Total transmission of electromagnetic waves and homogeneous plasma resonance of 2D electron gas in thin semiconductor film

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(Submitted 24 October 1990)

Pis'ma Zh. Eksp. Teor. Fiz. **53**, No. 3, 143–147 (10 February 1991)

The existence of a slightly dispersed homogeneous plasma (magnetoplasma) oscillations of a two-dimensional electron gas in a semiconductor layer with a large dielectric constant is predicted for the first time. The reflectivity of the film decreases rapidly and the dispersion law of nonradiative 2D plasmons changes near the resonance frequency with such collective oscillations of the 2D electron gas. The possible use of the resonance for a low-frequency 2D-electron-gas spectroscopy in the GaAs/AlGaAs heterojunctions is discussed.

The spectrum of the collective vibrations (plasmons) of a collisionless 2D plasma, in contrast with a 3*D* plasma, in the absence of magnetic field is a gapless spectrum which has a characteristic dispersion[1,2] $\omega^2 \propto k$. Because of their nonradiative nature, 2D plasmons can be excited by an external electromagnetic wave only in a periodically excited 2D electron gas—either in a structure with a static superlattice (a grating—see, for example, Ref. 3) or in a solid-state semiconductor which surrounds the 2D electron gas during the propagation of a (surface) acoustic wave which quasistatically modulates the reflectivity of the structure. These features of the spectrum of 2D plasmons manifest themselves as they propagate in an unbounded or screened system. In the present letter, we show that when a 2D electron gas is present in the semiconductor film with a large dielectric constant $\epsilon \gg 1$, the spectrum of its low-frequency plasma vibrations is greatly modified. In particular, at $k_x = 0$ it exhibits a slightly damped resonance at a frequency $\omega_0 = [4\pi n_S e^2/(m^* \epsilon d)]^{1/2}$, where n_S and m^* are the 2D density and effective mass of the carriers of the 2D electron gas, and d is the film thickness. A total resonance transmission of an electromagnetic wave through an optically dense layer occurs at such a frequency: the reflection coefficient r tends to zero and the transmission coefficient t tends to unity (in the case of a transparent medium). In contrast with a total transmission of an electromagnetic wave with a p polarization through an inhomogeneous plasma layer or through a plasma-like medium when surface waves are excited in it,[4,5] the total transmission described above occurs in the case of p and s polarizations of the incident electromagnetic wave. This effect can be used for the spectroscopy of 2D electron gas in heterojunctions based on GaAs/AlGaAs, since $\epsilon \approx 12$ in such compounds.

1. Let us consider the reflection of an s-polarized electromagnetic wave incident from a vacuum at an angle θ on a layer with a dielectric constant $\epsilon > 1$, whose leading edge has a 2D electron gas with a 2D conductivity $\sigma(\omega) \equiv \sigma_{xx}(\omega) = \sigma_{yy}(\omega)$. If $\omega d\,[\epsilon - \sin^2\theta\,]^{1/2}/c \ll 1$, we can then derive the following expression for the ratio of the amplitudes of the reflected and incident waves:

$$r = \frac{i(\epsilon - 1)\omega d - 4\pi\sigma\left(1 - i\cos\theta\frac{\omega d}{c}\right)}{2c\cos\theta - i\omega d(\epsilon - 1 + 2\cos^2\theta) + 4\pi\sigma\left(1 - i\cos\theta\frac{\omega d}{c}\right)}. \tag{1}$$

If $\omega d/c \ll 1$, it follows from Eq. (1) that for a collisionless 2D electron gas $(\omega\tau \gg 1)$ with a dynamic conductivity $\sigma(\omega) = in_S e^2/(m^*\omega)$ the reflection from the structure under consideration tends to zero (while the transmission t tends to unity) at the frequency

$$\omega_0 = \left[\frac{4\pi n_S e^2}{m^* d(\epsilon - 1)}\right]^{1/2}. \tag{2}$$

If the thickness of the layer with a large dielectric constant in this case satisfies the conditions

$$\frac{1}{\epsilon} \ll \frac{\omega_0 d}{c} \ll \frac{1}{\sqrt{\epsilon}}, \tag{3}$$

the reflection coefficient of light in the absence of 2D electron gas [or away from the resonance frequency (2)] is approximately equal to unity (see Ref. 6); i.e., a 2D electron gas renders a totally reflecting layer completely transparent at resonance. At higher frequencies ω_n a high transparency of the layer is attributable to the dimensional (interference) resonances:[7] $\omega_n = \pi cn/[d(\epsilon)^{1/2}] \gg \omega_0$ $(n = 1,2,...)$.

