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The effect of the conductivity of a film located near a piezoelectric resonator with a lateral electric field based on the PZT ceramics on its characteristics

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ABSTRACT

In this paper, we investigated theoretically and experimentally the effect of the conductivity of the film located in the immediate vicinity of the free side of a piezoelectric resonator based on the PZT ceramics on its characteristics. It is shown that with increasing the conductivity of the film at first the parallel resonant frequency does not change, then it decreases in a certain interval and after that remains practically constant. With increasing the width of the gap between the film and the resonator, the resonant frequency increases and reaches the saturation. At that the degree of the total frequency change decreases with decreasing the conductivity of the film. We also investigated the dependence of the maximum value of the real part of the electrical impedance on the film conductivity at the different values of the width of the gap between the film and the resonator. The dependences of the maximum value of the real part of the electrical impedance on the width of the gap between the film and the resonator are also obtained for different values of the film conductivity. A comparison of the theoretical and experimental data showed their good qualitative agreement.

1. Introduction

Recently, the piezoelectric resonators with a lateral electric field are increasingly being used as various kinds of the sensors [1–7]. It is known that these resonators have a number of the significant advantages in the comparison with the resonators using a longitudinal electric field [2]. The electrodes in the resonators with a lateral electric field are located on one side of the piezoelectric plate, and the electric field is concentrated not only in the piezoelectric plate, but also penetrates beyond it [5,6]. It has been theoretically and experimentally shown recently that a change in the electric boundary conditions in the immediate vicinity of the free side of the resonator with a lateral electric field based on lithium niobate of X-cut leads to a change in its characteristics [5,6]. It has been shown that this effect can be used to develop mechanical displacement sensors with temperature compensation [5], as well as the gas sensors using the gas sensitive films which conductivity changes in the presence of the analyzed gas [6]. Such gas sensors can be used to detect and analyze the explosive gases, since the probing voltage is applied to the resonator electrodes that do not directly contact the gas. In these studies it has been shown that as an informative parameter unambiguously associated with the conductivity of the film one can use the parallel resonant frequency (F_{par}) of a resonator with a lateral electric field. However, it should also be noted that, in addition to the widely used lithium niobate crystal [5–7], PZT piezoceramics [8] is also a promising material for the creation of the resonators with a lateral electric field, which are characterized by a high electromechanical coupling coefficient [9]. In this paper, we investigated the effect of the conductivity of the film located in the immediate vicinity of the free side of a piezoelectric resonator based on the PZT ceramics on its characteristics.

2. Theoretical study of the influence of the conducting layer on the characteristics of the lateral electric field excited resonator

The theoretical analysis of the effect of the surface conductivity of a thin film on the characteristics of a resonator with a lateral electric field made of the PZT piezoceramics was carried out. The geometric dimensions and location of the electrodes of the analyzed resonator in the plane formed by the normal to the plate and the polar axis Z completely corresponded to the experimental sample. This model under study including piezoelectric plate (1) with electrodes (2) and glass plate (3) with conducting film (4) is presented in Fig. 1. The resonator had a thickness of 3.58 mm and a shear dimension along the polar axis of 18 mm. In the third dimension, the structure was assumed to be infinite. On one side of the plate were applied two electrodes with a gap in the center 4 mm wide, which was perpendicular to the polar axis. The finite

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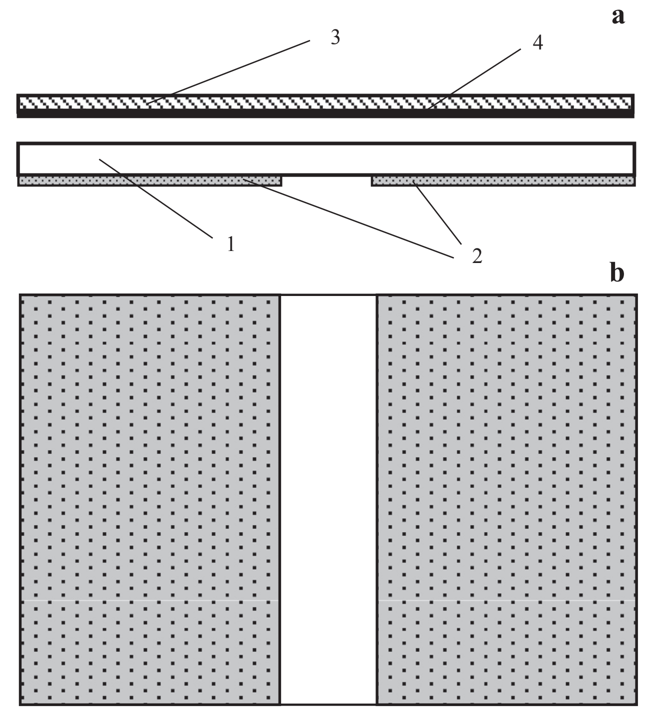

