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Interaction of Electromagnetic H-wave with the thin Metal Film is Located on the Dielectric Substrate

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Interaction of electromagnetic H-wave with thin metal film is located between two dielectric environments ε_1, ε_2 in the case of different incident angles of H-wave θ and in the case of different reflection coefficients q_1 и q_2 is calculated in this article. Behavior analysis of reflection coefficient *R*, transmission coefficient *T* and absorption coefficient *A* in the case of its frequency dependence *y* and variation dielectric permeability of its environments is done.

Keywords: the thin metal film, electromagnetic H-wave, dielectric environments, reflection coefficient, transmission coefficient, absorption coefficient.

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Introduction

Currently microelectronics, optoelectronics and thin-film technology are actively developing. In particular the greatest interest represents researching of interaction electromagnetic radiation with thin conductive films in the different frequency range [1-6]. This interest is related not only with extensive practical importance of thin conductive films, but with some unresolved theoretical tasks.

In our case thickness of the thin metal film *a* is not more, than thickness of skin-layer δ and this thickness comparable with the average free path of electrons Λ. For this reason skin-effect is not considered. Skin-effect was researched in [8] in the case of the thin metal cylindrical wire. Quantum effects are not taken into account. This effects were researched in [9] in the case of quantum film in the dielectric environment.

I. Problem Definition and Metods

Consider the thin metal layer thickness of *a* is located between two dielectric (non-magnetic) environments, with dielectric permeability ε_1 (the first environment) and ε_2 (the second environment) with reflection coefficients q_1 and q_2 in the case of falling electromagnetic H-wave (from the first environment) at the θ angle. Reflection coefficients q_1 and q_2 are associated with reflection of electrons from top and lower surfaces layer. Clarify, if electric field vector is parallel the surface of the thin layer, then this wave is called H-wave. Electric field of electromagnetic wave is parallel the thin metal layer and directed along *Y*-axis, while *X*-axis is directed into the layer.

Then behavior of electromagnetic field inside the thin metal layer is described by the equation system [10]:

$$\begin{cases} \dfrac{dE_y}{dx} - ikH_z = 0, \\ \dfrac{dH_z}{dx} + ik(\sin^2\Theta - 1)E_y = -\dfrac{4p}{c} j_y. \end{cases} \qquad (1)$$

$k = \omega/c$ – wave number, *c* – speed of light, *j* – electric current density.

We have reflections coefficient *R*, transmission coefficient *T* and absorption coefficient *A* of thin metal film, when H-wave falling on this film [11]:

$$T = \frac{1}{4}\left|P^{(1)} - P^{(2)}\right|^2,$$
$$R = \frac{1}{4}\left|P^{(1)} + P^{(2)}\right|^2, \qquad (2)$$
$$A = 1 - T - R.$$

Expression (2) contains $P^{(1)}$ and $P^{(2)}$ [12] :

$$P^{(1)} = \frac{\sqrt{e_1}\cdot Z^{(1)}\cos\Theta - 1}{\sqrt{e_1}\cdot Z^{(1)}\cos\Theta + 1},$$
$$P^{(2)} = \frac{\sqrt{e_1}\cdot Z^{(2)}\cos\Theta - 1}{\sqrt{e_1}\cdot Z^{(2)}\cos\Theta + 1}. \qquad (3)$$

$Z^{(1)}$ and $Z^{(2)}$ correspond to the impedance of lower surface the layer. In particular $Z^{(1)}$ corresponds antisymmetric, in electric field, configuration of the external field: $E_y(0) = -E_y(a)$, $H_z(0) = H_z(a)$, and $Z^{(2)}$ – corresponds symmetric configuration: $E_y(0) = E_y(a)$, $H_z(0) = -H_z(a)$ [11].

