Nonlocality in the Two-Dimensional Plasmon Dispersion

E. Batke,[a] D. Heitmann, and J. P. Kotthaus
Institut für Angewandte Physik, Universität Hamburg, D-2000 Hamburg 36, West Germany

and

K. Ploog
Max Planck Institut für Festkörperforschung, D-7000 Stuttgart 80, West Germany
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Two-dimensional plasmons have been investigated in AlGaAs-GaAs heterostructures with transmission spectroscopy. In a magnetic field B, we observe an interaction of the plasmon excitation with harmonics of the cyclotron-resonance frequency $\omega_c = eB/m$, which arises from nonlocal effects on the two-dimensional-plasmon excitation and is governed by the parameter $(q v_F/\omega_c)^2$ (q is the plasmon wave vector; v_F is the Fermi velocity). The dispersion and the excitation strengths of the combined resonances are in excellent quantitative agreement with a quasiclassical nonlocal theory.

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The dynamic spatial modulation of the charge density, which is induced by a plasmon excitation in a plasma, causes in a magnetic field B a nonlocal interaction of the plasmon with harmonics $n\omega_c$ ($n \geq 2$) of the cyclotron resonance (CR) $\omega_c = eB/m$. The strength of this nonlocal effect is governed by the parameter $(q v_F/\omega_c)^2$, where q is the plasmon wave vector and v_F is the Fermi velocity.[1] For two-dimensional (2D) plasmons nonlocal effects on the dispersion have been theoretically studied in great detail.[2–6] Previous experimental investigations of magnetoplasmon excitations in Si–metal-oxide-semiconductor (MOS) structures[7,8] demonstrated an interaction of plasmons with harmonics of the cyclotron resonance. However, it has been shown that under the experimental conditions of Refs. 7 and 8, the nonlocal corrections are too small to explain the observed interaction.[4,6] Rather the interaction observed in the Si inversion layer has been linked to the effect of scatterers on the line profile of Landau levels.[4] This interaction has the same origin as the excitation of so-called "subharmonic cyclotron resonances,"[9,10] which are strictly forbidden in a uniform, translationally invariant plasma.

We have investigated 2D plasmons in electron space-charge layers of AlGaAs-GaAs heterostructures[11,12] using frequency-domain transmission spectroscopy and grating-coupler[13] techniques. In a magnetic field perpendicular to the 2D plane, we observe an interaction of the plasmon resonance with the $n = 2$ harmonic of the CR that is in excellent quantitative agreement with a quasiclassical nonlocal theory.

The experiments are performed on modulation-doped AlGaAs-GaAs single-quantum-well structures. The samples are grown by molecular-beam epitaxy on (100) GaAs substrates and consist of a 1-μm GaAs buffer layer, a 5-nm undoped space layer of $Al_{0.3}Ga_{0.7}As$, a n-doped $Al_{0.3}Ga_{0.7}As$ ($n = 3\times10^{18}$ cm^{-3}) layer of thickness 60 nm, and a thin (15-nm) GaAs cover layer. Lateral Ag stripes with periodicity $a = 1.15$ μm are prepared on top of the heterostructure (see inset of Fig. 1). The Ag grating modulates normally incident far-infrared (FIR) radiation in the near field and couples radiation to plasmons of wave vectors $q = n2\pi/a$ ($n = 1, 2, \ldots$).[13] The excitation of plasmons is studied in a Fourier-transform spectrometer. Since here, in contrast to Si-MOS structures, the charge density N_s cannot be switched between 0 and N_s without complicated gate techniques, we evaluate from our experiment the relative change of transmission:

$$\Delta T/T = [T(0) - T(B)]/T(0)$$
$$\propto \mathrm{Re}[\sigma(\omega,B) - \sigma(\omega,B=0)], \tag{1}$$

where $T(B)$ and $T(0)$ are the transmission at finite magnetic field B and without magnetic field, respectively.[14] In the small-signal approximation this expression is proportional to the difference in the real parts of the dynamic conductivity $\sigma(\omega)$. $\sigma(\omega)$ contains contributions from both $q = 0$ and, due to the grating coupler, $q = n2\pi/a$. All experiments are performed at 4.2 K. The spectral resolution is 0.25 cm^{-1}. N_s can be increased by light pulses of a light-emitting diode (persistent photoeffect) from 2.5×10^{11} to 8.5×10^{11} cm^{-2} and is determined by Shubnikov–de Haas measurements *in situ* with an accuracy of 5%.

