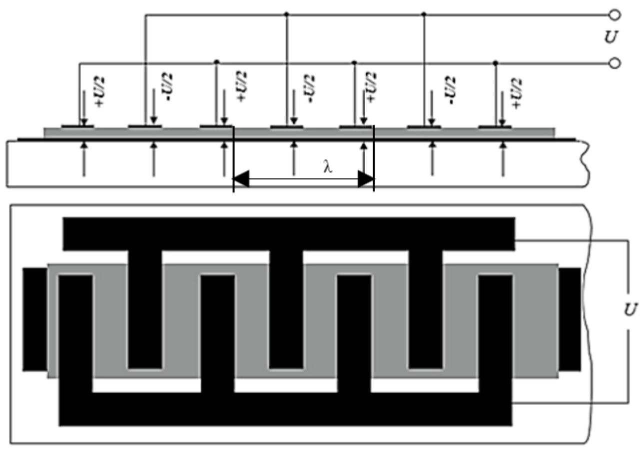

Fig. 2. The distribution of voltages on the piezoelectric film when using the IDT.

coupling coefficient (a large maximum of the electromechanical coupling coefficient is available at a film thickness close to the full SAW length).[4] Obtaining and manufacturing of a single-phase transducer is shown in Fig. 3.

To obtain such a thickness, it took 35,000 pulses with a duration of 10 ns with a pulse energy of 200 MJ of the KrF CL-7100 laser. The temperature of the substrate during spraying was maintained at 500°C. The oxygen pressure during spraying was controlled by an RMT-2 thermocouple sensor and remained equal to 2×10^{-2} mbar. The spraying was carried out in two stages of 15,000 pulses and 20,000 pulses each, a solid electrode with a width of about three times less than the aperture of the IDT equal to 1.24 mm was sprayed on top of the sprayed zinc oxide film.

2. Calculation Model of a Single-phase Transducer with Short-circuited Grid

We will consider the frequency range in which SAWs are excited, i.e., the excited waves are added in phase along the surface. Then the frequency response at the output of such a transducer when a harmonic signal is applied to its electrodes, taking into account the SAW attenuation in the film, will be written as

$$H = \frac{1}{M}\sqrt{\left[\sum_{k=1}^{M}\left(q_k \cdot \cos\left(\frac{2\cdot\pi\cdot k\cdot f}{f_0}\right)\right)\right]^2 + \left[\sum_{k=1}^{M}\left(q_k \cdot \sin\left(\frac{2\cdot\pi\cdot k\cdot f}{f_0}\right)\right)\right]^2} \qquad (2)$$

where $q_k = e^{-\alpha\cdot\left|k-\frac{M}{2}\right|}$, α is the attenuation coefficient, M is the number of electrodes of a short-circuited grid and $f_0 = V_{SAW}/\lambda_0$ is the central frequency.

The central frequency of the transducer f_0 = 193.5 MHz, which is close to twice the frequency of the IDT located on a substrate of the YX/128°-cut lithium niobate and having a central frequency equal to 100 MHz (Fig. 4). A slight discrepancy to the doubled frequency of the IDT is explained by the fact that SAW propagates along the surface on which the zinc oxide film is located, in which the SAW attenuation is significantly more than in lithium niobate, and also by the fact that zinc oxide film has a thickness of about 3 μm, with a period of 40 μm of the electrodes, and slightly affects the SAW velocity along the surface of the substrate.

As seen, the frequency response of the transducer has the type $\frac{\sin X}{X}$. Therefore, the active (G_a) and reactive (B_a) components of radiation conductivity have the forms close to: $G_a \approx 8\cdot f_0\cdot k^2 C_T\cdot N\cdot\left(\frac{\sin X}{X}\right)^2$, $B_a \approx 8\cdot f_0\cdot k^2 C_T\cdot N\cdot\left(\frac{\sin 2X-2X}{2X}\right)$,

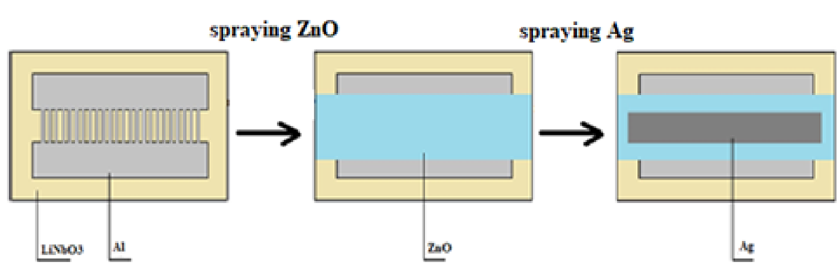

Fig. 3. Technological stages of manufacturing a single-phase transducer with a short-circuited grid.

