Quantized Dispersion of Two-Dimensional Magnetoplasmons Detected by Photoconductivity Spectroscopy

S. Holland,[1] Ch. Heyn,[1] D. Heitmann,[1] E. Batke,[2] R. Hey,[3] K. J. Friedland,[3] and C.-M. Hu[1,*]

[1]Institut für Angewandte Physik und Zentrum für Mikrostrukturforschung, Universität Hamburg, Jungiusstraße 11, 20355 Hamburg, Germany

[2]Physikalisches Institut der Universität Würzburg, Am Hubland, D-97074 Würzburg, Germany

[3]Paul-Drude-Institut für Festkörperelektronik, Hausvogteiplatz 5-7, D-10117 Berlin, Germany

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We find that the long-wavelength magnetoplasmon, resistively detected by photoconductivity spectroscopy in high-mobility two-dimensional electron systems, deviates from its well-known semiclassical nature as uncovered in conventional absorption experiments. A clear filling-factor dependent plateau-type dispersion is observed that reveals a so far unknown relation between the magnetoplasmon and the quantum Hall effect.

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Photoconductivity experiments on a two-dimensional electron system (2DES) have recently attracted enormous interest triggered off by the discovery of the zero resistance states in extremely high-mobility samples in the microwave regime [1]. Despite the latest progress in the resistive detection of the edge magnetoplasmon [2], the role of the magnetoplasmon is troublesome [3]. The question is whether the charge excitations detected resistively are identical to what we know from the absorption experiments, as one might naively anticipate. Indeed, carefully reanalyzing the original data in Ref. [1] revealed a shifted cyclotron resonance (CR) frequency $\omega_c = eB/m^*$ with a reduced effective mass m^* [4]. The critical question from above is not clarified because directly comparing photoconductivity and absorption spectroscopy in the microwave regime is a cumbersome task.

At first glance, two-dimensional plasmons seem to be an unlikely subject to give us surprises. Its dispersion in the long-wavelength limit was predicted as early as in 1967 by Stern [5] with

$$\omega_p^2(q) = \frac{N_s e^2}{2\varepsilon\varepsilon_0 m^*} q, \tag{1}$$

which describes the collective charge oscillation of a 2DES with charge density N_s at the wave vector q oriented in the 2D plane. The effective dielectric permittivity $\varepsilon(q)$ depends on the surrounding medium. In the presence of a perpendicular magnetic field the magnetoplasmon frequency ω_{mp} is given by [6]

$$\omega_{mp}^2(B) = \omega_p^2(q) + \omega_c^2. \tag{2}$$

Both Eqs. (1) and (2) have been confirmed by many experiments [7], which makes the plasmon a very well understood elementary excitation of the 2DES.

By combining Eqs. (1) and (2) it is straightforward to define a renormalized magnetoplasmon frequency Ω_{mp} and find

$$\Omega_{mp} \equiv \frac{\omega_{mp}^2(B) - \omega_c^2}{\omega_c} = \frac{\hbar \cdot q_{\mathrm{TF}} \cdot q}{2m^*} \nu, \tag{3}$$

where we define $q_{\mathrm{TF}} = m^* e^2 / 2\pi\varepsilon\varepsilon_0\hbar^2$ as the effective Thomas-Fermi wave vector depending on $\varepsilon(q)$. The monotonic linear dependence of Ω_{mp} on the filling factor $\nu = hN_s/eB$ emphasizes the semiclassical nature of the magnetoplasmon, because Eq. (2) was obtained by analyzing the self-consistent response of the 2DES to a longitudinal electric field in the semiclassical limit, in which the quantum oscillatory part of the polarizability tensor was disregarded [6]. The main result we present in this Letter is an astonishing deviation of Ω_{mp} from Eq. (3) for resistively detected magnetoplasmons in high-mobility 2DESs, where we find a quantized dispersion with plateaus forming around even filling factors. It reveals a previously unknown relation between the magnetoplasmon and the integer quantum Hall effect (QHE) which is intriguing for investigating the nature of both.

To explore a wide range of filling factors we choose a high-mobility 2DES with high density confined in a GaAs quantum well [8] (cf. the sample M1218 in Table I), and we compare it with 2DESs with different mobilities either formed at the interface (HH1295) or in a quantum well (M1266). Extremely long 2DES Hall bars with the length L of about 0.1 m and the channel width W of about 40 μm were defined by chemical wet etching. Ohmic contacts were made by depositing a AuGe alloy

TABLE I. Parameters of the samples. The two q_{TF} values for sample HH1295 are obtained for the $n = 1$ ($n = 2$) plasmon mode, respectively.

