Bound plasmon-phonon surface states on the interface between a semiconductor and a dielectric

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(Submitted April 30, 1973)
Zh. Eksp. Teor. Fiz. 65, 2280–2281 (December 1973)

It is shown that mixed plasmon-phonon surface states can exist on the interface between a semiconductor and an ionic dielectric. The energies of these states are calculated in the long-wave approximation for the case of a junction between a diatomic dielectric and a semiconductor. A new method of experimentally determining the concentration of the free carriers of the semiconductor is proposed.

Mixed states of surface optical phonons and plasmons on the interface between a polar semiconductor and vacuum were recently predicted theoretically[1] and observed experimentally[2].

Semiconductors are unique in that the plasma frequencies $\omega_p = (4\pi ne^2/m_*)^{1/2}$ of the free charges in them (n, m_*, and e are the concentration, effective mass, and charge of the conduction electrons) can be, unlike in metals, where $\omega_p \sim 10^{16}$ sec^{-1}, of the same order as the characteristic phonon frequencies, which usually lie in the infrared region. Thus, in the n-InSb samples investigated in[2], with carrier densities $n \sim 10^{16} - 10^{18}$ cm^{-3}, the corresponding plasma frequencies ranged from 10^{13} to 10^{14} sec^{-1}. It is therefore feasible in principle to observe effects connected with mixing of phonon and plasmon modes of a semiconductor.

An entirely different effect takes place if the semiconductor is in contact with an ionic dielectric. In this case, the frequency dispersion in the medium that bounds the semiconductor becomes important, and the surface plasmons of the semiconductor become coupled with the surface optical phonons of the dielectric.

We consider two plates, a semiconductor and a dielectric, in contact with each other, and obtain the frequencies of the modes localized near the interface. According to[3], these frequencies are determined by solving the equation

$$\frac{1}{\varepsilon_s(\omega)}\left[q_\parallel^2-\varepsilon_s(\omega)\frac{\omega^2}{c^2}\right]^{1/2}=-\frac{1}{\varepsilon_d(\omega)}\left[q_\parallel^2-\varepsilon_d(\omega)\frac{\omega^2}{c^2}\right]^{1/2}, \quad (1)$$

where $q_\parallel$ is the two-dimensional wave vector in the plane of the plate (it is assumed that $q_\parallel$ greatly exceeds the reciprocal plate thicknesses, for otherwise the influence of the external boundaries would come into play, but is much less than the reciprocal interatomic distances); $\epsilon_s(\omega)$ and $\epsilon_d(\omega)$ are the dielectric constants of the semiconductor and of the dielectric, neglecting spatial dispersion. Thus, for the contribution of the free carriers to $\epsilon_s(\omega)$, the latter is possible at $\omega \gg q_\parallel v_T$ (v_T is the thermal velocity of the carriers), a condition satisfied in the infrared region even at room temperature up to $q_\parallel \sim a^{-1}$, where a is the lattice constant of the semiconductor.

For simplicity, we neglect the delay in (1), taking $q_\parallel \gg \omega/c$, and assume that the frequency dispersion of the lattice part of $\epsilon_s(\omega)$ can be neglected (for example, for a monatomic semiconductor). The dielectric constant of the semiconductor can then be written in the form

$$\varepsilon_s(\omega)=\varepsilon_s^\infty-\omega_p^2/\omega(\omega+i\tau^{-1}), \quad (2)$$

where τ is the relaxation time and ϵ_s^∞ is the dielectric constant of the semiconductor at frequencies greatly exceeding the plasma frequencies.

We use the usual expression for the dielectric constant of an ionic dielectric (we consider a diatomic dielectric and neglect damping and anisotropy):

$$\varepsilon_d(\omega)=\varepsilon_d^\infty(\omega^2-\omega_l^2)/(\omega^2-\omega_t^2), \quad (3)$$

where ω_l and ω_t are the frequencies of the longitudinal and transverse optical phonons of the dielectric, and ϵ_d^∞ takes into account the deformability of the ions. Then, in the limit $\omega\tau \gg 1$, we obtain from (1)–(3) two modes of coupled plasmon-phonon surface oscillations:

$$\omega_{1,2}^2=[\varepsilon_d^\infty\omega_l^2+\varepsilon_s^\infty\omega_t^2+\omega_p^2\pm\{[\varepsilon_d^\infty\omega_l^2+\varepsilon_s^\infty\omega_t^2+\omega_p^2]^2 - 4(\varepsilon_d^\infty+\varepsilon_s^\infty)\omega_t^2\omega_p^2\}^{1/2}]/2(\varepsilon_d^\infty+\varepsilon_s^\infty) \quad (4)$$

with a width on the order of τ^{-1}. The last expression covers the limiting cases of a metal ($\omega_p \gg \omega_t$) and of a nonpolar dielectric ($\omega_p \ll \omega_t$).

As seen from (4), the frequencies of the surface modes in the dielectric depend on the densities and the effective masses of the carriers, so that these quantities can be measured (for example, in cases when direct measurements are impossible) by determining the frequencies of the surface optical oscillations in a dielectric plate in contact with a semiconductor.

The author thanks V. M. Galitskiĭ and R. O. Zaĭtsev for useful discussions of the work.

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Translated by J. G. Adashko
236