ELECTROACOUSTIC SURFACE WAVES IN SOLIDS

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We shall show in this paper that a surface sound wave not of the Rayleigh type, a purely transverse wave with a polarization vector parallel to the surface, can propagate along the surface of a homogeneous piezoelectric or conducting solid. The boundary conditions on the surface are satisfied here by the presence of a longitudinal and transverse electromagnetic field in such a wave. These fields can be connected either with the pure piezoeffect (in piezoelectric dielectrics) or with the redistribution of the free electrons and occurrence of volume charges as a result of electron-phonon interaction via the piezoeffect or the deformation potential (in conductors). Since the surface character of these waves is connected in principle with the interaction of the electric fields with the crystal lattice, we shall call them "electroacoustic"[1)].

Let us consider for concreteness a semi-infinite conducting piezoelectric crystal such as cadmium sulfide (class C_{6v}), so oriented that the hexagonal oz axis and the ox axis are parallel to the surface (the crystal occupies the half-space $y < 0$, with vacuum at $y > 0$). Let a transverse sound wave propagate along the ox axis, with the displacement vector u of the wave directed along the oz axis and dependent only on the coordinates x and y; the wave frequency ω is such that the condition $q\ell \ll 1$ (q - wave number of wave, ℓ - electron mean free path). In order to consider the possibility of amplification of the wave by the electron drift, we assume also that electrons drift with velocity v_0 along the wave propagation direction. The system of fundamental equations describing the propagation of such a wave consists of the equation of elasticity theory, Maxwell's equations, the continuity equation, and the phenomenological expression for the current density. Standard boundary conditions, including the vanishing of the normal component of the current density, are imposed on the free surface of the body.

Seeking, in accordance with the expected surface character of the wave, a solution of the initial system in the form $\exp[\kappa y + i(\omega t - qx)]$, where t is the time and κ the sought damping constant (of which there turn out to be several), we get from the boundary conditions the dispersion equation of the wave and the values of κ themselves[2)]. It turns out that, accurate to terms of first order in the electromechanical coupling constant inclusive, the dispersion equation of the wave coincides with the corresponding equation for the transverse volume sound wave having the same propagation direction and displacement vector. The

1)We note that sound wave can become surface waves for other reasons, too. Thus, in [1] they considered the amplification of volume sound waves in a piezoelectric dielectric by a beam of charged particles passing near the surface of the crystal. The authors indicate that owing to the interaction with the plasma wave in the beam, the amplified waves acquire a surface character. The wave considered by us, to the contrary, can be surface waves also in the absence of a free-carrier plasma.

2)It should be noted that the dispersion equation has one more solution, corresponding to a space-charge surface wave, but we are not interested in it here.

coefficient of electronic absorption (amplification) of the considered surface wave is thus given by the well-known formula of White [2]. The displacement vector of the wave is given by

$$u(x, y, t) = U_0(e^{\kappa_1 y} + \alpha e^{\kappa_3 y})e^{i(\omega t - qx)}, \quad (1)$$

where U_0 is a certain constant, and the damping constants κ_1 and κ_3 and the parameter α are given, accurate to terms of first order in the electromechanical-coupling constant $\eta = (4\pi e_{15}^2/\varepsilon_{\perp}C_{44})$($e_{15}$ and C_{44} are the corresponding components of the piezoelectric-modulus and elasticity tensors and $\varepsilon_{\perp}$ is the transverse dielectric constant of the crystal), by the expressions

$$\kappa_1 = \frac{\eta q}{\epsilon_{\perp} + 1}\left[\frac{q^2 r_D^2 + i\omega' \tau_M}{1 + q^2 r_D^2 + i\omega' \tau_M}\right]^2 \frac{1 + i\omega'\tau_M}{\dfrac{\epsilon_{\perp} + \dfrac{q}{\kappa_3}}{\epsilon_{\perp} + 1} + i\omega'\tau_M}, \quad (2)$$

$$\kappa_3 = 1/r_D\sqrt{1 + q^2 r_D^2 + i\omega'\tau_M} \quad (3)$$

$$\alpha = \frac{\kappa_1}{\kappa_3}(q^2 r_D^2 + i\omega'\tau_M)^{-1}. \quad (4)$$

Here r_D and τ_M are respectively the Debye screening radius and the Maxwell relaxation time, and $\omega' \equiv \omega - qv_0$. The transition to the piezodielectric case corresponds to the conditions $q^2 r_D^2 \to \infty$, $\omega'\tau_M \to \infty$, yielding $\kappa_1 = \eta q/(\varepsilon_{\perp} + 1)$ and $\alpha \to 0$. Thus, the electroacoustic wave under consideration attenuates in this case exponentially inside the body, at a distance on the order of $(\varepsilon_{\perp} + 1)/\eta q$, i.e., it penetrates at $\eta < 1$ much deeper than the Rayleigh wave, which propagates in a surface layer of thickness on the order of $1/q$. In the presence of free electrons, the quantities κ_1 and κ_3 turn out to be complex and the amplitude of the wave in question becomes an oscillating function of the distance from the surface to the interior of the body.

We note finally that the considered electroacoustic surface waves may be of interest from the point of view of their amplification by a drift current of electrons in the continuous regime at high frequency. Indeed, on the one hand, they propagate in a sufficiently thin surface layer to be able to ensure good dissipation of the released Joule heat, and on the other hand they penetrate much deeper than the Rayleigh waves, so that they should be less affected by the non-ideal character of the surface of the crystal, and furthermore they can transport much more acoustic power than Rayleigh waves.

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[1] Sh. M. Kogan and V. B. Sandomirskii, Fiz. Tverd. Tela 6, 3457 (1964) [Sov. Phys.-Solid State 6, 2763 (1965)].
[2] D.L. White, J. Appl. Phys. 33, 2547 (1962).