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Plasma dispersion in a layered electron gas: A determination in GaAs-(AlGa)As heterostructures

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The dispersion of the plasma frequency of layered electron gases in GaAs-(AlGa)As heterostructures was determined by inelastic light scattering. The measured dispersions differ from that in two- and three-dimensional plasmas. They are *linear* in the in-plane component of the wave vector. This observation confirms predictions of theoretical models.

The collective behavior in electron plasmas of lower dimensionality is quite different from that in three-dimensional (3D) systems. The differences occur because the electric fields remain 3D while the induced charge densities have reduced dimensionality. In this Communication we report a determination of the plasma frequency dispersion in layered electron gases that occur in multiple GaAs-(AlGa)As heterostructures. For the first time in a layered electron system, we observed a dispersion relation that is different from that in 3D and 2D plasmas. The measurements, carried out by inelastic light scattering, show a *linear* dispersion over a wide range of in-plane component of the wave vector. These results confirm predictions of the electrodynamics of layered electron plasmas.

In a layered electron gas, the free charges are constrained to move on parallel planes spaced by a distance d. This model system was introduced to describe dielectric screening[1] and the electrodynamics of layered solid-state plasmas,[2–5] including free electrons in semiconductor superlattices.[6,7] The plasma frequency is predicted to be[3,4,6,7]

$$\omega_p = \left[\frac{2\pi n e^2}{\epsilon_M m^*} k_\parallel \frac{\sinh k_\parallel d}{\cosh k_\parallel d - \cos k_\perp d}\right]^{1/2} , \qquad (1)$$

where n is the areal electron density in each plane, m^* the electron effective mass, and ϵ_M is the dielectric function of the medium supporting the planes. $k_\parallel$ and $k_\perp$ are the in-plane and normal components of wave vector. Equation (1) exemplifies the transition behavior between regimes of different dimensionality. For large separation between the planes ($k_\parallel d >> 1$) the dispersion reduces to that of a 2D plasma with the characteristic square-root dependence.[8] For long in-plane wavelengths ($k_\parallel d << 1$) and with all the planes oscillating in phase ($k_\perp = 0$), the dispersion is similar to that of a 3D system.[9] However, when $k_\perp \neq 0$ the contributions from induced electric fields in different planes tend to cancel.[3] Then, Eq. (1) takes the distinctive *linear* dependence[3,4,6]

$$\omega_p = k_\parallel \left[\frac{2\pi n e^2}{\epsilon_M m^*} \frac{d}{1-\cos k_\perp d}\right]^{1/2} . \qquad (2)$$

In this regime ($k_\parallel d << 1$ and $k_\perp \neq 0$) the calculated response is most different from that in 2D and 3D plasmas.

Until the present work, there has been no experimental test of these predictions. Previous studies in layered electron systems (intercalated graphite) by means of electron energy-loss spectroscopy showed a 3D-like plasma dispersion.[10] Plasma frequency dispersions have been also measured in the case of electrons on the surface of liquid He (Ref. 11) and in silicon inversion layers.[12] In the former a 2D dispersion was determined, with the characteristic square-root dependence.[11] In the case of the silicon inversion layer, the measurements probed the wave-vector range in which the dispersion also shows a square-root dependence.[12]

The GaAs-(Al_xGa_{1-x})As multiple-quantum-well heterostructures were grown by molecular-beam epitaxy on GaAs (001) substrates, and modulation doped with Si donors.[13] Their structure is shown schematically in Fig. 1(a). The electrons that vacated the donor impurities in the (AlGa)As layers (of widths d_2) become confined in the GaAs layers (of widths d_1), where they occupy lower-energy states in two-dimensional subbands.[14] These are the charges that constitute the layered electron gas with extremely high mobility, in excess of 5×10^4 cm^2/V sec. We present here data from two samples. Sample 1 consists of 20 periods with $d_1 = 262$ Å, $d_2 = 628$ Å, total thickness $L = 1.78$ μm, $x = 0.20$, and $n = 7.3 \times 10^{11}$ cm^{-2}. Sample 2 has 15 periods with $d_1 = 245$ Å, $d_2 = 258$ Å, $L = 1.24$ μm, $x = 0.11$, and $n = 5.5 \times 10^{11}$ cm^{-2}.