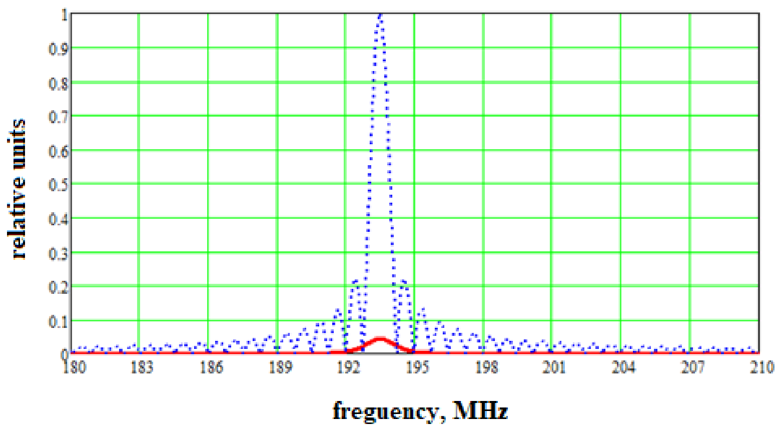

Fig. 4. The frequency responses of the transducer: dotted line: without taking into account the attenuation and solid line: taking into account the attenuation.

$X = \pi \cdot N \cdot \frac{f - f_0}{f_0}$, $C_T = \mathrm{W} \cdot \mathrm{N} \cdot C_s$, where N is the number of pairs of electrodes (periods) in IDT; k is the coefficient of electromechanical coupling and C_s is the single-wave section capacity of the IDT per unit length of aperture.[4] Then the equivalent circuit of the transducer, taking into account the losses in the metal film (R_{met}), the radiation of waves from the transducer into the substrate volume (R_{vol}) and the inductance of the conductors (L) connecting the transducer to the measuring device, has the form shown in Fig. 5.

The parameter S_{11} for the transducer is defined as

$$S_{11} = \frac{\frac{Z}{R} - 1}{\frac{Z}{R} + 1}, \qquad (3)$$

where $Z = \sqrt{(\mathrm{Re}Z)^2 + (\mathrm{Im}Z)^2}$, $\mathrm{Re}Z = z1 + R_{\text{met}}$, $\mathrm{Im}Z = z2 + 2 \cdot \pi \cdot f \cdot L$,

$$z1 = \frac{G_a + \frac{1}{R_{\text{vol}}}}{\left(G_a + \frac{1}{R_{\text{vol}}}\right)^2 + \left(B_a + 2 \cdot \pi \cdot f \cdot C_T\right)^2},$$
$$z2 = \frac{-\left(B_a + 2 \cdot \pi \cdot f \cdot C_T\right)}{\left(G_a + \frac{1}{R_{\text{vol}}}\right)^2 + \left(B_a + 2 \cdot \pi \cdot f \cdot C_T\right)^2}. \qquad (4)$$

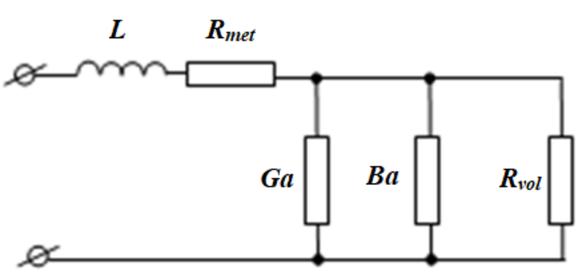

Fig. 5. Equivalent circuit of the transducer.

3. Experimental Results

Since the transducer is a two-pole one, we will measure the parameter S_{11} using the complex transmission coefficients meter “Obzor-304”.