Sample	μ (10^6 cm^2/V s)	N_s (10^{11} cm^{-2})	m^* (m_e)	q_{TF} (10^6 cm^{-1})
M1218	1.3	5.58	0.0726	1.83
HH1295	0.5	1.93	0.0695	1.55 (1.86)
M1266	0.3	7.18	0.0730	1.94

followed by annealing. A gold grating coupler with a period of $a = 1$ μm was fabricated on top of the meandering Hall bar perpendicular to the current path (see Fig. 1), which allows us to couple the 2D plasmon at $q = 2\pi n/a$ ($n = 1, 2, \dots$) with THz radiation. In this frequency regime, the excitations measured by far-infrared photoconductivity (FIR-PC) and absorption spectroscopy can be directly compared. All data presented in this Letter were measured at 1.8 K in the Faraday geometry. Details of our experimental setup as well as typical resistance traces (with and without FIR) obtained on similar samples in the QHE regime have been published elsewhere [9].

In Fig. 2 we plot and compare FIR-PC (solid curves) and absorption spectra (dotted curves) measured on sample M1218 around $\nu = 4$ and 6. The dominant resonance at the lower energy is the CR, while the weak resonance at the higher-energy side is the magnetoplasmon at $q = 2\pi/a = 6.28 \times 10^4$ cm^{-1}. Since the sensitivity for FIR-PC depends strongly on the filling factor [9], for better comparison of the excitation energy, which is the focus of this Letter, we normalize the CR and magnetoplasmon in the FIR-PC spectra in Fig. 2 so that they are displayed at the same level of that in the absorption spectra. At the even integer filling factors $\nu = 4$ and 6, no deviation of the magnetoplasmon energy is found. By increasing (decreasing) the B field, the resistively detected magnetoplasmon shifts to higher (lower) energy compared to that in the absorption spectra. No such changes in the CR energy are found, except that the CR line shape shows slight deviations in the higher-energy side.

In Figs. 3(a) and 3(b) we plot the B-field dispersions of the charge excitations determined from the absorption and FIR-PC spectra, respectively. In both cases the CR can be well fit (dashed lines) by $\omega_c = eB/m^*$ with $m^* = 0.0726m_e$. Knowing the effective mass, we fit (solid curve) in Fig. 3(a) the dispersion of the magnetoplasmon using Eqs. (1) and (2), and determine $q_{\mathrm{TF}} = 1.83 \times 10^6$ cm^{-1}. Similar fitting procedures are performed for other samples and the obtained values for m^* and q_{TF} are summarized in Table I. Equations (1) and (2) capture well the general feature of the magnetoplasmon dispersion except for the nonlocal effect [7], which is responsible for the anticrossing of the magnetoplasmon with the harmonics of CR (the Bernstein modes). Using the hydrodynamical model [10] taking into account the nonlocal effect and with the same parameters of m^* and q_{TF}, the calculated magnetoplasmon dispersions (dotted curves) agree well with that measured by absorption spectroscopy in the whole B-field range, in accordance with previous studies [7]. In contrast, compared to the theoretical curves and the absorption data, the magnetoplasmon dispersion measured by FIR-PC spectroscopy shows obvious deviations in Fig. 3(b). Plotted in this scale that covers the entire CR frequency range, the deviation looks small. In fact, it is well beyond the experimental accuracy. However, before we demonstrate it more clearly in Fig. 4 by plotting the renormalized magnetoplasmon frequency Ω_{mp} in which the CR frequency is subtracted, let us first check how important the problem is for deviation of the magnetoplasmon energy by studying two questions: why does the semiclassical magnetoplasmon dispersion describe the absorption data so well? And what differs in the FIR-PC experiment?

The answer to the first question lies in the long wavelength of the magnetoplasmons we investigate, for which $q\ell \ll 1$ at large B fields. Here $\ell = \sqrt{\hbar/eB}$ is the magnetic length. Under this condition influences of quantum [6] and correlation effects [11] on the magnetoplasmon are small. Therefore, deviations of the magnetoplasmon dispersion from the semiclassical prediction as shown in Fig. 3(b) are unexpected and bring us to the second question.

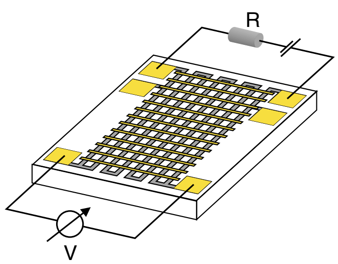

FIG. 1 (color online). Schematic view of the sample structure and bias circuit showing a meandering long Hall bar with Ohmic contacts and a grating coupler.