Low-temperature ($T \approx 10$ K) light scattering spec-

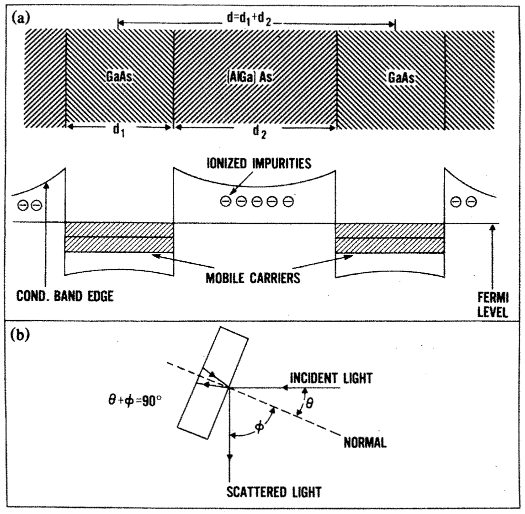

FIG. 1. (a) Sequence of the layers and profile of the conduction-band edge in the modulation doped GaAs-(AlGa)As heterostructures. (b) Scattering geometry adopted to perform the experiment. The components of the scattering wave vectors are given by Eqs. (3) and (4).

tra were excited with an Oxazine 750 dye laser operating between 7800 and 7850 Å.[15] Figure 1(b) displays the backscatteringlike geometry adopted to perform the experiment. θ and ϕ are the angles between the normal to the surface of the sample and the propagation directions of the incident and scattered photons outside the sample. They were chosen so that $\theta+\phi=90°$. The components of the scattering wave vector are thus given by

$$k_{\parallel}=\frac{2\pi}{\lambda}(\sin\theta-\cos\theta) \tag{3}$$

and

$$k_{\perp}\cong\frac{4\pi}{\lambda}\eta\left(1-\frac{1}{4\eta^2}\right) , \tag{4}$$

where λ is the wavelength of the incident laser light and η corresponds to the wavelength-dependent refractive index. By changing θ from 45° to 0°, $k_{\parallel}$ can be varied from a small value up to a maximum of $\sim 8\times10^4$ cm^{-1}, which satisfy the condition $k_{\parallel}d<1$ in samples 1 and 2. For $\eta\approx3.6$, $k_{\perp}$ has a large value of $\sim5.5\times10^5$ cm^{-1} and does not depend significantly on θ. Therefore, $k_{\perp}d$ is a well-defined parameter. By means of this geometry, we are able to probe the wave-vector range ($k_{\parallel}d<1$ and $k_{\perp}\neq0$) in which layering effects dominate. The (AlGa)As layers are transparent to the laser photons. The absorption length α^{-1} in the GaAs layers is $\sim0.6\mu$m, and consequently all the quantum wells are excited. The condition $k_{\perp}L>>1$ holds, and the electrons should respond as if they were in an infinite array of planes.

Figure 2(a) shows results from sample 1. The spectra display a low-energy peak at 3.5 meV and two bands labeled E_{01} and $E_{0\bar{1}}$. Spectra from sample 2 show equivalent features. For Stokes shifts larger than 20 meV, the high-energy tail of the luminescence across the direct gap of the GaAs layers dominates the spectra. The E_{01} and $E_{0\bar{1}}$ bands are similar to those reported in previous light scattering work.[14] They are associated with single-particle (E_{01}), and collective ($E_{0\bar{1}}$) intersubband excitations of the electrons confined in the GaAs layers. The low-energy band has not been reported before. The most remarkable feature is that its position depends strongly on the angle θ, as can be seen in Fig. 2(b). With increasing θ [decreasing $k_{\parallel}$ according with Eq. (3)] the band shifts to lower energies. For θ larger than 35° it is obscured under the tail of the laser line and can no longer be observed. The lines shown in Fig. 2(b) are present only in polarized spectra, where incident and scattered light polarizations are parallel.

The peak positions of the low-energy line are plotted as a function of $k_{\parallel}$ in Fig. 3. Besides the dependence on $k_{\parallel}$, we see that the energies also depend on

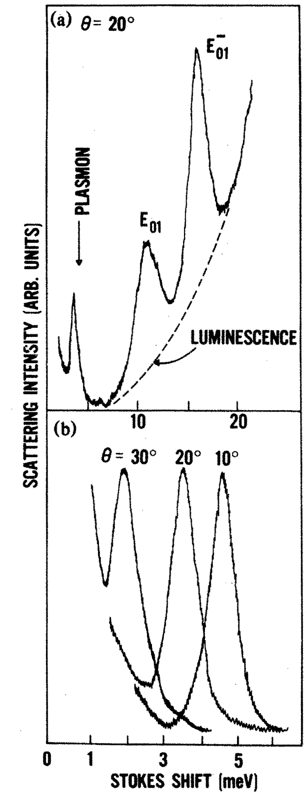

FIG. 2. (a) Typical light scattering spectra from sample 1. The low-energy band is the layered electron gas plasmon. (b) Plasmon lines of the layered electron gas for different angles θ. With increasing θ (decreasing $k_{\parallel}$) the plasmon band shifts to lower energies.