Expression for surface impedance in the case of interaction H-wave with the thin metal film, were obtained in [11] in the case when wavelength much more thickness of the thin layer:

$$Z^{(1)} = 0, \qquad Z^{(2)} = \frac{c}{2pas_a} \tag{4}$$

For σ_a expression (this is electrical conductivity of the thin metal layer, with average thickness of this layer) we used results [13]. In this article we compared our results with experiment data [14]. Our σ_a expression have look:

$$s_a = s_0 l \int_0^1 \left(1-t^2\right)\left[2a + \frac{at}{x-iy}\left[\frac{q_1\left[q_2\exp\left(-(x-iy)/t\right)-\exp\left(-(x-iy)/t\right)+1\right]-1}{q_1q_2\exp\left(-2(x-iy)/t\right)-1} + \frac{q_2\left[q_1\exp\left(-(x-iy)/t\right)-\exp\left(-(x-iy)/t\right)+1\right]-1}{q_1q_2\exp\left(-2(x-iy)/t\right)-1}\right]\left[\exp\left(-(x-iy)/t\right)-1\right]\right]dt \tag{5}$$

$x = a/(v_F\tau)$ – the dimensionless frequency of bulk electron collision, $y = a\omega/v_F$ – the dimensionless frequency of the electric field, $\lambda = x/(x-iy)$, $\sigma_0 = \omega^2_p\tau/4\pi$ – the static electrical conductivity, v_F – Fermi speed, τ – electron relaxation time, ω_p – plasma frequency, q_1 и q_2 – reflection coefficients.

Finally, reflection coefficient R, transmission coefficient T and absorption coefficient A (expression (2)) will have look [12]:

$$R = \left|\frac{\sqrt{e_{1,2}-\sin^2\Theta}\,(\overline{P}+P^{(1)}P^{(2)}) + \cos\Theta(\overline{P}-P^{(1)}P^{(2)})}{\sqrt{e_{1,2}-\sin^2\Theta}\,(1+\overline{P})+\cos\Theta(1-\overline{P})}\right|^2$$

$$T = \cos\Theta\,\mathrm{Re}\sqrt{e_{1,2}-\sin^2\Theta}\left|\frac{P^{(2)}-P^{(1)}}{\sqrt{e_{1,2}-\sin^2\Theta}\,(1+\overline{P})+\cos\Theta(1-\overline{P})}\right|^2 \tag{6}$$

$$A = 1-T-R. \quad \varepsilon_{1,2}=\varepsilon_2/\varepsilon_1, \qquad \overline{P} = \frac{1}{2}(P^{(1)}+P^{(2)}).$$

Now we will begin to analyze behavior of this coefficients (expression (6)).

II. Results and Discussion

Let us consider behavior of coefficients R, T and A in the case of their frequency dependence with variation dielectric permeability value of the second environment ε_2 and in the case of different reflection coefficients q_1 and q_2. Clarify some parameters of potassium for further calculations: $\omega_p = 6.5 \cdot 10^{15}$ 1/s, $v_F = 8.52 \cdot 10^5$ m/s, $\tau = 1.54 \cdot 10^{-13}$ s, $a = 10$ nm.

Conclusions

In figure 1 we can see that the descending velocity of the curve increases with increasing values of the dielectric permittivity of the second environment ε_2.

In figure 2 we can see that the increase velocity of the curve increases with increasing values of the dielectric permittivity of the second environment ε_2.

In figure 3, in the case of not large value of the dielectric permittivity ($\varepsilon_2 < 30$) we can see, that coefficient A increases, reaches maximum and descents. Cleary visible absorption maxima. In the case of large value of the dielectric permittivity ($\varepsilon_2 > 30$) coefficient A begin immediately descents.