Before preparing the grating, CR measurements have been performed on the same samples. From the cyclotron-resonance half-width, scattering times τ are extracted which are about 1×10^{-12} s for $N_s = 2.5\times10^{11}$ cm^{-2} and increase to 3×10^{-12} s for $N_s = 8.5\times10^{11}$ cm^{-2}. We like to note that on samples without gratings, excitation of harmonics of the cyclotron frequency could not be detected.

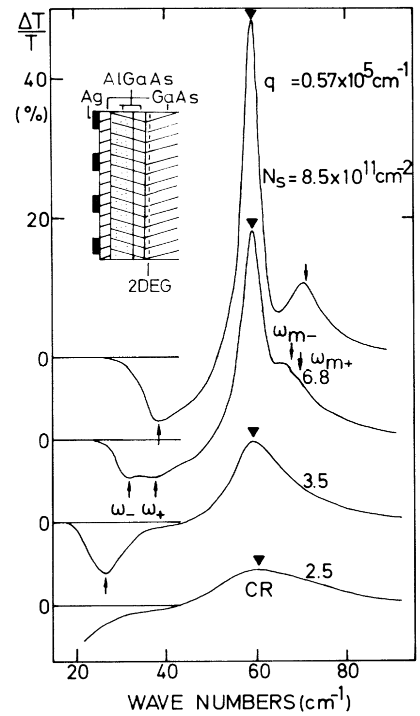

FIG. 1. Change of transmission by a magnetic field [see Eq. (1) in text] for a 2D electron gas at different charge densities N_s in an AlGaAs-GaAs single-quantum-well heterostructure. The spectra contain information for both $B=0$ and 4.56 T. Resonances (upward-pointing arrows) at low wave numbers are plasmon resonances for $B=0$. For high wave numbers cyclotron resonances (filled inverted triangles) and magnetoplasmon resonances (downward-pointing arrows) are indicated. For $N_s=6.8\times10^{11}$ cm^{-2} a splitting of the plasmon resonances, ω_-, ω_+, due to a spatial charge-density modulation is observed.

Spectra measured on a sample with a grating coupler are shown in Fig. 1 for different densities N_s. The spectra, which are evaluated according to Eq. (1), contain information for both finite B (here 4.56 T) and $B=0$. The resonances at low wave numbers, appearing as a negative signal, correspond to the grating-coupler induced 2D plasmon excitation at $B=0$. [The contribution $\sigma(\omega, q=0, B=0)$, the intraband Drude absorption, is at wave numbers above 15 cm^{-1} too small to be detected on the scale of Fig. 1.] The 2D-plasmon resonance frequency for $B=0$ increases with increasing charge density N_s and agrees within 5% with the plasmon frequency,[17]

$$\omega_0^2 = N_s e^2 q / 2\bar{\epsilon}\epsilon_0 m^*, \quad \bar{\epsilon} = [\epsilon_1 + \epsilon_2 \coth(qd)]/2, \quad (2)$$

if we use $\epsilon_1 = \epsilon_2 = 12$ for GaAs, m^* from the cyclotron mass, and $d = 80$ nm for the spacing between the 2D-electron-gas system and the grating coupler. At higher wave numbers the CR excitation appears as a positive signal $[\sigma(\omega,\ q=0,\ B=4.56\ \text{T})]$. The position depends slightly on the charge density because of the nonparabolicity of the GaAs conduction band.[15,16] With increasing charge density a resonance can be resolved at the high-frequency shoulder of the CR which corresponds to the 2D magnetoplasmon excitation $[\sigma(\omega,\ q=2\pi/a,\ B=4.56\ \text{T}]$. It follows within 5% the classical magnetoplasmon dispersion[17]: $\omega_m^2 = \omega_0^2 + \omega_c^2$.