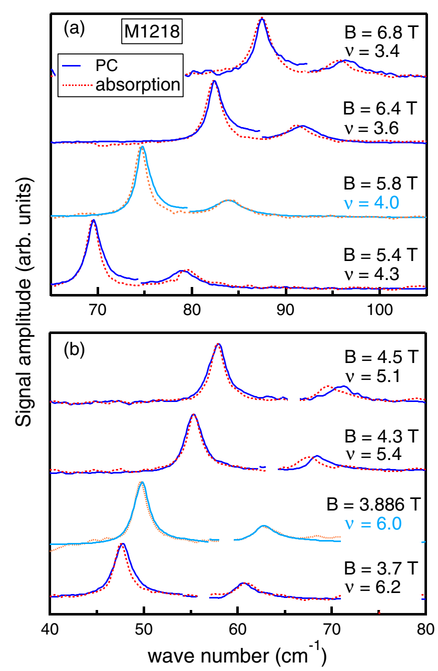

FIG. 2 (color online). FIR-PC spectra (solid curves) measured on sample M1218 around (a) $\nu = 4$ and (b) $\nu = 6$ in comparison with absorption spectra (dotted curves), displaying ν-dependent variations of the magnetoplasmon energy detected in the PC spectra.

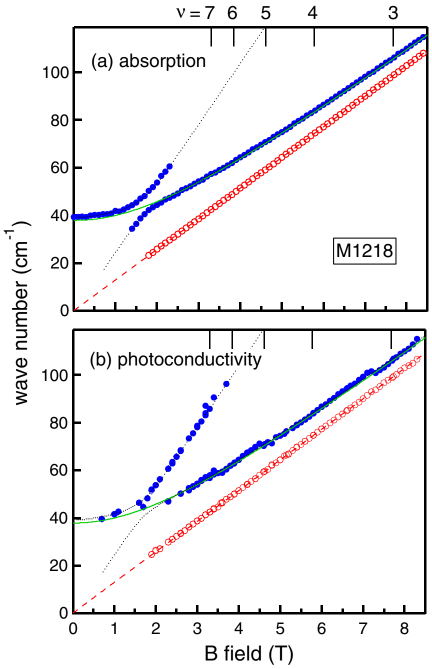

FIG. 3 (color online). B-field dispersion of the CR and magnetoplasmons measured in sample M1218 by (a) absorption and (b) FIR-PC spectroscopy. In (a) the CR frequency is fit to the relation $\omega_c = eB/m^*$ (dashed line), and the magnetoplasmon frequency is fit either to Eq. (2) (solid curve) or by the hydrodynamical model (dotted curve). Theoretical curves in (b) are identical to that plotted in (a).

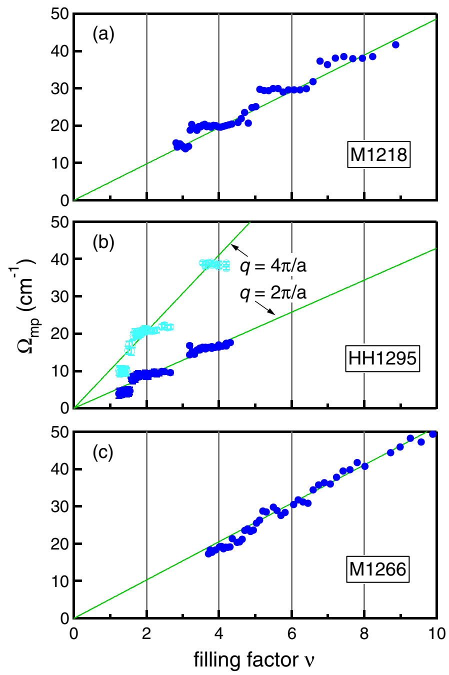

FIG. 4 (color online). Filling-factor dependence of Ω_{mp} for the resistively detected magnetoplasmons measured in three different samples. The solid lines are the semiclassical predictions calculated using Eq. (3), which fit exactly to the dispersions measured by the absorption experiments.

In the absorption spectroscopy, one detects the elementary excitations by measuring the transmitted radiation, assuming that absorption of photons does not change the properties of the electronic system. On the contrary in the PC experiments, elementary excitations are detected by measuring the photoinduced change of the resistance, which monitors exactly the change of the electronic system caused by absorption of photons. Only if the excited electronic system can reach a steady state characterized with a slightly raised temperature, which is known as the bolometric effect [12], will the same elementary excitation be detected by both the PC and the absorption spectroscopy. The bolometric model breaks down if intense radiation drives the electronic system far beyond equilibrium (as in the microwave PC experiments [1,2,4]), or if the energy relaxation is either spatially inhomogeneous as in the QHE regime [13] or spin-dependent as in the spin-polarized electronic system [14]. All provide us chances for exploring unique natures of elementary excitations unable to be investigated by conventional absorption spectroscopy.