Fig.1. Side view (a) and bottom view (b) of the resonator with lateral electric field: 1 – piezoelectric plate, 2 – electrodes, 3 – glass plate, 4 – conducting film.

element method [10] was used to numerically analyze the distribution of the mechanical displacement components inside the piezoceramic plate, as well as the electric potential inside the piezoceramic plate and in the surrounding vacuum. This analysis showed that the electric field penetrates into the vacuum to a depth much lower than the thickness of the resonator.

Then, the glass plate with a dielectric permittivity $\varepsilon = 10$ and a thickness $h_{diel} = 1$ mm was placed near the free surface of the resonator at a given distance $d = 50$–$300\,\mu$m. The side of the plate facing the resonator was covered with a thin film with a given surface conductivity σ_s. The presence of this film was taken into account with the help of the boundary condition [6]

$$(D_j^{diel} - D_j^{vac})n_j = -\frac{I\sigma_s}{\omega}\frac{\partial^2\varphi}{\partial x_j^2} \tag{1}$$

Here D^{diel} and D^{vac} are the electrical displacements in the dielectric plate and in the vacuum between the plate and resonator, respectively, n_j is the normal to the surface of the plate, φ is the electrical potential, ω is the angular frequency of oscillations, I is the imaginary unit. The dependences of the parallel resonant frequency and the maximum of the real part of the electrical impedance for the lowest vibration mode near the frequency ~98 kHz on the conductivity of the film σ_s and the distance d between the plate and the resonator were calculated. The results of the calculations are shown in Figs. 2–5. It is seen from Fig. 2 that at a fixed value of the gap width d with increasing the film conductivity the frequency of the parallel resonance initially remains practically constant and then in a certain interval it changes sharply. With a further increase in the conductivity, the frequency of parallel resonance decreases insignificantly with a gap width of less than 50 μm, while for other cases it remains practically constant. The maximum change in F_{par} with an increase in the conductivity of the film from 1 μS to 0.2 mS with a gap between the film and resonator of 50 μm is equal to 1.6%. Fig. 3 shows that as the conductivity of the film increases, the value of the maximum value of the real part of the impedance R_{max} decreases, reaches a minimum, and then again increases. In both cases, the effect of the conductivity of the film weakens as it moves away from the resonator. With an increase in the conductivity of the film from 0.1 μS to the value corresponding to the minimum of R_{max} the change in R_{max} is ~56 and 15% for the gap width of 50 and 300 μm, respectively. Figs. 4 and 5 show that as the gap width between the conductive film and the resonator increases, the frequency of parallel resonance and the value of R_{max} increase monotonically and reach saturation for the conductivity of the film greater than 1.4×10^{-2} mS. With a lower value of conductivity, the presence of a glass substrate begins to play a dominant role, and these dependencies acquire a different character.

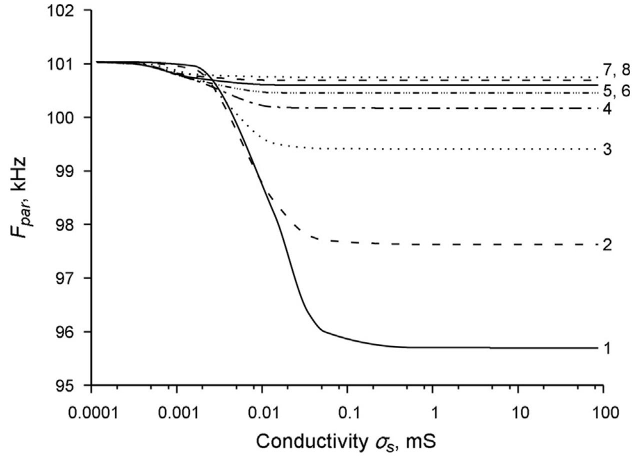

Fig. 2. Theoretical dependences of the resonant frequency F_{par} of the resonator on the film conductivity σ_s at the various width d of the gap between the film and free surface of the resonator (1 – 10 μm, 2 – 20 μm, 3 – 50 μm, 4 – 100 μm, 5 – 150 μm, 6 – 200 μm, 7 – 250 μm, 8 – 300 μm).