An interesting feature in Fig. 1 is that for $N_s = 6.8\times10^{11}$ cm^{-2} two plasmon resonances, (+) and (−), can be resolved, both at $B=0$ and for finite B. We attribute this small splitting to energy gaps in the plasmon dispersion which arise from superlattice effects of a spatially modulated charge density. Energy gaps in the plasmon dispersion for a charge-density–modulated 2D plasma[18] have been observed recently in microstructured oxide-modulated Si-MOS systems.[19] Here the origin of the charge-density modulation is the following. To increase the electron density N_s we illuminate the sample with a light pulse. Since this illumination is performed through the Ag grating, the persistent photoeffect is spatially modulated.[20] This explanation is confirmed by the fact that the splitting is not observed for continuous illumination (spectra for $N_s = 8.5\times10^{11}$ cm^{-2}), where because of scattered light, donors are more uniformly spatially ionized.

The splitting of the magnetoplasma dispersion

$$\omega_{m+} - \omega_{m-} = (\omega_+^2 + \omega_c^2)^{1/2} - (\omega_-^2 + \omega_c^2)^{1/2},$$

is smaller than for plasmons ω_+ and ω_- at $B=0$. This is confirmed in the experimental data in Fig. 1 and will also appear in the results presented in Figs. 2 and 3. There one observes clearly that the excitation strength of the ω_- resonance is always smaller than that of the ω_+ resonance. This is a characteristic feature of a charge-density–modulated system.[19] The ω_--plasmon branch has an antisymmetric electric field distribution with decreased optical activity.

Figure 2 shows measurements for $N_s = 6.5\times10^{11}$ cm^{-2} at different magnetic fields B. For $B = 2.55$ T two well-resolved plasmon resonances ω_u and ω_l are observed. (For the ω_l resonance the small splitting due to the spatial charge-density modulation, ω_{l+}, ω_{l-}, can be resolved.) The ω_u resonance cannot be detected at magnetic fields higher than 3 T. With decreasing B the ω_u resonance approaches ω_l and increases in intensity. For $B = 1.64$ T both resonances have about the same strength. For $B = 1.46$ T ω_u is the stronger resonance.

The experimental resonance positions are plotted in Fig. 3. Here it becomes clear that the resonances ω_u and ω_l arise from an interaction of the 2D plasmon resonance with the first harmonic of the cyclotron resonance. We will show in the following that this interaction is caused by nonlocal effects. At the crossing

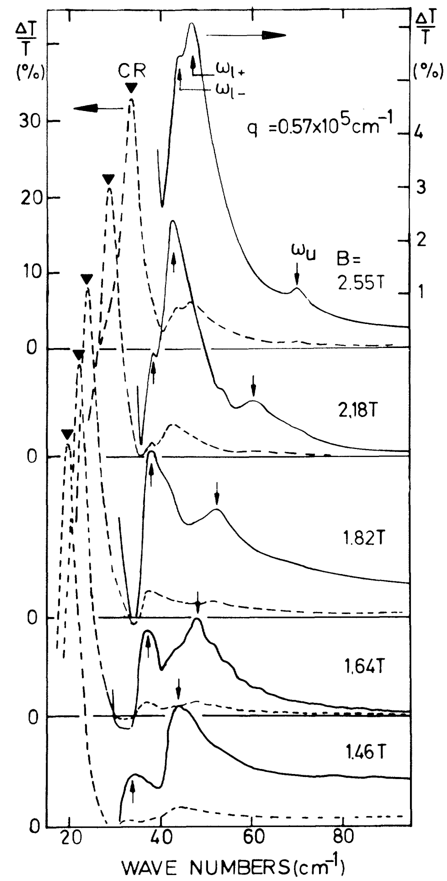

FIG. 2. Cyclotron resonances (filled inverted triangles) and magnetoplasmon resonance for $N_s = 6.5\times10^{11}$ cm^{-2} and different magnetic fields B. The nonlocal interaction with the harmonic cyclotron frequency splits the magnetoplasmon dispersion into an upper (ω_u, downward-pointing arrow) and lower (ω_l, upward-pointing arrow) branch. An additional splitting (ω_{l+}, ω_{l-}) due to the spatial charge density modulation is indicated. (Dashed lines, left scale; solid lines, expanded right scale.)