It can be shown that at $\omega_0 d \ll c$ the total transmission frequency (2) does not depend on the position of the 2D electron gas in the dielectric layer. In the presence of a 2D electron gas the layer acquires an effective anisotropic dielectric constant at low frequencies, $\epsilon^*_{\parallel} \equiv \epsilon^*_{xx} = \epsilon^*_{yy}$, $\epsilon^*_{\perp} \equiv \epsilon^*_{xx}$:

$$\epsilon^*_{\parallel} = \epsilon - \frac{4\pi n_S e^2}{m^* d\omega^2}, \qquad \epsilon^*_{\perp} = \epsilon. \tag{4}$$

The resonance (2) of the total transmission in this case corresponds to a frequency at which the effective longitudinal susceptibility of the layer vanishes ($\epsilon^*_{\parallel} = 1$). If the electromagnetic wave interacts with the semiconductor layer (with $\epsilon > 1$), which contains a superlattice consisting of N parallel 2D channels, then the parameters σ and

n_S in expressions (1), (2), (4), and (6) should be replaced by $N\sigma$ and Nn_S. For a 2D electron gas in a thin film of a semiconductor heterojunction based on a GaAs/AlGaAs ($n_S 10^{12}$ cm^{-2}, $m^* \approx 10^{-28}$ g, $\epsilon \approx 10$, and $d \approx 10^{-2}$ cm) we have $\omega_0 \approx 10^{11}$–10^{12} s^{-1} if conditions (3) are satisfied.

2. Let us consider a spectrum of the normal modes of a 2D electron gas in a layer with a large dielectric constant which can be determined, for example, from the poles of the reflections of the s and p waves for an imaginary incidence angle θ (see Ref. 7). We can show that in the limit $\omega d(\epsilon - c^2k_x^2/\omega^2)^{1/2}/c \ll 1$ this spectrum coincides with the spectrum of long-wavelength waveguide modes ($k_x d \ll 1$) which propagate in a vacuum along the layer with an anisotropic dielectric constant $\epsilon^*_{ik}(\omega)$ [Eq. (4)] (see Ref. 8, k_x is the wave number of the surface wave). At frequencies $\omega \ll \omega_0$ [Eq. (2)], for example, the dispersion relation of nonradiative 2D plasmons ($k_x \gg \omega/c$) is the same as that in the absence of a dielectric layer: $\omega_1^2(k_x) = 2\pi n_S e^2 k_x/m^*$ (see curve 1 in Fig. 1). At a frequency ω_0 the dispersion relation for nonradiative plasmons, when $1/\epsilon \ll k_x d \ll 1$, has a slightly dispersing region $\omega \approx \omega_0$, and at $k_x = 0$ the structure exhibits a collective resonance, whose frequency satisfies the equation

$$\omega^2 + i\frac{2\omega c}{d\epsilon} - \frac{4\pi n_S e^2}{m^* d\epsilon} = 0. \tag{5}$$

It follows from (5) that if conditions (3) are satisfied, the uniform plasma vibrations of a 2D electron gas in a film with a large dielectric constant are slightly damped and ω_0 coincides with the frequency of the bulk plasma vibrations in the film with a uniformly "smeared" 2D electron gas. At frequencies $\omega \gg \omega_0$ the dispersion relation for nonradiative 2D plasmons is the same as that for boundless medium with a dielectric constant ϵ: $\omega_2^2(k_x) = 2\pi n_S e^2 k_x/(m^*\epsilon) \ll \omega_1^2(k_x)$ (curve 2 in Fig. 1). In the frequency region $\omega > \omega_0$, when $\epsilon^*_\parallel(\omega) > 1$, a slightly dispersed surface electromagnetic wave ($\omega \approx ck_x$) with an s polarization (surface s polariton), whose spectrum is deter-

