Direct manifestation of the Fermi pressure in a two-dimensional electron system

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We have measured the dispersion of magnetoplasmons in high-density InAs/GaSb quantum wells. At zero magnetic field we find an offset $\frac{3}{4}v_F^2q^2$ (q is the plasmon wave vector, v_F is the Fermi velocity) with respect to the local plasmon frequency which is a direct manifestation of the Fermi pressure in a two-dimensional electron system. [S0163-1829(96)06136-X]

A real electron system has an inherent compressibility, the so-called Fermi pressure. In a three-dimensional electron system (3DES) it manifests itself in a dispersive plasmon frequency

$$\omega_P^2=\omega_{\rm PL}^2+\tfrac{3}{5}v_F^2q^2, \qquad (1)$$

where $\omega_{\rm PL}^2=N_Ve^2/\epsilon_0m^*$ is the local plasmon frequency, N_V the 3D density, m^* the effective mass, v_F the Fermi velocity, and q the plasmon wave vector. This well-known approximation can be achieved from a lowest-order expansion in q for the polarization propagator, and is equivalent to the hydrodynamic approach. The $v_F^2q^2$ term leads to a nonlocal dielectric response, thus associated effects are often called ''nonlocal'' effects. The dispersion [Eq. (1)] has been well verified in energy-loss spectroscopy (see, e.g., Ref. 1 for a review in this field).

For a 2DES within the same approximation,[2] one obtains

$$\omega_P^2(q)=\omega_{\rm PL}^2+\tfrac{3}{4}v_F^2q^2=\omega_{\rm PL}^2(1+\tfrac{3}{4}a_0^*q), \qquad (2)$$

where

$$\omega_{\rm PL}^2=\frac{N_se^2}{2\overline{\epsilon(\omega,q)}\epsilon_0m^*}q$$

is the ''local'' plasmon frequency, with N_s being the 2D density, $\overline{\epsilon(\omega,q)}$ the effective dielectric function of the surrounding of the 2DES, and $a_0^*=a_0\overline{\epsilon}m_0/m^*$ the effective Bohr radius (for a review on 2D plasmons, see Ref. 3). For a 2DES, it is not so easy to verify the nonlocal effects, because of the small effective Bohr radius, which is for example in modulation-doped $Al_xGa_{1-x}As$-GaAs heterostructures $a_0^*=8.3$ nm. In experiments, $q=2\pi/a$ is usually produced by periodic metal stripe grating couplers (see below) with typical periods $a=800$ nm. Thus the term $\frac{3}{4}a_0^*q=0.05$, which governs the nonlocal effects, is small. Moreover, the dielectric function is normally not known with such an accuracy that this small effect can be measured unambiguously. In addition, in typical $Al_xGa_{1-x}As$-GaAs 2DES the nonlocal effect is partly compensated for due to the finite thickness of the 2DES, as discussed in detail by Batke, Heitmann, and Tu.[4]

In this work, we have studied InAs/GaSb quantum wells with low effective masses $m^*\approx0.04m_0$ and high carrier densities $N_s\approx1\times10^{12}$ cm^{-2}. These samples have the advantages, that (a) nonlocal effects are much stronger than in an $Al_xGa_{1-x}As$-GaAs 2DES [Eq. (2)], and (b) finite-size effects become negligible, as shown below.

In Fig. 1 we calculate the magnetoplasmon dispersion within the nonlocal approach,[5] and compare it with the well-known local dispersion[6]

$$\omega_{\rm MP}^2=\omega_{\rm PL}^2+\omega_c^2, \qquad (3)$$

where $\omega_c=eB/m^*$ is the cyclotron frequency. In the dispersion calculated within the nonlocal approach we see two significant effects. First, the magnetic field produces anticross-