The relation between the QHE and the resistively detected magnetoplasmon is clearly revealed in Fig. 4 in which we summarize the filling-factor dependence of Ω_{mp} resistively measured on all our samples. For comparison, semiclassical predictions for Ω_{mp} calculated by Eq. (3) using the parameters of m^* and $q_{\rm TF}$ listed in Table I are plotted as solid lines. In Fig. 4(a) Ω_{mp} measured on sample M1218 with the highest mobility deviates clearly from the semiclassical prediction. Very interestingly, the data show plateaus forming around even filling factors of $\nu = 4$, 6, and 8. In Fig. 4(b) we plot Ω_{mp} obtained on the sample HH1295 with a smaller density. The grating coupler of this sample has a higher efficiency which allows us to measure the magnetoplasmon modes at $q = 2\pi n/a$ with $n = 1$ *and* 2. Both show plateaus in the dispersion around the even filling factors of $\nu = 2$ and 4. The oscillatory behavior is less obvious in Fig. 4(c) for the sample M1266 which has the lowest mobility.

The results shown in Fig. 4 are astonishingly reminiscent of the celebrated QHE measured by dc magnetotransport [15], where the Hall conductivity equals its semiclassical prediction $\sigma_H = (e^2/h)\nu$ at even filling factors (if the spin degeneracy is not lifted), with plateaus forming around them. Decades after its discovery, consensus for QHE has been established for the coexistence of the compressible and incompressible strips [15]. But confusion or controversy remains regarding where the current flows in a Hall bar [16]. Dynamic properties are very helpful for understanding the physics of QHE; however, investigations have so far been focused on the edge magnetoplasmon mode that has the one-dimensional character with energy much smaller than the cyclotron energy [17]. Deviations of the long-wavelength high-energy magnetoplasmon mode exhibiting quantized features in the QHE regime have neither been predicted nor been measured. Here we follow the most recent theoretical model of Güven and Gerhardts which is improved by Siddiki and Gerhardts (GGSG) [16] to give a tentative explanation of the quantized dispersion observed in Fig. 4.

On the basis of a quasilocal transport model including nonlinear screening effects on the conductivity, GGSG [16] study the current and charge distribution in the 2DES in the QHE regime. In contrast to previous pictures [15], GGSG find that a broad incompressible strip exists at the center of the Hall bar at even filling factors. With decreasing B, the incompressible strip moves from the center towards the sample edges and disappears before the next is formed. Assuming local equilibrium, they find that the total applied dissipative current flows through the incompressible strips. This theory provides an appealing basis for a simple explanation of the Ω_{mp} plateau we observe: in contrast to the semiclassical magnetoplasmon determined by the macroscopic motion of all electrons in the sample that is measured by the absorption spectroscopy, the resistively detected magnetoplasmon is sensitive to the local density of the incompressible strip, in which the total applied dissipative current flows [16]. At exact even filling factors its excitation energy is equal to the semiclassical one. With decreasing B field, the filling factor in the incompressible strip is kept, and therefore the magnetoplasmon frequency deviates from the semiclassical prediction and results in the plateau. GGSG also point out that the effect of the broadening of the Landau levels reduces the width of the incompressible strips, in accordance to the mobility dependence of the plateau we observed. This simple interpretation seems to match nicely the striking simplicity of the data shown in Fig. 4, and in principle PC spectroscopy is able to detect local excitations in the QHE regime [18]. However, the GGSG model does not provide us with a simple explanation for the plateau observed below the integer filling factors. We note that without a microscopic model, the question is open whether quasilocal plasmon modes may be stabilized in the incompressible strips [19].

In summary, we have demonstrated directly by experiments that the magnetoplasmon measured by photoconductivity and absorption spectroscopy differs even under weak illumination. The dispersion of the resistively detected magnetoplasmon shows unexpected but clearly resolved plateaus for high-mobility 2DESs in the QHE regime, which we interpret as effects of the dynamic response of the incompressible strips. The unique effect provides a new basis for developing a microscopic theory that could bring insight into the dynamic properties of QHE as well as the nature of the resistively detected charge excitations in the photoconductivity experiments; both are currently of great interest.

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*Electronic address: hu@physnet.uni-hamburg.de

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[19] Via private communications, Mikhailov suggests that a "mixed" photoconductivity response of the 2DES under simultaneous action of dc and ac electric fields may lead to shifts of the resistively detected resonances due to the influence of the Landau quantization on the dc conductivity in the QHE regime. It is an interesting theoretical task to check whether such a special property of a nonlinear photoconductivity response for semiclassical plasmons may result in the quantized plateaus we observed.