Surface acoustic plasmons at a *p-n* junction

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A quasilongitudinal surface wave can propagate along the interface between two conducting media in which the current carriers have very different effective masses. In contrast with the familiar collective branch in the spectrum of a two-component plasma—the acoustic plasmon—this new branch has an unusual dispersion, which is proportional to the square root of the wave vector. This wave can be observed at a *p-n* junction or at a metal-semiconductor junction.

Pinczuk *et al.*[1] have recently reported observing a low-frequency plasma wave—an acoustic plasmon—in a semiconductor plasma. This volume collective branch of the wave spectrum of a two-component solid-state plasma, in principle a well-known branch,[2] had not previously been seen experimentally. This wave has a linear dispersion law and a slight Landau damping. The damping is slight because the difference in effective masses puts the phase velocity of the wave between the Fermi velocities of the two carrier groups. That a wave can propagate in the volume of a two-component plasma also implies that the medium is homogeneous.

In this letter we consider the very inhomogeneous situation in which two components with different masses—electrons and holes, for example—are spatially separated. The situation arises at a *p-n* junction or at a metal-semiconductor junction. In this

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case we find that a surface wave can propagate with an electric field which decays over distance on either side of the interface. The physical reason for the propagation of a surface wave is that the dielectric function in a medium with heavy carriers is negative in the corresponding frequency range, while in a medium with light carriers the electric field of the wave is a static field screened by the Coulomb interaction of the light carriers. The surface wave has an unusal dispersion which distinguishes it from an acoustic plasmon. The presence of the interface does not impose any important restrictions on the conditions for the existence of the wave.

Let us consider the propagation of a surface electrostatic wave at the interface between two conducting media, which we specify by the indices "p" and "n." The x axis runs along the normal to the interface, and the z axis is along the direction of the wave vector **k**.

In the quasistatic limit, the equations determining the electric field of the wave in both media are

$$\operatorname{div} \mathbf{D} = 0 \text{ and } \operatorname{rot} \mathbf{E} = 0. \tag{1}$$

We expand the electric displacement and the electric field in these equations in a Fourier integral, using

$$D_x^n(x) = \int_0^\infty D_x^n(k_x) \sin k_x x \, dk_x, \quad D_x^p(x) = \int_{-\infty}^0 D_x^p(k_x) \sin k_x x \, dk_x,$$

$$D_z^n(x) = \int_0^\infty D_z^n(k_x) \cos k_x x \, dk_x, \quad D_z^p(x) = \int_{-\infty}^0 D_z^p(k_x) \cos k_x x \, dk_x.$$

The solution of the boundary-value problem for the field in both media is

$$E_z^n(0) = \frac{2}{\pi i} D_x^n(0) \int_0^\infty k_z \, dk_x / k^2 \epsilon_n(\omega, \mathbf{k}), \tag{2}$$

$$E_z^p(0) = -\frac{2}{\pi i} D_x^p(0) \int_0^\infty k_z dk_x / k^2 \epsilon_p(\omega, \mathbf{k}), \tag{3}$$

where $\epsilon_{n,p}$ are the dielectric functions of the media.

As usual, the boundary conditions are that the normal component of the electric displacement and the tangential components of the electric field are continuous. Using these boundary conditions, we find the dispersion relation for the surface wave to be

$$\int_0^\infty \frac{dq}{1+q^2} (\epsilon_n^{-1}(\omega, k_z, q) + \epsilon_p^{-1}(\omega, k_z, q)) = 0. \tag{4}$$

[Equation (4) is a generalization of the dispersion relation for surface plasmons at a sharp conductor-vacuum interface (see Ref. 3, for example) to the case of an inhomogeneous two-component medium.]

At frequencies $v_p < \omega/k < v_n$, where $v_{p,n}$ are the Fermi velocities (or thermal velocities) of the carriers, the condition of weak spatial dispersion holds for the p component, while the condition of strong spatial component holds for the n component:

$$\mathrm{Re}\,\epsilon_p = 1 - \omega_{pp}^2/\omega^2, \quad \mathrm{Re}\,\epsilon_n = 1 + k_{Dn}^2/k^2.$$

(Here ω_{pp} is the plasma freuqency of the heavy carriers, and k_{Dn}^{-1} is the Debye length of the light carriers.)

Substituting these expressions into (4), we find the following result for frequencies $\omega \ll \omega_{pp}$ and wave vectors $k \ll k_{Dn}$:

$$\omega = \omega_{pp}(k_z/k_{Dn})^{1/2}. \tag{5}$$

For comparison, the dispersion law of the volume acoustic plasmon is

$$\omega = \omega_{pp} k/k_{Dn}. \tag{6}$$

The dispersion of the surface wave is thus proportional to the square root of the wave vector, in contrast with the case for volume acoustic plasmons. We wish to call attention to a similarity with the dispersion law for plasma waves in a 2D electron gas,[4] which is caused by an effective lowering of the dimensionality of the phase space of the wave.

The dissipation of the energy of the surface wave, as in an unbounded medium, is determined by the Landau damping of the more mobile component. Working from the expression for the imaginary part of the dielectric function,

$$\mathrm{Im}\,\epsilon_n = \frac{\pi}{2}\frac{k_{Dn}^2\,\omega}{k^3 v_n},$$

we find

$$\mathrm{Im}\,\omega = -\frac{\pi}{8}\frac{\omega_{pp}^2}{k_{Dn}v_n} \sim \omega_{pp}\frac{v_p}{v_n}. \tag{7}$$

The wave damping is slight, as in the case of an acoustic plasmon, because of the difference between the Fermi velocities of the two carrier groups.

Let us examine the differences between the conditions for the existence of volume and the surface waves. Comparison of dispersion laws (5) and (6) shows that the frequency of the surface wave is slightly higher than that of the volume wave. Another difference follows from the requirement that the damping be small in comparison with the dispersion. While the Landau condition $kv_n > \omega$ holds automatically for the volume wave because of the difference between the Fermi velocities of the carriers, for the surface wave this criterion leads to an additional lower limit on the wave vector,

$$k \gg k_{Dn}(v_p/v_n)^2, \tag{8}$$

and thereby slightly narrows the region in which the wave exists.

We thus conclude that the surface wave can be observed in a variety of situations in which the necessary condition of different effective carrier masses is satisfied. As suitable systems we might cite p-n junctions in InSb ($m_n = 0.013m_0$, $m_p = 0.2m_0$), Si ($m_n = 0.123m_0$, $m_p = 0.523m_0$), and GaAs, which was used in Ref. 1 to observe the body wave.

The surface wave can be observed by measuring the reflection of a laser beam (in the same way that the body wave can be observed), or it can be observed by the method of attenuated total reflection, which is the method ordinarily used for surface plasmons.[5]

There is also the possibility that a surface wave might be amplified by the drift of light carriers at a drift velocity v_d greater than the wave phase velocity, $kv_d > \omega$. The growth rate of the surface wave would be

$$\frac{\pi}{8}\frac{v_d}{v_n}\left(\frac{k}{k_{Dn}}\right)^{1/2}\omega_{pp} \tag{9}$$

In this paper we have considered a sharp interface, which corresponds best to a metal-semiconductor junction. For a contact between two semiconductors it would be more realistic to expect a boundary which is not sharp, in which case we could expect some substantial changes in the dispersion and damping of surface waves.[6]

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