In figure 4, 5, 6 we can see, that variation of the thin

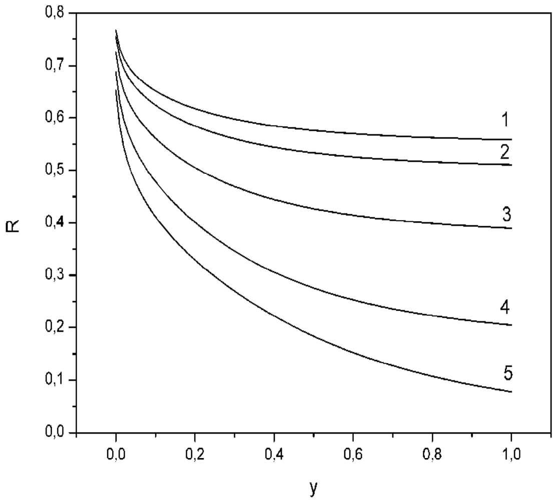

Fig. 1. The dependence of reflection coefficients *R* on the dimensionless frequency of the electric field *y*. Curve 1: $x = 0.002$, $\theta = 20^0$, $\varepsilon_1 = 1$, $\varepsilon_2 = 40$, $q_1 = 0.5$, $q_2 = 0.6$; curve 2: $x = 0.002$, $\theta = 20^0$, $\varepsilon_1 = 1$, $\varepsilon_2 = 30$, $q_1 = 0.5$, $q_2 = 0.6$; curve 3: $x = 0.002$, $\theta = 20^0$, $\varepsilon_1 = 1$, $\varepsilon_2 = 15$, $q_1 = 0.5$, $q_2 = 0.6$; curve 4: $x = 0.002$, $\theta = 20^0$, $\varepsilon_1 = 1$, $\varepsilon_2 = 5$, $q_1 = 0.5$, $q_2 = 0.6$; curve 5: $x = 0.002$, $\theta = 20^0$, $\varepsilon_1 = 1$, $\varepsilon_2 = 1$, $q_1 = 0.5$, $q_2 = 0.6$.

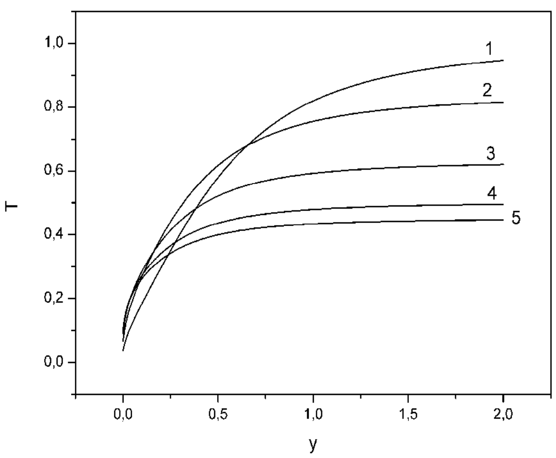

Fig. 2. The dependence of transmission coefficients *T* on the dimensionless frequency of the electric field *y*. Curve 1: $x = 0.002$, $\theta = 20^0$, $\varepsilon_1 = 1$, $\varepsilon_2 = 1$, $q_1 = 0.5$, $q_2 = 0.6$; curve 2: $x = 0.002$, $\theta = 20^0$, $\varepsilon_1 = 1$, $\varepsilon_2 = 5$, $q_1 = 0.5$, $q_2 = 0.6$; curve 3: $x = 0.002$, $\theta = 20^0$, $\varepsilon_1 = 1$, $\varepsilon_2 = 15$, $q_1 = 0.5$, $q_2 = 0.6$; curve 4: $x = 0.002$, $\theta = 20^0$, $\varepsilon_1 = 1$, $\varepsilon_2 = 30$, $q_1 = 0.5$, $q_2 = 0.6$; curve 5: $x = 0.002$, $\theta = 20^0$, $\varepsilon_1 = 1$, $\varepsilon_2 = 40$, $q_1 = 0.5$, $q_2 = 0.6$.

