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THE INFLUENCE OF THE ELECTRIC FIELD ON SURFACE WAVE PROPAGATION IN A PIEZOELECTRIC—SEMICONDUCTOR SYSTEM

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The present paper describes the influence of a transverse electric field on surface wave propagation in a piezoelectric–semiconductor system, with consideration of surface states. The calculations show that a transverse electric field causes a change in the value of the attenuation coefficient and propagation velocity and can be used to control the magnitude of the attenuation.

1. Introduction

A surface Rayleigh wave with two displacement components causes longitudinal and transverse components of the acoustoelectric field to occur in a piezoelectric medium. The longitudinal acoustoelectrical field has been investigated in a number of papers [1-3]. Many aspects of the acoustoelectric transverse effect can be studied. Papers [4-7] report on the investigations of the acoustoelectric transverse effect, which determined the influence of various parameters on the electromotive force of the acoustoelectric transverse effect. The amplification of the wave can be controlled by the application of a variable electric field causing a transverse drift of the current carriers [8-10].

In a piezoelectric–semiconductor system without acoustic contact the electric field penetrates into the semiconductor to the depth of the screening radius [11]. At this depth the influence of the surface states is greatest. Thus account of the surface states [3] should be taken in consideration of the behaviour of acoustoelectronic phenomena.

This paper discusses the influence of a dc transverse electric field on Rayleigh surface wave propagation with consideration of the surface states.

2. The basic equations

In a piezoelectric—semiconductor system (Fig. 1) the wave propagating on the surface of the piezoelectric is described by the following equations

$$\varrho \frac{\partial^2 U_i}{\partial^2 t^2} = \frac{\partial T_{ik}}{\partial x_k}, \qquad T_{ik} = c_{iklm} U_{lm} - e_{jik} E_j^{(1)},$$
$$D_n^{(1)} = e_{nlm} U_{lm} - \varepsilon_{jm} E_j^{(1)}, \qquad \frac{\partial D_n^{(1)}}{\partial x_n} = 0, \tag{1}$$

where U_i are the displacement components, T_{ik} are the components of the strain tensor, U_{lm} are the components of the deformation tensor, $E_j^{(1)}$ are the components of the vector of the electric field in the piezoelectric, $D_n^{(1)}$ are the components of the vector of electric induction in the piezoelectric, c_{iklm} are the components of the tensor of the elastic constants, e_{ijk} are the components of the tensor of the piezoelectric constants, ε_{jm} are the components of the tensor of the dielectric permittivity, and ϱ is the density of the piezoelectric.

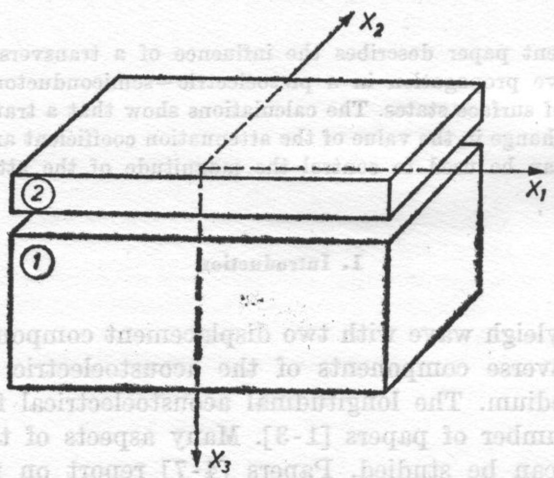

Fig. 1. The piezoelectric—semiconductor system in which a surface Rayleigh wave propagates

1 – piezoelectric, *2* – semiconductor, X_1 – the propagation direction of the wave, X_3 – the direction perpendicular to the propagation plane of the wave

In the piezoelectric, the electric field coupled with the surface wave, and the electric currents that it causes are described by the equations

$$\frac{\partial D_n}{\partial x_n} = -qn, \qquad j_k = \sigma_{ik} E_i^{(2)} + qD_{ik} \frac{\partial n}{\partial x_k},$$
$$\frac{\partial j_k}{\partial x_k} = q \frac{\partial n}{\partial t}, \tag{2}$$

where $D_n^{(2)}$ are the components of the vector of electric induction in the piezoelectric, n is the variation of the bulk density of the carriers caused by the wave, j_k are the components of the current, $E_i^{(2)}$ are the components of the vector of the electric field in the piezoelectric, σ_{ik} are the components of the tensor of electric conductivity, D_{ik} are the components of the tensor of the diffusion coefficient, and q is the charge of the carriers.