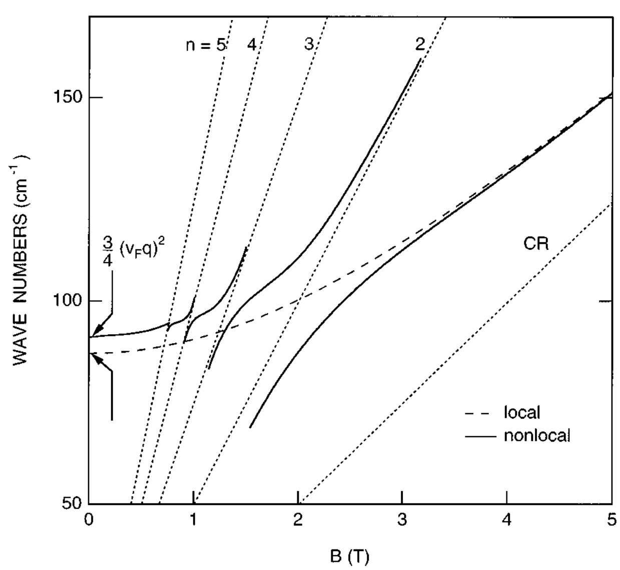

FIG. 1. Nonlocal effects in the magnetoplasmon dispersion. The solid line is the theoretical dispersion, calculated within the nonlocal approach (Ref. 5) for $m^*=0.0376m_0$, $N_s=0.94\times10^{12}$ cm^{-2}, $\overline{\epsilon}=11.75$, and $\tau=10\times10^{-12}$ s. The dashed line is the theoretical dispersion ignoring nonlocal interaction [Eq. (3)]. Cyclotron resonance (CR) and their harmonics $n=2,3,\ldots$ are shown as dotted lines.

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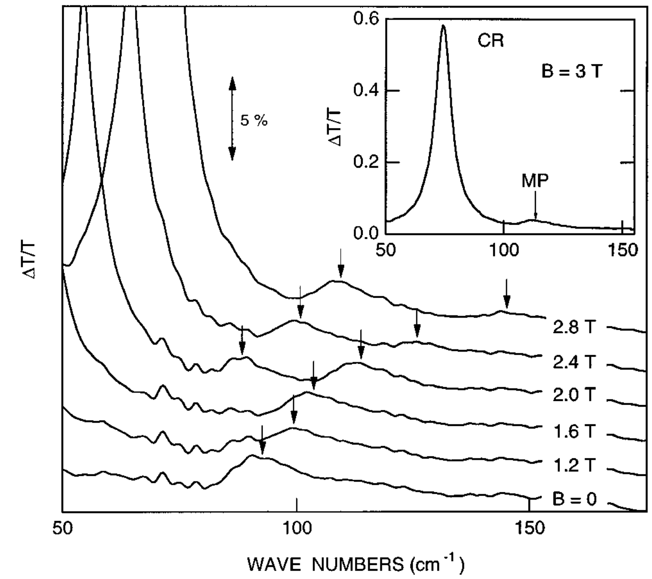

FIG. 2. Relative change of transmission for various magnetic-field strengths. Resonance positions of magnetoplasmons are marked by arrows. For clarity, the traces have been successively shifted upwards. The inset shows the full cyclotron resonance (CR) signal and the magnetoplasmon (MP) at 3 T.

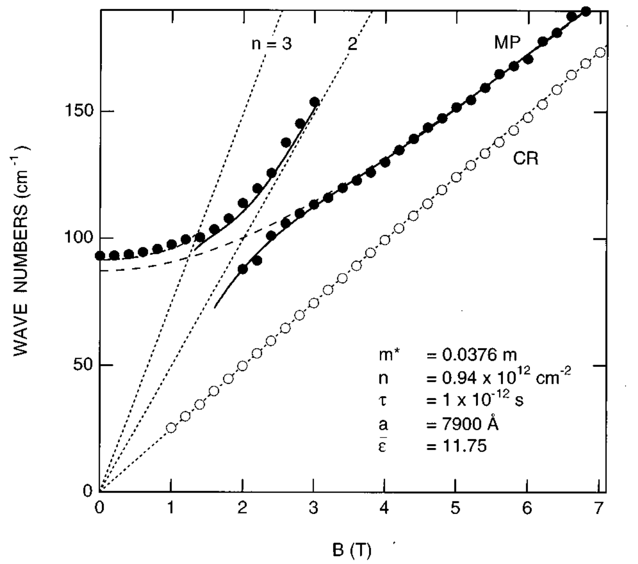

FIG. 3. Experimental resonance positions of magnetoplasmon (●) and cyclotron resonances (○). The theoretical dispersions are calculated within the local (dashed) and nonlocal (solid) approaches using the parameters of the experiment: $m^*=0.0376m_0$, $N_s=0.94\times10^{12}$ cm^{-2}, $\overline{\epsilon}=11.75$, and $\tau=1\times10^{-12}$ s. The scattering time is obtained from the linewidth of the CR.

ing with harmonics $n\omega_c$ $(n=2,3,4\ldots)$, the so-called Bernstein modes. This behavior has been verified in very good agreement with theory by Batke and co-workers.[4,7] The second effect is that there is an offset at low magnetic field with respect to the local plasmon dispersion. This offset is caused by the Fermi pressure and is, at zero magnetic field, $\frac{3}{4}v_F^2q^2$. The theoretical curves in Fig. 1 have been calculated for the nominal parameters of our sample. Only the scattering time $\tau=10\times10^{-12}$ s has been chosen about ten times larger than expected from the linewidth of the cyclotron resonance to make splittings clearer. We have performed experiments and can, free of any parameters, reproduce the theoretical curve, in particular the $\frac{3}{4}v_F^2q^2$ offset, and thus directly prove the Fermi pressure.