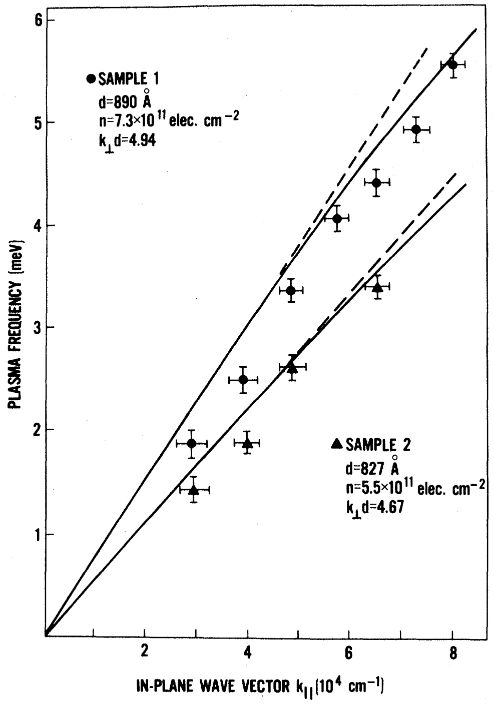

FIG. 3. Dispersion relations of the plasma frequency of the layered electron gas in the two samples. The solid lines represent the calculated dispersions with Eq. (1). The dashed lines are evaluations of Eq. (2).

the electron density. This evidence leads us to assign the new low-energy lines to the plasma oscillations of the layered electron gas. The assignment is consistent with the polarization selection rules we measure, which apply to light scattering by collective excitations via the charge-density fluctuations.[16]

Figure 3 shows that there is a linear relation between the measured plasma energies and $k_{\parallel}$, in qualitative agreement with the dispersion predicted by the theory. We give below a quantitative interpretation of the data on the basis of Eqs. (1) and (2). In taking this approach, we are implicitly assuming that the GaAs layers can be considered extremely thin; and we are also ignoring tunneling effects. These approximations, justified because $k_{\parallel}d_1 << 1$ and $d_2 \approx 600$ Å, also lead us to take $d = d_1 + d_2$. In addition, the plasma oscillations are screened by the polar optical phonons that occur at higher energies. This effect is included in ϵ_M. We shall not consider here nonresonant interactions with intersubband excitations. They are beyond the scope of existing theoretical models and are anticipated to be small. We note that intersubband excitations create very small in-plane components of macroscopic electric field when $k_{\parallel}d_1 << 1$.

In the evaluations of Eqs. (1) and (2), we set $m^* = 0.07m_0$; and $\epsilon_M = 13.1$, the static dielectric constant of GaAs. $k_{\perp}$ was estimated by using values of η from the current literature.[17] The lines in Fig. 3 represent the calculated plasma dispersions. There is good agreement with experiment. The relatively small differences could be accounted for by the uncertainties in the determination of the sample parameters n, η, and d.

In our experiments $\omega_p > k_{\parallel}v_F$, where v_F is the Fermi velocity of the free carriers. This implies that the plasma oscillations are not subject to Landau damping. The absence of Landau damping suggests that investigations of lifetime effects in these solid-state plasmas are possible. The observed linewidths are related to electron relaxation times and to the spread in $k_{\parallel}$ associated with the finite aperture of the collection optics. The sharpness of the peaks in Fig. 2(b), are consistent with the high-electron mobilities in the samples.

The linear dispersion of ω_p on $k_{\parallel}$ resembles that of an acoustic mode. Acoustic oscillations of 3D plasmas are Landau damped.[18] Undamped acoustic plasma modes have been predicted for two-component 2D systems.[19]

In conclusion, we have observed a *linear* dispersion relation of the plasma frequency in a layered electron gas. Our results confirm that collective electron behavior in GaAs-(AlGa)As heterostructures is well described by the electrodynamics of layered plasma. The observation by inelastic light scattering of the plasma oscillation, and its dependence on $k_{\parallel}$, exemplifies a new approach to study elementary excitations related with the in-plane degrees of freedom in semiconductor heterostructures.

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