Assuming that the piezoelectric crystal is hexagonal and that the wave propagates in the plane (001) in the direction [100]; and after an isotropic approximation of the elastic, piezoelectric and electric constants [1, 3], i.e. introducing

$$c_{11}-c_{44} = c_{13}+c_{44}, \quad c_{33} = c_{11}, \quad c_{44} = \mu', \quad c_{13} = \lambda,$$

$$e_{31} = e_{15} = e, \quad e_{33} = -2e, \quad \varepsilon_{11} = \varepsilon_{22} = \varepsilon_{33} = \varepsilon,$$

equations (1) will take the following form

$$\varrho U_{1,tt} = (\lambda+\mu')(U_{1,1}+U_{3,3})_{,1}+\mu' \Delta U_1+2e\varphi^{(1)}_{,13}\ , \tag{3}$$

$$\varrho U_{3,tt} = (\lambda+\mu')(U_{1,1}+U_{3,3})_{,3}+\mu' \Delta U_3+e\varphi^{(1)}_{11}-2e\varphi^{(1)}_{,33},$$

$$e(U_{1,13}+U_{3,11}-2U_{3,33})-\varepsilon_0\varepsilon_1 \Delta\varphi^{(1)} = 0.$$

Equations (2), after taking into account the external longitudinal electric field E_1 and the transverse field E_3 will be expressed in the following way

$$\mathrm{div} D^{(2)} = \varepsilon_0\varepsilon_2 \Delta\varphi^{(2)} = -qn, \quad qn_{,t} = -\sigma\Delta\varphi^{(2)}+q\mu E_1 n_{,1}+q\mu E_3 n_{,3}+qD\Delta n. \tag{4}$$

Introducing the acoustic potentials as in [3] and considering that all the variable quantities in the piezoelectric depend on the coordinates and time as

$$\exp[i(kx_1-\omega t)+k\beta_n x_3],$$

where k is the wave number, ω is the angular frequency of the wave and β_n is the coefficient of penetration of the wave into the medium; from calculation by the method of successive approximations and considering that the value of the electromechanical coupling coefficient $\eta = e^2/\varepsilon_0\varepsilon_1\varrho a_2^2$ (a_2 is the propagation velocity of the transverse wave) is low, equations (3) give the coefficients of penetration of the wave, β_1, β_2, β_3 and the relations between the amplitudes Ψ, Φ, $\varphi^{(1)}$. Thus the solutions will have the form [3]

$$\Psi = \sum_{n=1}^{3} A_n e[i(kx_1-\omega t)+k\beta_n x_3],$$

$$\Phi = \sum_{n=1}^{3} B_n e^{[i(kx_1-\omega t)+k\beta_n x_3]} = \sum_{n=1}^{3} \alpha_n A_n e^{[i(kx_1)-\omega t)+k\beta_n x_3]}, \tag{5}$$

$$\varphi^{(1)} = \sum_{n=1}^{3} C_n e^{[i(kx_1-\omega t)+k\beta_n x_3]} = \sum_{n=1}^{3} \gamma_n A_n e^{[i(kx_1-\omega t)+k\beta_n x_3]}.$$

3. The boundary conditions

The boundary conditions for the assumed piezoelectric – semiconductor system are the following:

— the elastic strains become zero

$$T_{3i} = 0, \quad i = 1, 2;$$

— the tangential components of the electric field are continuous

$$\varphi^{(1)}_{,1} = \varphi^{(2)}_{,1};$$

— the normal components of the vector of the electric induction are discontinuous

$$D^{(1)}_3 - D^{(2)}_3 = -qn_s,$$

where n_s is the variation in the surface density of the carriers in the conduction band,

$$D^{(1)}_3 = -\varepsilon_0\varepsilon_1\varphi^{(1)}_{,3} + e(U_{1,1} - 2U_{3,3}), \quad D^{(2)}_3 = -\varepsilon_0\varepsilon_2\varphi^{(2)}_{,3}.$$

Considering that

$$n = F\exp[i(kx_1 - \omega t) - \Omega kx_3] \tag{6}$$

and thus from Poisson's equation

$$\varphi^{(2)} = (C_4 e^{-kx_3} + C_5 e^{-k\Omega x_3}) e^{i(kx_1 - \omega t)}. \tag{7}$$