Figure 6 shows the frequency dependence of the parameter S_{11}. The calculated values differ significantly from the measured one. First, the calculated attenuation is significantly larger, and the working band is narrower than in the experiment.

It is known that the inductance of the gold wire that connects the transducer to the contact pads is determined by the formula

$$L_{\text{wire}} = \frac{\mu_0 l}{2 \cdot \pi} \cdot \left(\ln \frac{4 \cdot l}{d} - 1\right), \qquad (5)$$

where l is the length of the wire and d is the diameter of the wire. It follows from this formula that with a wire length

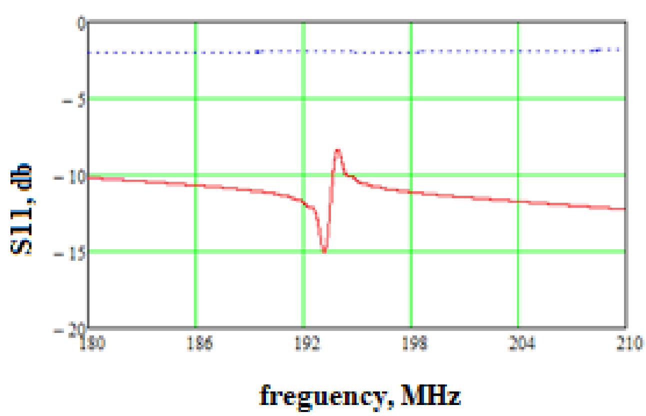

Fig. 6. Frequency dependence of parameter S_{11}: solid curve: calculation without taking into account the inductances, SAW attenuation, losses in a metal film and radiation of volume waves; and dotted curve: experiment.

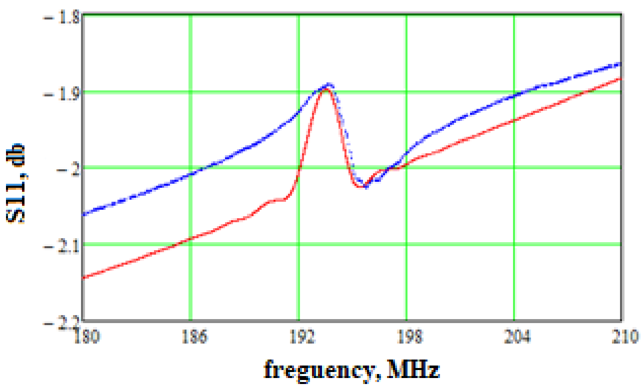

Fig. 7. Frequency dependence of parameter S_{11}: solid curve: calculation taking into account the inductances, SAW attenuation, losses in a metal film and radiation of volume waves; and dotted curve: experiment.

of 10 mm and a diameter of 50 μm, the inductance does not exceed 11 nH. The calculation according to formula (2) shows that the transducer band expands significantly if the SAW attenuation in the film is taken into account. As the calculations using formula (2) show, in order to expand the bandwidth more than twice, it is necessary to assume that the attenuation $\alpha \approx 9.25$ 1/cm. To take this into account, we will increase R_{met} to 282 Ω. We will assume that the radiation into the volume is quite small due to the large attenuation for propagation ($\alpha \approx 9.25$ 1/cm).

Therefore, let us put $R_{vol} = 1200$ Ω (with a further increase in R_{vol}, the frequency dependence of the parameter S_{11} almost does not change). At the same time, the attenuations of the measured and calculated curves in the region of surge are close to each other (Fig. 7). The coefficient of electromechanical coupling, which determines the magnitude of surge on the frequency response of the parameter S_{11}, is set to 0.0011, and it is necessary to increase the inductance to $L = 400$ nH. The latter is due to that only with such an inductance, the slope of the frequency dependence of the parameter S_{11} is close to the measured one.

Such a significant increase in the inductance leads to the case that the inductance is much greater than the inductance of the connecting wires. This can be explained by the fact that the zinc oxide film has semiconductor properties and in the contacts of the metal film with the zinc oxide film, shut-off layers of the *p–n* junction type can be formed. In some cases, such transitions have inductive properties.

