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THE DEPTH OF PENETRATION OF THE ELECTRIC FIELD INDUCED BY A SURFACE ACOUSTIC WAVE IN A PIEZOELECTRIC — SEMICONDUCTOR SYSTEM

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This paper presents calculations of the penetration depth of the electric field accompanying an acoustic wave for penetration into a semiconductor layer over the plane of propagation when a *dc* electric field is applied to the piezoelectric – semiconductor system perpendicular to the propagation direction of the wave.

In a piezoelectric – semiconductor system the wave propagating on the surface of the piezoelectric, which has two displacement components, causes longitudinal and transverse components of the electric field to occur in the piezoelectric element (if the displacement directions coincide with the directions of the piezoelectric effect). These components also penetrate into the semiconductor when there is no mechanical contact between the piezoelectric and the semiconductor. The penetration depth is essential in the investigation of the electronic properties of the semiconductor surface using acoustical methods [17]. When the *dc* external electric field applied to the piezoelectric – semiconductor system has no transverse component (perpendicular to the propagation direction of the wave), then the penetration depth is of the order of r_D for $r_D k < 1$ and k^{-1} for $r_D k > 1$ (r_D is the Debay screening radius, k is the wave number) [1-3].

This paper considers the penetration depth of the electric field when the component of the external electric field is perpendicular to the propagation direction of the Rayleigh surface acoustic wave.

The electric field caused by the surface acoustic wave propagating on the piezoelectric surface penetrates into the semiconductor causing the electric field to occur. The electric field in the semiconductor and the resultant currents are described by Poisson's equations, the current equations and the equations of the continuity of current

$$\varepsilon_0 \varepsilon \Delta\varphi = qn, \tag{1}$$

$$\boldsymbol{j} = \mu q(n_0+n)(\boldsymbol{E}+\boldsymbol{E}^0)+qD\nabla n, \tag{2}$$

$$\nabla j = qn_t, \tag{3}$$

where n_0 is the density of carriers in the conduction band without the acoustic wave, n is the change in the density of carriers in the conduction band when the acoustic wave propagates, φ is the electric potential in the semiconductor, $\boldsymbol{j}$ is the current density in the semiconductor, $\boldsymbol{E} = \boldsymbol{E}_1+\boldsymbol{E}_3$ is the strength of the electric field in the semiconductor due to the propagation of the wave, $E_1 = -\partial\varphi/\partial x_1$ is the component of the field in the direction of propagation of the wave, $E_3 = -\partial\varphi/\partial x_3$ is the component perpendicular to the direction of propagation of the wave, $\boldsymbol{E}^0 = \boldsymbol{E}_1^0+\boldsymbol{E}_3^0$ is the strength of the external *dc* electric field, E_0^1 is the component along the direction of propagation, ε, ε_0 are the dielectric constants in a vacuum and in the semiconductor respectively, q is the charge of the carriers, μ is the mobility of the carriers, D is the diffusion coefficient, and E_3^0 is the component perpendicular to the direction of propagation.

From equations (1)-(3) and considering that n changes in the following way

$$e^{[i(kx_1-\omega t)-k\alpha x_3]}, \tag{4}$$

where x_1 is the direction of propagation of wave, x_3 is the direction perpendicular to the direction of propagation of the wave, ω is the angular frequency of the wave, k is the wave number, α is the coefficient of the depth of penetration into the semiconductor, the following equation for α can be obtained

$$\alpha^2 \pm \frac{\mu k E_3^0}{\omega}\frac{\omega_D}{\omega}\alpha - \left(1+\frac{1}{r_0^2 k^2}\right)+i\gamma\frac{\omega_D}{\omega} = 0, \tag{5}$$

where $\omega_D = \omega^2/k^2 D$ is the diffusion frequency, $\omega_C = \sigma_0/\varepsilon_0\varepsilon = \mu q n_0/\varepsilon_0\varepsilon$ is conduction relaxation frequency, $r_D k = \sqrt{\omega^2/\omega_D\omega_C}$, and $\gamma = 1+\mu k E_1^0/\omega$ is the drift parameter.