Then considering that the equation of continuity for the layer at the surface has the form

$$qn_{s,3t} = -\sigma\varphi_{,11} + q\mu E_1 n_{s,13} + q\mu E_3 n_{s,33} + qDn_{s,113} - qn_{t,3t} \tag{8}$$

one obtains the boundary conditions in the form

$$\sum_{n=1}^{3} A_n[(\beta_n^2 - 1 + 2m)\alpha_n - 2im\beta_n - 2m\eta\gamma_n] = 0,$$

$$\sum_{n=1}^{3} A_n[2i\beta_n\alpha_n + 1 + \beta_n^2 + i\eta\gamma_n] = 0,$$

$$\sum_{n=1}^{3}\left\{\left[\left(C_n\beta_n + \frac{\varepsilon_2}{\varepsilon_1}(C_4 + \Omega C_5) - \frac{\varepsilon_2}{\varepsilon_1}\,\frac{C_n}{i\omega\tau_M\Omega\left(\gamma + \varkappa + i\Omega\dfrac{\mu kE_3}{\omega} + i\dfrac{\omega}{\omega_D}\right)}\right]\gamma_n + \right.\right.$$

$$\left. + [(1 + 2\beta_n^2)\alpha_n - 3i\beta_n]C_n\right\} = 0, \tag{9}$$

where Ω is the coefficient of penetration into the semiconductor [12], $n_t = \varkappa n_s$ is the surface density of the carriers in traps,

$$\varkappa = \tau_2(1+i\omega\tau_2)/\tau_1(1+\omega^2\tau_2^2)$$

is the occupation coefficient for the surface states [3],

$$\tau_1 = [C_n(N_t - n_{t0})]^{-1}$$

is the lifetime of the carriers in the conduction band,

$$\tau_2 = [C_n(n_{s0}+n_1)]^{-1}$$

is the lifetime of the carriers in the traps, C_n is the coefficient of capture of the carriers by the traps, N_t is the surface density of the traps, n_{t0} is the filling density of the traps if no wave propagates, n_{s0} is the surface density of the carriers in the conduction band in the equilibrium state, n_1 is the density of the carriers thermally ejected from the traps, F, C_4, C_5 are determined from the equation of continuity for the layer at the surface (8), Poisson's equation and the continuity of the tangential components of the electric field,

$$F = -\frac{\varepsilon_0\varepsilon_2 k^2 \sum_{n=1}^{3} C_n}{i\omega\tau_M q\left(\gamma+\varkappa+i\Omega\frac{\mu k E_3}{\omega}+i\frac{\omega}{\omega_D}\right)},$$

$$C_4 = \left[1-\frac{1}{i\omega\tau_M\left(\gamma+\varkappa+i\Omega\frac{\mu k E_3}{\omega}+i\frac{\omega}{\omega_D}\right)(1-\Omega^2)}\right]\sum_{n=1}^{3} C_n, \tag{10}$$

$$C_5 = \frac{1}{i\omega\tau_M\left(\gamma+\varkappa+i\Omega\frac{\mu k E_3}{\omega}+i\frac{\omega}{\omega_D}\right)(1-\Omega^2)}\sum_{n=1}^{3} C_n,$$

α_n, γ_n are the relations between A_n, B_n and C_n,

$$\tau_M = \omega_c = \sigma/\varepsilon_0\varepsilon_2$$

is the Maxwell frequency,

$$\gamma = 1+\mu k E_1/\omega$$

is the drift parameter and $\omega_D = v^2/D$ is the diffusion frequency.

4. The solution of the problem and conclusions

In order to determine the variation of the propagation velocity and of the attenuation coefficient, the determinant of the boundary conditions (9) $W(k)$ should be equated to zero and k should then be found from this equation.

Since $k = k_0 + k_1$, where k_1 results from the consideration of the piezoelectric effect, the surface states, the longitudinal and transverse electric fields, and thus $k_1 < k_0$, $W(k) = 0$ can be expanded into a series with respect to k_1. By inserting the expressions for C_4 and C_5 into the third boundary condition (9) we obtain

$$\sum_{n=1}^{3} C_n \left\{\left[\beta_n + \frac{\varepsilon_2}{\varepsilon_1} - \frac{\varepsilon_2}{\varepsilon_1}\,\frac{2\Omega+1}{i\omega\tau_M\left(\gamma+\varkappa+i\Omega\,\frac{\mu k E_3}{\omega}+i\,\frac{\omega}{\omega t}\right)\Omega(1+\Omega)}\right]\gamma_n + (1+2\beta_n^2)\,a_n - 3i\beta_n\right\} = 0, \qquad (11)$$