This is a fictitious inductance, since the accumulation of magnetic energy in the *p–n* junction does not occur, as does the excitation of the self-induction EMF. The nature of this inductance lies in the inertia of voltage redistribution between the *p–n* junction and the modulated resistance of the quasi-neutral base, which leads to a current delay relative to the voltage (the inductive nature of inertia).

Also, a delay line was made based on the studied single-phase transducer, by dividing the transducer into two as shown in Fig. 8. Further, the transducers are manufactured

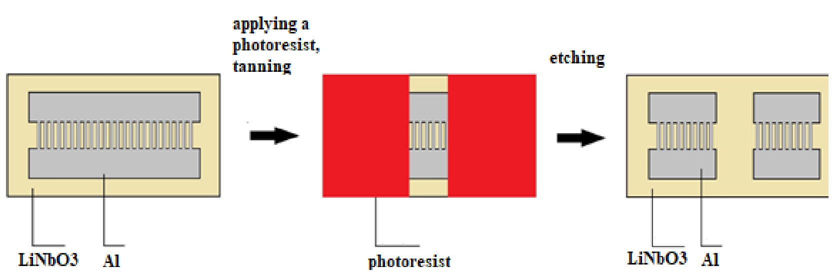

Fig. 8. Schematic representation of the stages of substrate preparation.

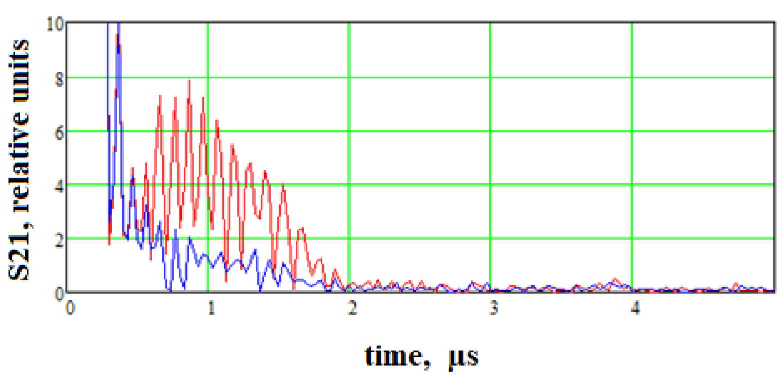

Fig. 9. (Color online) Pulse responses of the resulting delay line: red curve in the presence of UV and blue curve without UV.

in accordance with Fig. 3. A film of zinc oxide with a thickness of 200–250 nm remained between the formed transducers.

Figure 9 shows the time dependence of parameter S_{21} (pulse response of the delay line), where a thin film of zinc oxide is affected by UV. The radiation power is about 30 mW/cm^2 and wavelength 325 nm. At the same time, the distance between single-phase converters does not exceed 3 mm.

It can be seen that under the action of UV, the SAW attenuation increases by four times, which corresponds to an attenuation of 36 dB/cm. At the same time, measurements carried out at frequencies around 100 MHz showed that the attenuation there did not exceed 18–20 dB/cm, which occurs in accordance with formula (1), where attenuation is obtained the greater the shorter the SAW length (or the higher the frequency).[5]

4. Conclusion

1. The technology of obtaining a SAW transducer based on a zinc oxide film with a thickness of up to 3 μm has been developed.
2. A method for calculating such a transducer has been developed, and its equivalent circuit has been compiled, taking into account propagation losses, losses in the metal film and the inductance of the connecting wires.
3. The calculated and experimental curves are compared. The parameters of the equivalent circuit are selected in such a way that the calculated frequency dependence of the parameter S_{11} would be close to the measured one: $\alpha \approx 9.25$ 1/cm, $R_{met} = 282\ \Omega$, $R_{vol} = 1200\ \Omega$ and $L = 400$ nH.
4. The large calculated inductance shows that this transducer has shut-off layers of the *p–n* junction type, in which there is an inertia of voltage redistribution between the *p–n* junction and the modulated resistance of the quasi-neutral base, which leads to a current delay relative to the voltage (the inductive nature of inertia).
5. When the frequency is doubled, the SAW attenuation per unit length increases in accordance with formula (1).

Acknowledgments

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