It follows from equation (5) that

$$\alpha = \alpha_1 + i\,\alpha_2 \tag{6}$$

is a complex number. Accordingly equation (5) can take the form

$$\alpha_1^2-\alpha_2^2 \pm \frac{\mu k E_3^0}{\omega}\frac{\omega_D}{\omega}\alpha_1 - \left(1+\frac{1}{r_D^2 k^2}\right) = 0, \tag{7a}$$

$$2\alpha_1\alpha_2 \pm \frac{\mu k E_3^0}{\omega}\frac{\omega_D}{\omega}\alpha + \gamma\frac{\omega_D}{\omega} = 0. \tag{7b}$$

The real part of the penetration coefficient α_1 plays an important role in the depth of penetration of the field. Solving equation (7a) and neglecting a_2 (i.e. without considering the oscillatory character of the decay of the field) one obtains

$$a_1 = \frac{\pm \frac{\mu k E_3^0}{\omega} \frac{\omega_D}{\omega} + \sqrt{\left(\frac{\mu k E_3^0}{\omega} \frac{\omega_D}{\omega}\right)^2 + 4\left(1+\frac{1}{r_D^2 k^2}\right)}}{2}. \tag{8}$$

The variation of the value of a_1 as a function of $r_D k$ for different E_3^0 for $\gamma = 0$ and, as a result, for $a_2 = 0$ is shown in Fig. 1.

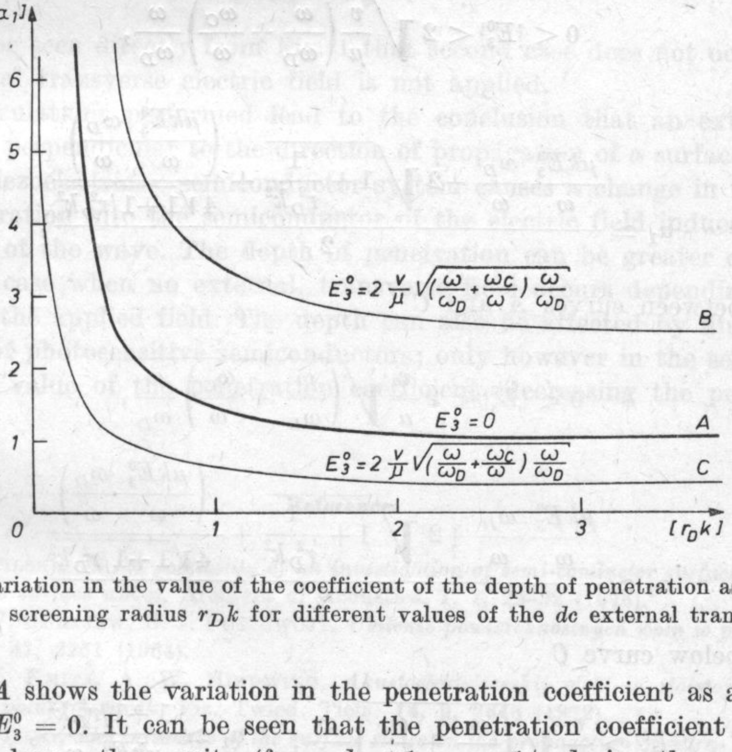

Fig. 1. The variation in the value of the coefficient of the depth of penetration as a function of the Debay screening radius $r_D k$ for different values of the dc external transverse field

Curve A shows the variation in the penetration coefficient as a function of $r_D k$ for $E_3^0 = 0$. It can be seen that the penetration coefficient is in this case always larger than unity (for $r_D k \ll 1$, $a_1 \simeq 1/r_D k$, i.e. the penetration depth is of the order of r_D; for $r_D k \gg 1$, $a_1 \simeq 1$, the penetration depth is of the order of k^{-1}) as was mentioned above.

The area above curve A represents the values of a_1 as a function of $r_D k$ for different values of a transverse field which brings the charge carriers to the surface on which the wave propagates, while the area below curve A is appropriate when the field is in the opposite direction.