The samples are InAs quantum wells with GaSb barriers and a grating coupler on top. The quantum-well structures are grown by molecular-beam epitaxy on semi-insulating GaAs, and consist of a 8000-Å GaAs buffer layer, a 8000-Å GaSb bottom barrier, a 200-Å InAs quantum well, and a 200-Å top barrier. All layers are nominally undoped. The quantum-well structure is covered by a 500-Å thin SiO_2, grown with plasma enhanced vapor deposition and a 35-Å NiCr layer. This NiCr layer can be used as a gate electrode to control the electron density in the quantum well. Data presented in this work are taken at zero gate voltage. The grating coupler on top of the NiCr layer consists of 200-Å-thick Ag stripes of 7900-Å periodicity and 4000-Åwidth. All experiments are performed at 2 K in a Bruker Fourier-transform spectrometer with unpolarized far-infrared radiation at normal incidence.

Experimental spectra are plotted in Fig. 2. The figure shows the relative change of transmission $\Delta T/T=1-T(B)/T(B=12\text{ T})$ with an applied perpendicular magnetic field. The amplitude of the cyclotron resonance exceeds 50% due to the grating coupler effect.[8] Resonance positions of the cyclotron resonance and magnetoplasmon as a function of magnetic field are shown in Fig. 3. The slope of the dispersion of the cyclotron resonance corresponds to an effective mass of $m^*=0.0376m_0$. Small deviations from the linear behavior indicate filling-factor-dependent oscillations of the effective mass.[9] From the periodicity of these oscillations, we obtain a 2D density of $N_s=0.94\times10^{12}$ cm^{-2}. The linewidth of the cyclotron resonance also oscillates with the filling factor, namely, with $\Delta\omega_c=(10\pm3)$ cm^{-1}. The averaged linewidth corresponds to a scattering time $\tau=1\times10^{-12}$ s. The experimentally obtained resonance positions are in good agreement with the calculated nonlocal dispersion.[5] A splitting is observed at about 2 T at the crossing with the first harmonic of the cyclotron resonance. The kink at about 1.2 T indicates the interaction with the second harmonic. For magnetic fields higher than 3 T, nonlocal corrections become small.

At low fields the behavior is different. Due to the low effective mass and high electron density in our system, the influence of the nonlocal correction at zero field $(\frac{3}{4}a_0^*q=0.12)$ becomes important. We observe a plasmon frequency at zero field of 93 cm^{-1}, in good agreement with the value of 91.1 cm^{-1} calculated within the nonlocal approach. The deviation of 2% can be explained by the uncertainty in the effective dielectric constant $\overline{\epsilon}$.

In this calculation we use $\overline{\epsilon}=[\epsilon_{GaSb}+\epsilon_{SiO2}\coth(qd)]/2=11.75$, assuming an effective dielectric function in the surrounding of the 2DES dominated by the thick GaSb barriers and the SiO_2 gate oxide, and a distance of $d=700$ Å between the two-dimensional electron gas and the grating coupler. Taking into account the thin InAs layer would slightly decrease the effective dielectric function $(\epsilon_{GaSb}=15.69>\epsilon_{InAs}=15.15)$ and could therefore explain the small deviation in the resonance positions. In addition, we checked the effect of the finite thickness. For this, we performed cyclotron-resonance experiments in tilted magnetic fields. Such experiments allow us to estimate the extent L of the wave function in the growth direction,[10,11] i.e., the finite-size effect[4,12] on the plasmon dispersion. We find that the resonance position follows the so-called $\cos\theta$ law[13] within experimental error. This means that there is an electric field built into the quantum well leading to a more triangular shape of the potential. Qualitatively, we obtained $qL<0.02$, hence we can ignore any finite-size correction. Other corrections like electron correlations and coupling to intraband plasmons lead to errors less than 1%, and are neglected as well.[4] Therefore, we explain the observed zero-field offset between the experimental plasmon frequencies and the theoretical local plasmon dispersion by nonlocal interaction. The zero-field offset of 5.9 cm^{-1} is in good agreement with the calculated value (see Fig. 3).

In conclusion, we demonstrated that nonlocal effects, governed by $\frac{3}{4}v_F^2q^2$, do not only cause splittings in the 2D plasmon dispersion, but also produce an offset at zero magnetic field with respect to the local plasmon dispersion. This is a direct manifestation of the Fermi pressure.

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