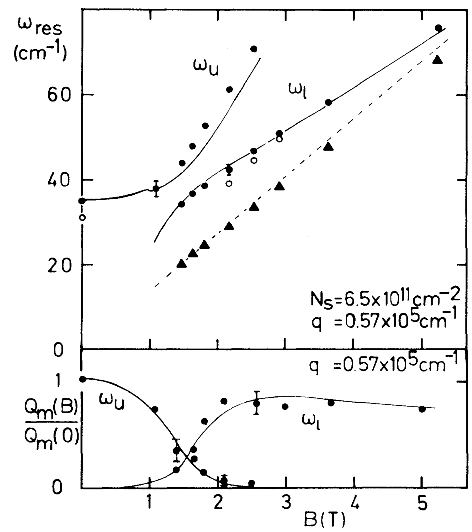

FIG. 3. Splitting of the magnetoplasmon dispersion due to the nonlocal interaction with the harmonic cyclotron frequency. Filled and open circles indicate experimental resonance position for the ω_{l+}, ω_{u+} and ω_{l-}, ω_{u-} resonances. The solid line is the theoretical dispersion (Ref. 6) calculated for the parameters of the experiment. The experimental CR frequencies (filled triangles) do not increase in proportion with B (dashed line) because of nonparabolicity. In the lower part, experimental (filled circles) and theoretical (Ref. 6) (full lines) normalized excitation amplitudes are compared. $Q_m(B)$ is the peak absorption of the plasmon excitation in an ω sweep at fixed B.

of the noninteracting magnetoplasmon and the harmonic cyclotron frequency, i.e., when $\omega_m^2 = \omega_0^2 + \omega_c^2 = (2\omega_c)^2$, one finds $(q v_F/\omega_c)^2 = 3a_0^* q/g_v$. $a_0^* = a_0 \bar{\epsilon} m_0/m^*$ is the effective Bohr radius, and g_v the valley degeneracy. In the first magnetoplasmon experiment[7] on Si(100) $(q v_F/\omega_c)^2$ was 0.005. Here the small mass of GaAs ($m^* = 0.071 m_0$), the valley degeneracy $g_v = 1$ [instead of 2 for Si(100)] with a correspondingly higher Fermi velocity, and the large wave vector q give a value of 0.18 for $(q v_F/\omega_c)^2$. Therefore, nonlocal effects are expected to be important.

To confirm this quantitatively we have calculated the absorption of an electric field component with wave vector q $\{\mathrm{Re}[\sigma(\omega, q = 2\pi/a, B)]\}$ for the parameters of our experiment with the theory of Ref. 6. This theory includes nonlocal effects for all orders of $q v_F/\omega_c$ and finite scattering times τ. The full lines in Fig. 3 are the calculated resonance positions of the ω_u and ω_l branches. There is an excellent quantitative agreement of the nonlocal theory with the experimental resonance positions. (The small kink at $B \approx 0.9$ T in the theoretical curve arises from an interaction of the plasmon with the second harmonic of the cyclotron frequency, which cannot be resolved in the experiment.) In the lower part of Fig. 3 we compare experimental and theoretical values for the normalized excitation amplitude $Q_m(B)/Q_m(B=0)$. Within experimental accuracy also the excitation strengths for both branches ω_u and ω_l are in good agreement with the theory. Note, that no fit parameter has been used. The mass $m = 0.071 m_0$ is extracted from the CR position and $\tau = 2.4\times10^{-12}$ s from the CR half-width. The excellent agreement of the nonlocal theory with the experiments, and the fact that we do not observe harmonic cyclotron resonances at samples without grating coupler $[\sigma(\omega, q=0, B)]$, demonstrate that the interaction that is observed here is not of the scatterer-induced type discussed for experiments on Si,[4] but is of classical nonlocal origin.

A nonlocal effect on the plasmon dispersion is also expected for $B = 0$. The plasmon frequency including first-order nonlocal corrections is[2] $\omega^2=\omega_0^2+3(qv_F)^2/4=\omega_0^2(1+3a_0^*q/4g_v)$. The corrections to ω_0 [Eq. (2)] are here considerably larger than for experiments on Si,[7,8,13] but the effect, an absolute shift in plasmon frequency of about 1.5 cm^{-1}, is still too small to be extracted unambiguously from the experiment.

In conclusion, we have demonstrated that nonlocal effects, governed by (qv_F/ω_c),[2] can be observed in the dynamic 2D conductivity. The nonlocality induces a strong interaction of 2D plasmons with harmonics of the cyclotron resonance. In addition we observe a small splitting of the 2D plasmon resonance which is caused by a static, lateral modulation of the charge density. This charge density modulation is induced via a spatially modulated persistent photoeffect.

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[a]Present address: AT&T Bell Laboratories, Murray Hill, N.J. 07974.

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