or in an approximate, but much more convenient form,

$$\sum_{n=1}^{3} C_n \left\{\left[\beta_n + \frac{\varepsilon_2}{\varepsilon_1} - \frac{\varepsilon_2}{\varepsilon_1}\,\frac{p}{i\omega\tau_M\,\Omega\left(\gamma+\varkappa+i\Omega\,\frac{\mu k E_3}{\omega}+i\,\frac{\omega}{\omega_D}\right)}\right]\gamma_n + (1+2\beta_n^2)\,a_n - 3i\beta_n\right\} = 0; \qquad (11a)$$

where $p = 1$ for $\Omega \ll 1$, $p = 3/2$ for $\Omega = 1$ and $p = 2$ for $\Omega \gg 1$.

Considering that $\Omega = \Omega_1 + i\Omega_2$ and analyzing the case $\Omega_2 \ll \Omega_1$ after the calculation of the variation of the propagation velocity and the attenuation coefficient we obtain the following expressions

$$\frac{\Delta v}{v} = \frac{\eta\omega\tau_M N_1}{M}\times$$

$$\times\frac{\omega\tau_M\left(1+\frac{\varepsilon_2}{\varepsilon_1}\right)(\gamma+a)^2+\left(b+\Omega_1\frac{\mu k E_3}{\omega}+\frac{\omega}{\omega_D}\right)\left[\left(1+\frac{\varepsilon_2}{\varepsilon_1}\right)\left(b+\Omega_1\frac{\mu k E_3}{\omega}\right)\omega\tau_M+\frac{p}{\Omega_1}\frac{\varepsilon_2}{\varepsilon_1}\right]}{\left(1+\frac{\varepsilon_2}{\varepsilon_1}\right)^2(\gamma+a)^2\omega^2\tau_M^2+\left[\left(1+\frac{\varepsilon_2}{\varepsilon_1}\right)(b+\Omega_1)\,\frac{\mu k E_3}{\omega}+\frac{\omega}{\omega_D}\Big)\,\omega\tau_M+\frac{p}{\Omega_1}\frac{\varepsilon_2}{\varepsilon_1}\right]\Omega_1}$$

$$a = -\frac{\eta\omega\tau_M N_1}{M}\times \qquad (12)$$

$$\times\frac{p\,\frac{\varepsilon_2}{\varepsilon_1}(\gamma+a)}{\left\{\left(1-\frac{\varepsilon_2}{\varepsilon_1}\right)^2(\gamma+a)^2\omega^2\tau_M^2+\left[\left(1+\frac{\varepsilon_2}{\varepsilon_1}\right)\left(b+\Omega_1\,\frac{\mu k E_3}{\omega}+\frac{\omega}{\omega_D}\right)\omega\tau_M+\frac{p}{\Omega_1}\frac{\varepsilon_2}{\varepsilon_1}\right]^2\right\}\Omega_1},$$

where $a+ib = \varkappa$,

$$M = \frac{\partial N_2}{\partial \beta_n}\left(\frac{\partial \beta_n}{\partial k}\right) k = k_0,$$

$$N_1 = 3\beta_2\left[(\beta_1^2-1+2m)\frac{a_1}{2im}\,2m\beta_1-1-\beta_1^2+4m\beta_1\frac{a}{2im}-\right.$$
$$\left.-(1+\beta_2+\beta_2^2)\left[(\beta_1^2-1+2m)\frac{a}{2im}-3\beta_1\right]\right],$$

$$N_2 = (1+\beta_2^2)[(\beta_1^2-1+2m)\frac{a}{2im}-2m\beta_1+\beta_2\left(1+\beta_1^2-4m\beta_1\frac{a}{2im}\right).$$

The above expressions show that the values of the attenuation coefficient and the velocity depend on the longitudinal and transverse electric fields and on the parameters characterizing the surface states. The change in the sign of the attenuation coefficient, i.e. the change from attenuation to amplification can thus only be caused by a longitudinal field. The transverse field only changes the value of the attenuation coefficient and the velocity.