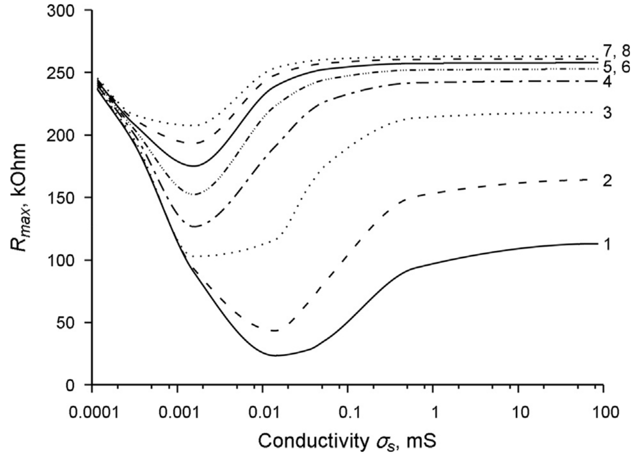

Fig. 3. Theoretical dependences of the maximum value of the real part of the electrical impedance R_{max} of the resonator on the film conductivity σ_s at the various width d of the gap between the film and free surface of the resonator (1 – 10 μm, 2 – 20 μm, 3 – 50 μm, 4 – 100 μm, 5 – 150 μm, 6 – 200 μm, 7 – 250 μm, 8 – 300 μm).

3. Experimental study of the influence of the conductivity of thin film set near the free side of the resonator with the lateral electric field

In the experiments we used a resonator made of PZT piezoceramics. All parameters of the resonator, excluding the size of the plate and electrodes along the third dimension (20 mm), have already been indicated in the theoretical part of the article. The resonator was connected to the meter of the LCR parameters 4285A (Agilent) with which the frequency dependences of the real and imaginary parts of the electrical impedance and admittance of the resonator in the range

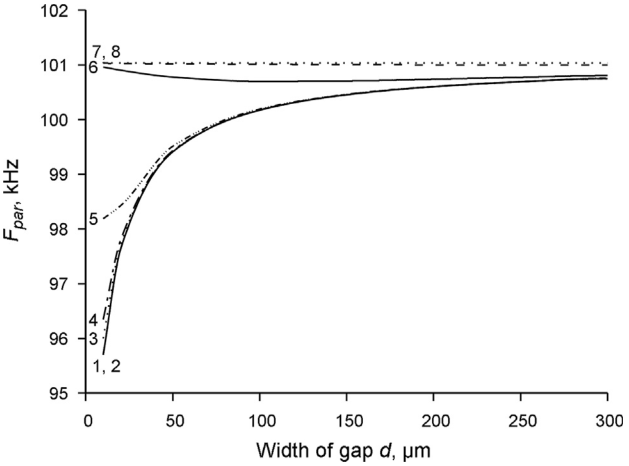

Fig. 4. Theoretical dependences of the resonant frequency F_{par} of the resonator on the width d of the gap between the film and free surface of the resonator for the various values of the film conductivity (1 – 87 mS, 2 – 6.25×10^{-1} mS, 3 – 5.4×10^{-2} mS, 4 – 3.5×10^{-2} mS, 5 – 1.4×10^{-2} mS, 6 – 1.56×10^{-3} mS, 7 – 3.1×10^{-4} mS, 8 – 11.5×10^{-5} mS).