It can be seen from Fig. 1 that the penetration coefficient for a field which brings the charge carriers to the surface on which the wave is propagating, is always larger than unity, while for a field in the opposite direction it can be larger or smaller than unity, e.g. for $r_D k > 1$ it is practically always smaller than unity.

The approximate value of α_1 in the individual areas is, according to (8),

1 – above curve B: $|E_3^0| > 2\frac{v}{\mu}\sqrt{\left(\frac{\omega}{\omega_D}+\frac{\omega_C}{\omega}\right)\frac{\omega}{\omega_D}}$, v is the velocity of propagation of the surface wave, $\alpha_1 = \frac{\mu k E_3^0}{\omega}\frac{\omega_D}{\omega}$ i.e. α_1 is directly proportional to E_3^0;

2 – between curves A and B

$$0 < |E_3^0| < 2\sqrt{\frac{v}{\mu}\left(\frac{\omega}{\omega_D}+\frac{\omega_C}{\omega}\right)\frac{\omega}{\omega_D}},$$

$$\alpha_1 \simeq \frac{\frac{\mu k E_3^0}{\omega}\frac{\omega_D}{\omega} + 2\sqrt{1+\frac{1}{r_D^2 k^2}+\frac{\left(\frac{\mu k E_3^0}{\omega}\frac{\omega_D}{\omega}\right)^2}{4\sqrt{1+1/r_D^2 k^2}}}}{2},$$

3 – between curves A and C

$$0 < |E_3^0| < 2\frac{v}{\mu}\sqrt{\left(\frac{\omega}{\omega_D}+\frac{\omega_C}{\omega}\right)\frac{\omega}{\omega_D}},$$

$$\alpha_1 \simeq \frac{\frac{\mu k E_3^0}{\omega}\frac{\omega_D}{\omega} + 2\sqrt{1+\frac{1}{r_D^2 k^2}+\frac{\left(\frac{\mu k E_3^0}{\omega}\frac{\omega_D}{\omega}\right)}{4\sqrt{1+1/r_D^2 k^2}}}}{2},$$

4 – below curve C

$$|E_3^0| > \frac{v}{\mu}\sqrt{\left(\frac{\omega}{\omega_D}+\frac{\omega_C}{\omega}\right)\frac{\omega}{\omega_D}}, \quad \alpha_1 \simeq \frac{1+1/r_D^2 k^2}{\frac{\mu k E_3^0}{\omega}\frac{\omega_D}{\omega}},$$

i.e. α_1 is inversely proportional to E_3^0.

Solving (1) with consideration of (4) leads to

$$\varphi = (C_1 e^{-kx_3} + C_2 e^{-\alpha k x_3})\, e^{i(kx_1-\omega t)}, \tag{9}$$

where C_1, C_2 are constants which can be determined from the boundary conditions. Thus the value of the penetration coefficient has a strong influence on the value and distribution of the potential within the semiconductor. The value of the potential in turn effects the variation in the propagation velocity and the attenuation coefficient of the surface acoustic wave in a piezoelectric-semiconductor system [4].

If

(1) $a_1 \ll 1$, then the second term in expression (9) is considerably less significant than the first and therefore

$$\varphi \sim e^{-kx_3} e^{i(kx_1 - \omega t)},$$

(2) $a_1 \gg 1$, in this case the greater influence on the value of φ in equation (9) is exerted by the second term, i.e.

$$\varphi \sim e^{-akx_3} e^{i(kx_1 - \omega t)}.$$

It can be seen directly from Fig. 1 that second case does not occur at all if an external transverse electric field is not applied.

The calculations performed lead to the conclusion that an external, *dc* electric field perpendicular to the direction of propagation of a surface acoustic wave in a piezoelectric – semiconductor system causes a change in the depth of the penetration into the semiconductor of the electric field induced by the propagation of the wave. The depth of penetration can be greater or smaller than in the case when no external, transverse field occurs depending on the direction of the applied field. The depth can also be affected by illumination in the case of photosensitive semiconductors; only however in the sense of increasing the value of the penetration coefficient (decreasing the penetration depth).

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