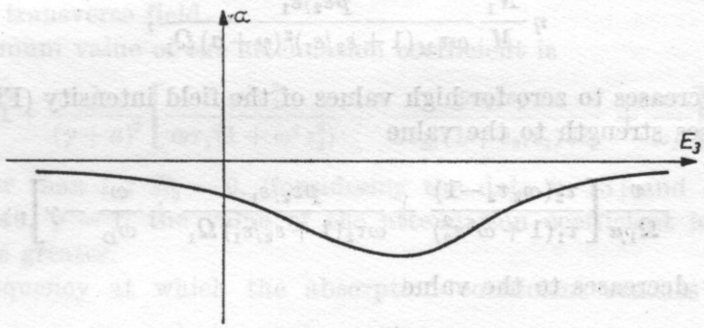

Fig. 2. The dependence of the attenuation coefficient on the transverse electric field E_3

The transverse field, depending on its direction of application, imposes an inflow or outflow of the energy carriers to the surface on which the wave propagates. In other words it causes a change in the conduction near this surface, and thus has an effect similar to that of illumination in the case of a photo-semiconductor.

If the transverse field causes an outflow of the charge carriers from the surface, then as its value increases, the attenuation decreases, tending to zero for high values of the field intensity (Fig. 2). With increasing field strength the velocity increases to the value $\eta(N_1/M)(1+\varepsilon_2/\varepsilon_1)^{-1}$ (Fig. 3).

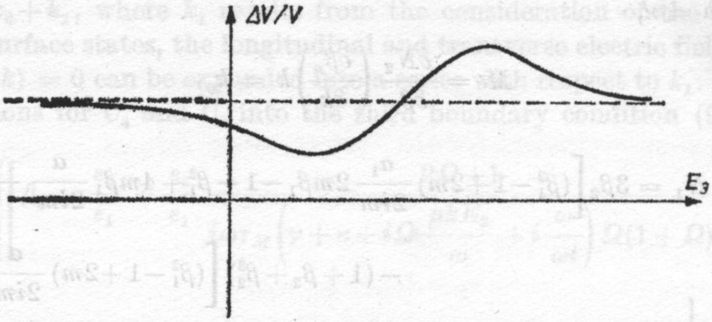

Fig. 3. The dependence of the relative change in the wave propagation velocity, on the transverse electric field E_3

If the transverse field causes an inflow of the charge carriers to the surface, then increasing the field strength to:

$$\frac{v}{\Omega_1 \mu}\left[\frac{\omega\tau_2^2}{\tau_1(1+\omega^2\tau_M^2)}+\frac{p\varepsilon_2/\varepsilon_1}{\omega\tau_M(1+\varepsilon_2/\varepsilon_1)\,\Omega_1}+\frac{\omega}{\omega_D}\right]$$

the attenuation increases to the value

$$\eta\,\frac{N_1}{M}\,\frac{p\varepsilon_2/\varepsilon_1}{\omega\tau_M(1+\varepsilon_2/\varepsilon_1)^2(\gamma+a)\,\Omega_1},$$

and then decreases to zero for high values of the field intensity (Fig. 2). As the field increases strength to the value

$$\frac{v}{\Omega_1 \mu}\left[\frac{\tau_2(\omega_2\tau_2-1)}{\tau_1(1+\omega^2\tau_2^2)}+\frac{p\varepsilon_2/\varepsilon_1}{\omega\tau_2(1+\varepsilon_2/\varepsilon_1)\,\Omega_1}+\frac{\omega}{\omega_D}-\gamma\right],$$

the velocity decreases to the value

$$\eta\,\frac{N_1}{M}\,\frac{2(\gamma+a)\left(1+\dfrac{\varepsilon_2}{\varepsilon_1}\right)\omega\tau_M-\dfrac{p}{\Omega_1}\dfrac{\varepsilon_2}{\varepsilon_1}}{2(\gamma+a)(1+\varepsilon_2/\varepsilon_1)^2\omega\tau_M},$$

and then increases, taking the value $\eta(N_1/M)(1+\varepsilon_2/\varepsilon_1)^{-1}$ for a field strength of

$$\frac{v}{\Omega_1 \mu}\left[\frac{\omega\tau_2^2}{\tau_1(1+\omega^2\tau_2^2)}+\frac{p\varepsilon_2/\varepsilon_1}{\omega\tau_M(1+\varepsilon_2/\varepsilon_1)\,\Omega_1}+\frac{\omega}{\omega_D}\right],$$