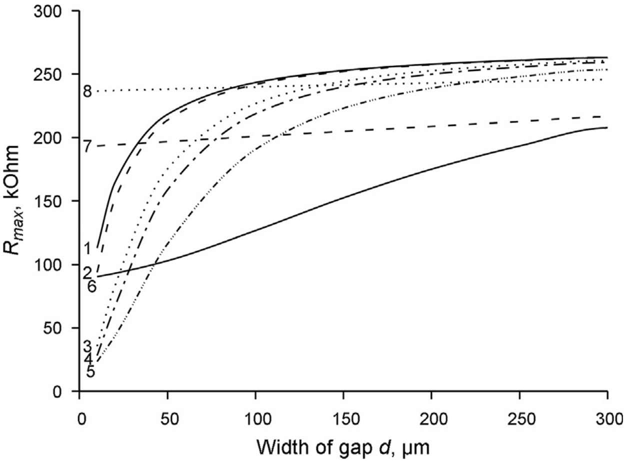

Fig. 5. Theoretical dependences of the maximum value of the real part of the electrical impedance R_{max} of the resonator on the width d of the gap between the film and free surface of the resonator for the various values of the film conductivity (1 – 87 mS, 2 – 6.25×10^{-1} mS, 3 – 5.4×10^{-2} mS, 4 – 3.5×10^{-2} mS, 5 – 1.4×10^{-2} mS, 6 – 1.56×10^{-3} mS, 7 – 3.1×10^{-4} mS, 8 – 11.5×10^{-5} mS).

75–150 kHz were measured. To carry out the study of the influence of the gap between the free side of the resonator and the glass plate with a conductive film, a specially constructed micrometric device, which allowed to establish a definite air gap between the film and the resonator with an accuracy of 10 μm was used [5,6]. In this paper we used 5 samples of the tin dioxide films with the values of a surface conductivity 11.5×10^{-5}, 3.1×10^{-4}, 1.4×10^{-2}, 6.25×10^{-1} and 87 mS [6]. The samples of the conducting films were deposited in the Orion-40 T setup (VTC, Korea) on the glass substrates (Citotest, China) by the high-frequency reactive magnetron sputtering of the 99.99% tin target (iTASCO, Korea) in the oxygen-argon mixture (Praxair, Russia) [5]. We measured the frequency dependences of the real and imaginary parts of the electrical impedance of the resonator in the frequency range 75–150 kHz for all 5 samples of the pointed films for the different values of the width of the gap between the resonator and the film. These frequencies were used to determine the frequencies of the parallel resonance (F_{par}), as well as the maximum values of the real parts of the impedance (R_{max}).

As a result, the dependences of the F_{par} of resonator with the lateral

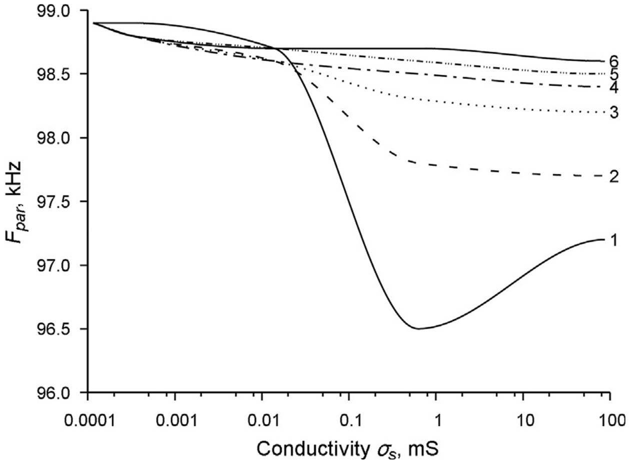

Fig. 6. Experimental dependences of the resonant frequency F_{par} of the resonator on the film conductivity σ_s at the various width d of the gap between the film and free surface of the resonator (1 – 0–50 μm, 2 – 100 μm, 3 – 150 μm, 4 – 200 μm, 5 – 250 μm, 6 – 300 μm).

electric field on the conductivity of the film was obtained for different values of the gap width between the film and the free surface of the resonator, which are shown in Fig. 6. It is seen that when the conductivity is increased from ~0.1 μS to ~0.014 mS, the value of F_{par} insignificantly decreases and practically does not depend on the value of the gap width. In the range of the conductivity changes from ~0.014 mS to ~0.625 mS, the F_{par} value sharply decreases in all cases. With a further increase in the conductivity, the frequency of parallel resonance increases insignificantly with a gap width of less than 50 μm, while for other cases it remains practically constant. The maximum change in F_{par} with an increase in the conductivity of the film from 0.014 mS to 0.625 mS with a gap between the film and resonator of 50 μm is 2.42%. With an increase in the gap width from 50 μm to 300 μm, absolute changes in the value of F_{par} decrease substantially. A comparison of the experimental (Fig. 6) and theoretical (Fig. 2) dependences of the frequency of the parallel resonance on the conductivity of the film for different values of the width of the gap between the film and the resonator shows their good qualitative agreement.