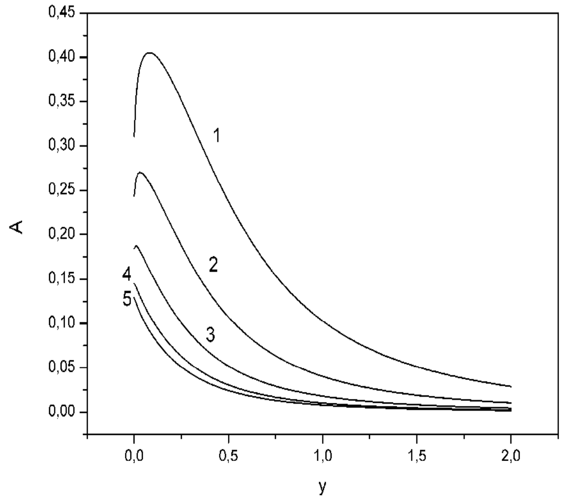

Fig. 3. The dependence of absorption coefficients *A* on the dimensionless frequency of the electric field *y*. Curve 1: $x = 0.002$, $\theta = 20^0$, $\varepsilon_1 = 1$, $\varepsilon_2 = 1$, $q_1 = 0.5$, $q_2 = 0.6$; curve 2: $x = 0.002$, $\theta = 20^0$, $\varepsilon_1 = 1$, $\varepsilon_2 = 5$, $q_1 = 0.5$, $q_2 = 0.6$; curve 3: $x = 0.002$, $\theta = 20^0$, $\varepsilon_1 = 1$, $\varepsilon_2 = 15$, $q_1 = 0.5$, $q_2 = 0.6$; curve 4: $x = 0.002$, $\theta = 20^0$, $\varepsilon_1 = 1$, $\varepsilon_2 = 30$, $q_1 = 0.5$, $q_2 = 0.6$; curve 5: $x = 0.002$, $\theta = 20^0$, $\varepsilon_1 = 1$, $\varepsilon_2 = 40$, $q_1 = 0.5$, $q_2 = 0.6$.

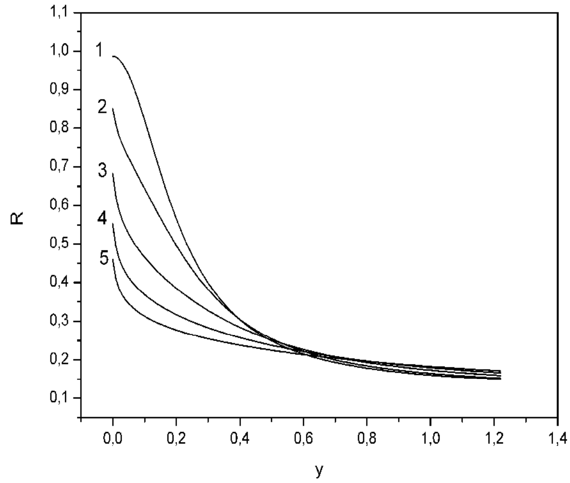

Fig. 4. The dependence of reflection coefficients *R* on the dimensionless frequency of the electric field *y*. Curve 1: $x = 0.002$, $\theta = 20^0$, $\varepsilon_1 = 1$, $\varepsilon_2 = 4$, $q_1 = 1$, $q_2 = 1$; curve 2: $x = 0.002$, $\theta = 20^0$, $\varepsilon_1 = 1$, $\varepsilon_2 = 4$, $q_1 = 0.8$, $q_2 = 0.9$; curve 3: $x = 0.002$, $\theta = 20^0$, $\varepsilon_1 = 1$, $\varepsilon_2 = 4$, $q_1 = 0.5$, $q_2 = 0.6$; curve 4: $x = 0.002$, $\theta = 20^0$, $\varepsilon_1 = 1$, $\varepsilon_2 = 4$, $q_1 = 0.2$, $q_2 = 0.3$; curve 5: $x = 0.002$, $\theta = 20^0$, $\varepsilon_1 = 1$, $\varepsilon_2 = 4$, $q_1 = 0$, $q_2 = 0$.