increasing again to the value

$$\eta\,\frac{N_1}{M}\,\frac{2(\gamma+a)\left(1+\dfrac{\varepsilon_2}{\varepsilon_1}\right)\omega\tau_M+\dfrac{p}{\Omega_1}\dfrac{\varepsilon_2}{\varepsilon_1}}{2(\gamma+a)(1+\varepsilon_2/\varepsilon_1)\,\omega\tau_M}$$

at a field strength of

$$\frac{v_1}{\Omega_1\mu}\left[\frac{\tau_2(1+\omega\tau_2)}{\tau_1(1+\omega^2\tau_2^2)}+\frac{p\varepsilon_2/\varepsilon_1}{\omega\tau_M(1+\varepsilon_2/\varepsilon_1)\Omega_1}+\frac{\omega}{\omega_D}+\gamma\right],$$

and with further increase in the field strength, the velocity variation decreases tending to the value $\eta(N_1/M)(1+\varepsilon_2/\varepsilon_1)^{-1}$ for high field intensities (Fig. 3).

These considerations lead to the conclusion that the value of the transverse field for which the variation of propagation velocity has an extremum and the attenuation its greatest value may be calculated using the parameters characterizing the semiconductor, i.e. the lifetime of the carriers in the conduction band τ_1 and the lifetime of the carriers in the traps τ_2. The behaviour of the attenuation coefficient with respect to the transverse field applied which was obtained in the present investigation was the same as in the experimental paper [9].

For the transverse field leading the charge carriers to the surface on which the wave propagates when its value is in the range

$$0<E_3<2\frac{v}{\Omega_1\mu}\left[\frac{\omega^2\tau_2^2}{\omega\tau_1(1+\omega^2\tau_2^2)}+\frac{p\varepsilon_2/\varepsilon_1}{\omega\tau_M(1+\varepsilon_2/\varepsilon_1)\Omega_1}+\frac{\omega}{\omega_D}\right],$$

the attenuation coefficient is greater, while in other ranges it is smaller than without the transverse field.

A maximum value of the attenuation coefficient is

$$1+\frac{1}{(\gamma+a)^2}\left[\frac{\omega^2\tau_2^2}{\omega\tau_1(1+\omega^2\tau_2^2)}+\frac{p\varepsilon_2/\varepsilon_1}{\omega\tau_M(1+\varepsilon_2/\varepsilon_1)\Omega_1}+\frac{\omega}{\omega_D}\right]$$

times greater than for $E_3=0$. Considering the data in [3] and $\omega\tau_M\approx 1$, $\varepsilon_2=10$, $\varepsilon_1=40$, $\gamma=1$, the value of the attenuation coefficient is between 1 and 10 times greater.

The frequency at which the absorption coefficient reaches its highest value is

$$\omega_m=\frac{1}{\tau_M}\frac{p\varepsilon_2/\varepsilon_1}{\left(1+\dfrac{\varepsilon_2}{\varepsilon_1}\right)\left\{(\gamma+a)^2+\left[\dfrac{\omega^2\tau_2^2}{\omega\tau_1(1+\omega^2\tau_2^2)}+\dfrac{\omega}{\omega_D}+\Omega_1\dfrac{\mu k E_3}{\omega}\right]^2\right\}^{1/2}}.$$

If the transverse field leads the charge carriers and is

$$0<E_3<2\frac{v}{\Omega_1\mu}\left[\frac{\omega^2\tau_2^2}{\omega\tau_1(1+\omega^2\tau_2^2)}+\frac{\omega}{\omega_D}\right],$$

then the frequency at which the maximum absorption occurs is higher, while for other values and in the directions of E_3, it is lower than without the transverse field.

It follows from the above considerations that since with a transverse field one can change the value of the electronic attenuation (amplification), it has a similar influence as a change in the illumination of the semiconductor. Affecting concentration variation by illumination requires photosensitive semiconductors and the possibility of illuminating them, which is not always possible. It is thus more convenient to cause changes in concentration by changes in the transverse electric field. It is significant for the determination of the value of the critical field. Measurements always provide the total attenuation coefficient, with consideration of the losses resulting from reasons other than electronic attenuation. The value of the critical field depends only on the propagation velocity and mobility, while the value of the attenuation coefficient also depends on the concentration of the carriers, which can be changed using illumination or, as was shown above, by a transverse field. By changing the concentration of the carriers we obtain various dependencies of the attenuation coefficient on the drift parameter, which will cross at a point where the parameter is zero.

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