Fig. 7 shows the experimental dependences of R_{max} of the resonator with a lateral electric field on the conductivity of the films at different values of the gap width between the film and the free surface of the resonator. One can see that as the conductivity of the film increases, the

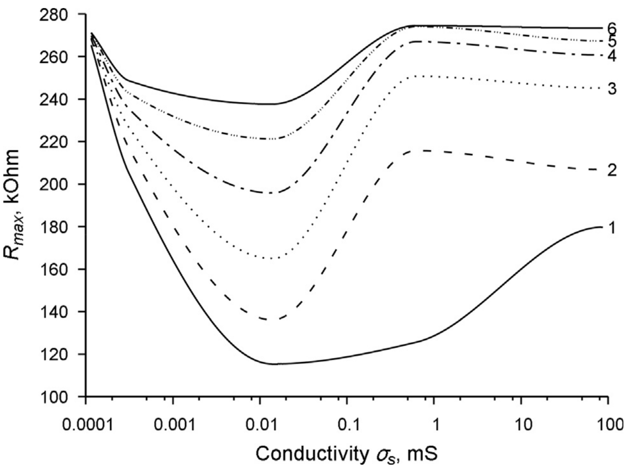

Fig. 7. Experimental dependences of the maximum value of the real part of the electrical impedance R_{max} of the resonator on the film conductivity σ_s at the various width d of the gap between the film and free surface of the resonator (1 – 0–50 μm, 2 – 100 μm, 3 – 150 μm, 4 – 200 μm, 5 – 250 μm, 6 – 300 μm).

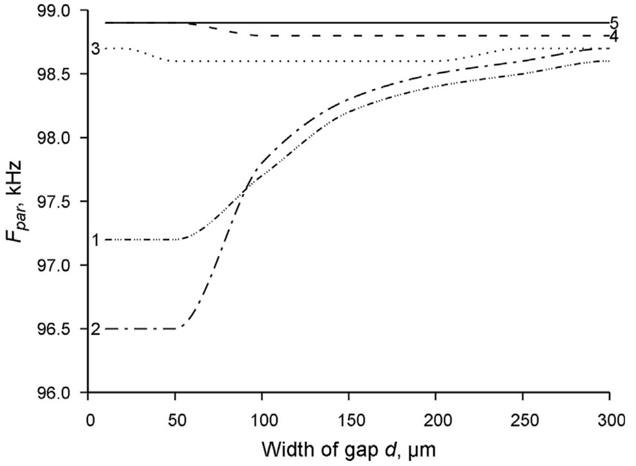

Fig. 8. Experimental dependences of the resonant frequency F_{par} of the resonator on the width d of the gap between the film and free surface of the resonator for the various values of the film conductivity (1 – 87 mS, 2 – 6.25×10^{-1} mS, 3 – 1.4×10^{-2} mS, 4 – 3.1×10^{-4} mS, 5 – 11.5×10^{-5} mS).

value of the maximum value of the real part of the impedance R_{max} decreases, reaches a minimum, and then again increases. At that, the effect of the conductivity of the film weakens as it moves away from the resonator. With an increase in the conductivity of the film from 0.1 μS to 0.014 mS the change in R_{max} is ~57 and 13% for the gap width of 50 and 300 μm, respectively. This fact is of great practical importance in the development of gas sensors for choosing the range of the variation in the conductivity of a film in the presence of gases.

Fig. 8 shows the dependence of F_{par} on the width of the gap for different values of the conductivity of the film. It is seen that for the conductivity values of more than 0.625 mS, this value increases and reaches saturation at a gap of the order of 200 μm. In this case, the maximum change in F_{par} reaches 2.2% when the air gap varies from 50 to 300 μm for a film conductivity of 0.625 mS. The comparison of the experimental (Fig. 8) and theoretical (Fig. 4) dependences of the frequency of the parallel resonance on the width of the gap between the film and the resonator for different values of the film conductivity shows their qualitative correspondence with the exception of the initial sections of the dependences. It can be seen that the experimental dependences with a gap width in the range of 0–50 μm have initial saturation regions, which are absent on the theoretical dependences. This is due to the impossibility of realizing in the experiment the ideal plane-parallel gaps with a width less than 50 μm.