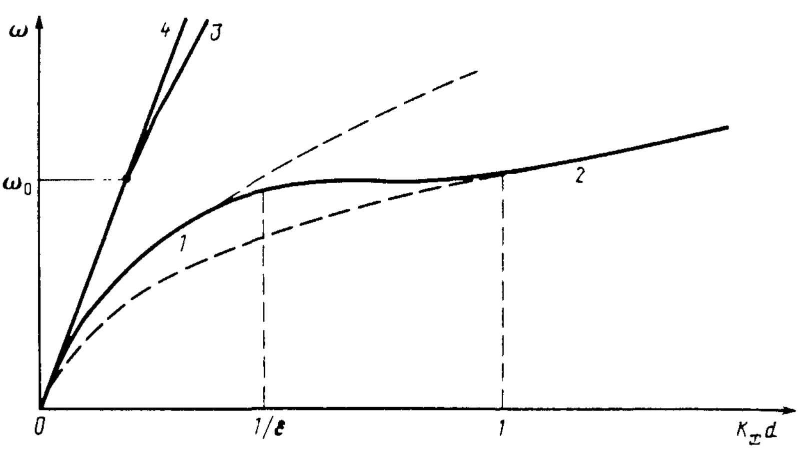

FIG. 1. $\omega(k_x d)$ Spectrum of low-frequency electromagnetic normal modes of a thin dielectric layer with $\epsilon \gg 1$ in a vacuum, which contains a collisionless 2D electron gas.

mined from the dispersion relation $(k_x^2 - \omega^2/c^2)^{1/2} = d/2(\epsilon_\parallel^* \omega^2 (c^2 - k_x^2) > 0$ (curve 3 in Fig. 1), can also propagate in the system. In addition, as in the case of the distribution of 2D electron gas in the bulk of the dielectric crystal,[8] a slightly dispersive surface p polariton, whose spectrum is determined from the equation $(k_x^2 - \omega^2/c^2)^{1/2} = d/2(\omega^2/c^2 - k_x^2/\epsilon_\perp^*) > 0$, can propagate in the entire frequency range in the layered structure (line 4 in Fig. 1).

3. If the conditions for the quantum Hall effect hold in the 2D electron gas (or in its superlattice) in a semiconductor film in a magnetic field (when $|\sigma_{xy}| \gg \sigma_{xx}$), the total resonance transmission of a circularly polarized electromagnetic wave through the film will occur at a frequency $\omega_0 = 4\pi|\sigma_{xy}|/(\epsilon d) \ll \omega_c$ and at $k_x = 0$ a slightly dispersed magnetoplasma resonance, whose frequency satisfies the equation such as (5), appears in the structure:

$$\omega^2 + i\frac{4\omega c}{\epsilon d} - \left(\frac{4\pi\sigma_{xy}}{\epsilon d}\right)^2 = 0. \tag{6}$$

The collective magnetoplasma oscillations (6) of N conducting channels in the film with a large dielectric constant ϵ are slightly damped oscillations if $1 \ll 4\pi N|\sigma_{xy}|/c \ll \sqrt{\epsilon}$. The spectrum of surface nonradiative s polaritons for $1/\epsilon \ll k_x d \ll 1$ in this case has a slightly dispersed region $\omega \approx \omega_0$ (see also Ref. 9).

4. When an electromagnetic wave is incident at a total external reflection angle $\sin^2\theta_r = \epsilon$ on a transparent dielectric layer with $\epsilon < 1$ and thickness $\cos\theta_r d \gg c/\omega$, it is completely reflected ($r \approx 1$, $t \approx 0$) from the bulk layer. As follows from (1) and from further analysis, the 2D electron gas situated at the front of the layer can, however, lead to a total cessation of the reflection ($r \approx 0$, $t \approx 0$) and to a total absorption ($P \equiv 1 - |r|^2 - |t|^2 \approx 1$) of the s-polarized electromagnetic wave if $(1-\epsilon)^{1/2} = 4\pi\sigma/c < 1$ (in the dissipative regime $\omega\tau \ll 1$ when $\sigma' \gg \sigma''$). If a p-polarized wave is incident on a dielectric layer of arbitrary thickness with $\epsilon = 0$, its total nonreflection and absorption of 2D electron gas by the layer at the front side occur at an incidence at such an angle θ, where $\cos\theta = c/(4\pi\sigma) < 1$. In each case, the total nonreflection occurs in the case of resonant interaction of the incident wave with the surface leakage wave which propagates along the 2D electron gas at the interfaces with the phase velocity which exceeds the speed of light in a vacuum. The velocity of the s-polarized leakage wave is $v_s = c/[1 - (4\pi\sigma/c)^2]^{1/2}$, and that of p-polarized wave is $v_p = c/[1 - (c/4\pi\sigma)^2]^{1/2}$. Near the exciton resonances in a semiconductor film with a frequency-dependent dielectric constant[10] $\epsilon(\omega)$, the 2D electron gas can thus lead to a sharp decrease of the film's reflectivity and to an increase in the absorption of incident electromagnetic radiation of one of the polarizations—as a function of the value of the ratio $4\pi\sigma/c$.

I wish to thank M. I. Kaganov and B. P. Orlov for useful discussions.

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Translated by S. J. Amoretty