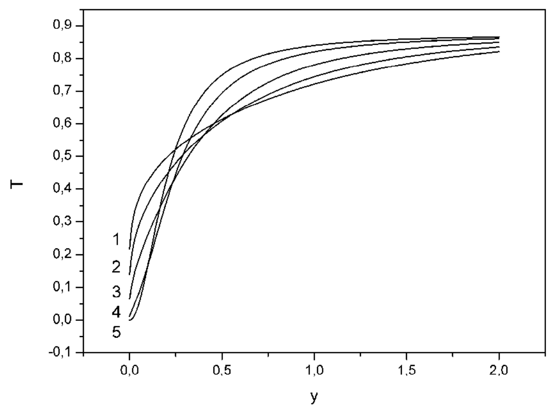

Fig. 5. The dependence of transmission coefficients *T* on the dimensionless frequency of the electric field *y*. Curve 1: $x = 0.002$, $\theta = 20^0$, $\varepsilon_1 = 1$, $\varepsilon_2 = 4$, $q_1 = 0$, $q_2 = 0$; curve 2: $x = 0.002$, $\theta = 20^0$, $\varepsilon_1 = 1$, $\varepsilon_2 = 4$, $q_1 = 0.2$, $q_2 = 0.3$; curve 3: $x = 0.002$, $\theta = 20^0$, $\varepsilon_1 = 1$, $\varepsilon_2 = 4$, $q_1 = 0.5$, $q_2 = 0.6$; curve 4: $x = 0.002$, $\theta = 20^0$, $\varepsilon_1 = 1$, $\varepsilon_2 = 4$, $q_1 = 0.8$, $q_2 = 0.9$; curve 5: $x = 0.002$, $\theta = 20^0$, $\varepsilon_1 = 1$, $\varepsilon_2 = 4$, $q_1 = 1$, $q_2 = 1$.

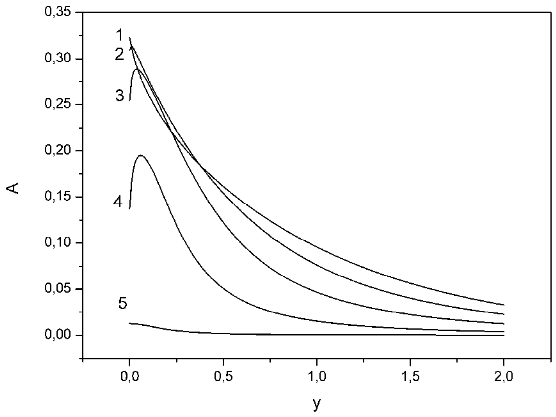

Fig. 6. The dependence of absorption coefficients *A* on the dimensionless frequency of the electric field *y*. Curve1: $x = 0.002$, $\theta = 20^0$, $\varepsilon_1 = 1$, $\varepsilon_2 = 4$, $q_1 = 0$, $q_2 = 0$; curve 2: $x = 0.002$, $\theta = 20^0$, $\varepsilon_1 = 1$, $\varepsilon_2 = 4$, $q_1 = 0.2$, $q_2 = 0.3$; curve 3: $x = 0.002$, $\theta = 20^0$, $\varepsilon_1 = 1$, $\varepsilon_2 = 4$, $q_1 = 0.5$, $q_2 = 0.6$; curve 4: $x = 0.002$, $\theta = 20^0$, $\varepsilon_1 = 1$, $\varepsilon_2 = 4$, $q_1 = 0.8$, $q_2 = 0.9$; curve 5: $x = 0.002$, $\theta = 20^0$, $\varepsilon_1 = 1$, $\varepsilon_2 = 4$, $q_1 = 1$, $q_2 = 1$.

metal layer reflection coefficients q_1 and q_2 (from diffuse $q_1 = q_2 = 0$ to reflection $q_1 = q_2 = 1$ cases) affects to *R*, *T*, *A* coefficients. It is obvious that reflection coefficients will change, when the thin metal film borders with different environments. In particular, in figure 6, in the reflection case, coefficient *A* immediately descent. In all other cases coefficient *A* increases reaches its maximum and descents.

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