Fig. 9 shows the dependences of R_{max} on the gap width for different values of the film conductivity. The comparison of the experimental (Fig. 9) and theoretical (Fig. 5) dependences of R_{max} on the width of the gap between the film and the resonator for different values of the film conductivity shows their qualitative correspondence with the exception of the initial sections of the dependences. The reason of these sections was explained above.

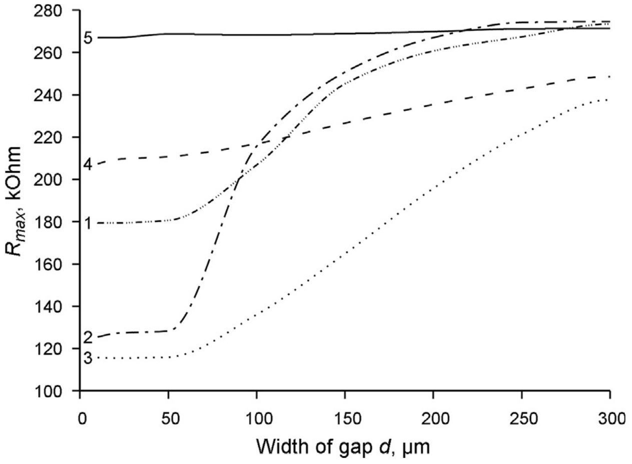

Fig. 9. Experimental dependences of the maximum value of the real part of the electrical impedance R_{max} of the resonator on the width d of the gap between the film and free surface of the resonator for the various values of the film conductivity (1 – 87 mS, 2 – 6.25×10^{-1} mS, 3 – 1.4×10^{-2} mS, 4 – 3.1×10^{-4} mS, 5 – 11.5×10^{-5} mS).

4. Conclusion

The effect of the conductivity of the film located in the immediate vicinity of the free side of a piezoelectric resonator based on the PZT ceramics on its characteristics was studied theoretically and experimentally. It has been shown that with increasing the film conductivity the parallel resonant frequency practically does not change in the beginning, then decreases in a certain interval and after that remains practically constant. With increasing the width of the gap between the film and the resonator, the resonant frequency increases and reaches the saturation. At that the degree of the total frequency change decreases with decreasing the conductivity of the film. The comparison of the experimental and theoretical dependences of the frequency of the parallel resonance on the width of the gap between the film and the resonator for different values of the film conductivity shows their qualitative correspondence with the exception of the initial sections of the dependences. This discrepancy is due to the impossibility of realizing in the experiment the ideal plane-parallel gaps with a width less than 50 μm.

The dependence of the maximum value of the real part of the electrical impedance on the film conductivity at the different values of the width of the gap between the film and the resonator was also constructed. It has been shown that as the conductivity of the film increases, the value of the maximum value of the real part of the impedance R_{max} decreases, reaches a minimum, and then again increases. At that, the effect of the conductivity of the film weakens as it moves away from the resonator. The dependences of the maximum value of the real part of the electrical impedance on the width of the gap between the film and the resonator are also obtained for different values of the film conductivity. The comparison of the experimental and theoretical dependences of the value of R_{max} on the width of the gap between the film and the resonator for different values of the film conductivity also shows their qualitative correspondence with the exception of the initial sections of the dependences.

In a whole the obtained results may be useful for the development of the gas sensors based on the lateral electric field excited piezoelectric resonator conjugated to the gas sensitive film, the conductivity of which changes in the presence of gas. The gas sensors based on a resonator with a lateral electric field and a gas sensitive film can be used to detect and analyze the explosive gases, since the probe voltage is applied to the resonator electrodes that do not directly contact the gas. These results show that in this case as the informative parameter one can use the parallel resonant frequency (the range of the film conductivity is 0.014–0.625 mS) or the maximum value of the real part of the electrical impedance (the range of the film conductivity 0.01μS – 0.014 mS). In these intervals, the changes in the resonant frequency and the maximum value of the real part of the electrical impedance are equal to 2.42 and 57%, respectively, for the gap width of 50 μm. In addition, based on the results obtained, it is possible to develop a non-contact method for determining the surface conductivity of thin films.

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