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AMPLIFICATION OF SURFACE WAVES IN SEMICONDUCTORS

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Amplification of singular surface waves can be obtained in a system consisting of a thin semiconducting layer and a semi-infinite piezoelectric (or vice versa). Amplification occurs when the directed velocity of the carriers in the semiconductor is greater than the phase velocity of the surface waves.

IT was observed relatively recently that acoustic waves can be excited in semiconductors[1,2] when the carrier drift velocity exceeds the phase velocity of the acoustic wave. Physically, the amplification is due to the Cerenkov radiation of phonons by the drifting space charge. We shall show in this article that such amplification of surface waves can be realized in a layered system consisting of a piezoelectric and a semiconductor, by using the phenomenon whereby the electric field that accompanies the elastic wave in the piezoelectric penetrates into a semiconductor in which there is directional motion of the current carriers.

Assume that a piezoelectric dielectric plate of thickness h is placed over a semiconductor occupying the half-space $z < 0$. As shown in the book of Landau and Lifshitz[3] (see the problem of Sec. 24, Ch. III), unique surface waves can propagate in such a system: a transverse wave with a displacement vector parallel to the plane of the plate propagates in the plate, while the wave propagating in the semi-infinite medium is also transverse, has the same displacement-vector direction, but attenuates in the interior of the medium. The phase velocity of such waves is determined from the dispersion equation[3] (without account of the piezoeffect)

$$\tan \varkappa_1 = \mu_2\varkappa_2 / \mu_1\varkappa_1,$$
$$\varkappa_1 = [(\omega / c_{t1})^2 - k^2]^{1/2}, \quad \varkappa_2 = [k^2 - (\omega / c_{t2})^2]^{1/2}, \qquad (1)$$

where μ_1 and μ_2—effective shear moduli of the contacting media (the subscripts 1 and 2 pertain to the plate and to the semi-infinite medium, respectively), and c_{t1} and c_{t2}—corresponding velocities of the transverse sound waves. It is assumed that the wave propagates in the x-direction, and that the dependence of the displacement on the time t and on x is given by the factor $\exp(i\omega t - ikx)$, where ω—oscillation frequency.

If the plate is a piezoelectric, then the elastic wave in it is accompanied by the appearance of an electric field that penetrates into the second medium. It can be readily shown (for example, in the quasi-hydrodynamic approximation[4]), that the penetration of the field into the semiconductor is described by a factor ($z \le 0$)

$$\frac{\Lambda[1 - (\Lambda^2 - k^2) r_D^2] e^{kz} - k e^{\Lambda z}}{\Lambda[1 - (\Lambda^2 - k^2) r_D^2] - k} \qquad (2)$$

where

$$\Lambda^2 = \frac{1 + k^2 r_D^2}{r_D^2} + i\frac{\nu\omega}{v_T^2}\left(1 - \frac{v_d}{v_{\text{ph}}}\right), \qquad (3)$$

r_D—Debye radius, z_T—thermal velocity of the carriers, v_d—drift velocity of the carriers, v_{ph}—phase velocity of the wave, ν—effective collision frequency, and k—wave vector. In the case of a degenerate semiconductor, when $kT \ll \mathscr{E}_F$ ($\mathscr{E}_F$—Fermi energy, T—temperature, κ—Boltzmann constant), v_T is replaced by $v_F/\sqrt{3}$, where v_F—Fermi velocity.

We see therefore that the depth of penetration of the electric fields of a slow electric wave into a semiconductor is determined by the smaller of the two quantities, the Debye radius or the wavelength. By solving the system of coupled equations for the elastic waves and the electric field in both media and "joining" the solution on the boundary $z = 0$, we obtain a dispersion equation that differs from (1) by corrections that are proportional to the square of the constant of an electromagnetic coupling:

$$\zeta^2 = 4\pi\beta^2_{x,\,yx} / \rho_1 c_{t1}^2 \varepsilon_1 \ll 1,$$

where $\beta_{x,\,yx}$—piezotensor component leading to the appearance of the longitudinal electric field in the transverse acoustic wave, and ρ_1 and ϵ_1—

density and dielectric constant of the plate. The solution of the dispersion equation determines the imaginary part of the wave vector

$$\frac{\operatorname{Im} k}{k} = -\zeta^2 \frac{\varepsilon_1 \varepsilon_2 \operatorname{Im} \Phi}{|(\varepsilon_1 + \varepsilon_2)\Phi - \varepsilon_1|^2} \frac{F(\omega, k)}{kh}, \qquad kh > 1, \quad (4)$$

where $\Phi = \Lambda(\Lambda + k) r_D^2$, $F(\omega, k)$—some real positive function close to unity in magnitude, and k is determined from the dispersion equation (1).

We can easily see that Im Φ contains as a factor $(1 - v_d/v_{ph})$, and consequently when $v_d > v_{ph}$ absorption should give way to amplification, and the surface wave in question will grow. An analysis shows that amplification at a specified frequency depends essentially on the density concentration n_0 of the carriers in the semiconductor. When n_0 is small we have Im $k \sim n_0$, and when n_0 is large we get Im $k \sim n_0^{-1}$. To the contrary, for a specified carrier density the frequency characteristic of the amplification has a maximum.

We have considered above a case when a thin piezoelectric layer is placed on top of a semiconductor. Another system, however, is also possible, in which a thin semiconductor is located over a piezoelectric. It can be shown that in this case, too, the depth of penetration of the electric field will be the same when $kh > 1$, and the final expression for the growth increment differs from (4) only in the form of the function $F(\omega, k)$, which is close to unity as before.

We note that in the case of amplification of these waves, the power released per unit volume of semiconductors can be greatly reduced by using a semiconductor with large mobility. Thus, for pure InSb samples with $n_0 \approx 10^{12}$ cm^{-3} and mobility 10^4/V-sec, the dissipated power is approximately 0.1 W/cm^2, which is much lower than in the case of amplification in CdS[1].

In conclusion we note that although the foregoing quasi-hydrodynamic analysis is valid when the Debye radius and the wavelength are much smaller than the mean free path, it can be assumed that the deductions remain qualitatively the same even if this condition is violated. In addition, we can consider in similar fashion the amplification of other types of surface waves, especially plasma waves[5].

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