Collective excitations in two-dimensional electron stripes: Transport and optical detection of resonant microwave absorption

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Transport and optical detection schemes are used for the investigation of resonant microwave absorption of two-dimensional electrons in stripes with different sizes. Fundamental and several excited transverse collective magneto-plasma modes have been detected. The transport and optical methods are found to be in good agreement with each other. The influence of retardation on the collective excitations is investigated in wide stripes with large electron densities.

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The spectrum of two-dimensional (2D) plasmons was calculated a long time ago by Stern in Ref. 1. In the long-wavelength limit, it is described by

$$\omega_p^2(q) = \frac{n_s e^2}{2m^\star \epsilon_0 \epsilon(q)} q. \tag{1}$$

Here, n_s and $m^\star$ are the density and the effective mass of the 2D electrons, and ϵ_0 and $\epsilon(q)$ are the permittivity of vacuum and the effective permittivity of the surrounding medium, respectively. Here, we have taken an effective permittivity of 6.9, the average value for GaAs (12.8) and vacuum (1). In the presence of a perpendicular magnetic field and as a result of the finite size of the sample, a hybridization between the plasma and cyclotron excitations takes place. The frequency of the combined mode is described by the formula

$$\omega^2 = \omega_p^2 + \omega_c^2, \tag{2}$$

where $\omega_c = eB/m^\star$ is the cyclotron frequency and ω_p^2 of Eq. (1) is evaluated at a wave number determined from a characteristic length scale of the sample. The dispersion described by Eq. (1) and the hybridization with the cyclotron resonance ω_c have been well established in a series of experiments (for reviews see Refs. 2 and 3).

Recent experimental investigations of the microwave absorption spectra of macroscopic disk geometries with diameters up to 1 mm have shed however new light on the collective excitations of 2D electrons.[4] Disks with diameters as large as 0.1–0.2 mm exhibited similar excitation spectra as the thoroughly investigated microscopic disks or dots.[5] In both cases, the absorption spectrum consists of two sharp resonances corresponding to the bulk and edge magnetoplasmon modes. In larger disks however, both bulk and edge magneto-plasmon modes undergo substantial changes. The plasma frequency at zero magnetic field deviates considerably from the value estimated with the help of Eq. (1). Moreover, the magnetic field dependence of both modes becomes substantially weaker. At a certain magnetic field, the bulk mode even intersects the cyclotron resonance line and broadens dramatically. Additional absorption lines appear at higher frequencies with a comparable or even larger amplitude. These unusual features in the magnetoplasma spectrum were attributed to retardation effects.[4]

In disk-shaped samples, only a single dimension—the diameter of the disk—determines the importance of retardation. Samples in the shape of a stripe have an additional degree of freedom to influence the relevance of electrodynamic effects. Here, we explore the collective excitations in such stripes to clarify retardation phenomena in this more complex geometry. Two distinct experimental techniques have been employed to detect the resonant absorption of microwave radiation: transport and luminescence measurements. They yield in essence the same results and retardation manifests itself in a similar way.

The transport experiments have been performed on a conventional 30 nm wide GaAs/AlGaAs single quantum well heterostructure. Hall bars were patterned with a width of 0.4 mm and a total length of 2.6 mm. The distance between adjacent voltage probes was 0.5 mm. The electron density n_s and electron mobility μ were in the range of $(1.5-2.5)\cdot 10^{11}\ \mathrm{cm}^{-2}$ and $(1.2-3.9)\cdot 10^{6}\ \mathrm{cm}^2/\mathrm{Vs}$, respectively. A variation of the electron density was achieved by additional illumination. The transport measurements were carried out with a standard lock-in technique by driving a sinusoidal current through the sample with a frequency of 13 Hz and an amplitude of 100–1000 nA. The magnetoresistance was acquired under continuous microwave radiation from a set of generators, which covered the frequency range from 20 to 80 GHz. The microwaves were inserted in a 16 mm waveguide mounted in a cryostat with a superconducting coil and submerged in liquid helium. Some optical measurements were performed on the same Hall bar sample, however most of the optical investigations were carried out on rectangular stripes with aspect ratios of 1:20, 1:15, 1:10, 1:5, or 1:3 (width:length). The width W varied from 0.05 to 3 mm. For these stripes, the electron concentration and mobility covered $(0.1-6.6)\cdot 10^{11}\ \mathrm{cm}^{-2}$ and $(0.4-6.0)\cdot 10^{6}\ \mathrm{cm}^2/\mathrm{Vs}$. The magnetoplasma excitations were detected optically by comparing the luminescence spectra obtained in the presence and absence of microwave radiation.[4,6] The luminescence was recorded with the help of a charge-coupled device (CCD) camera and a double-grating

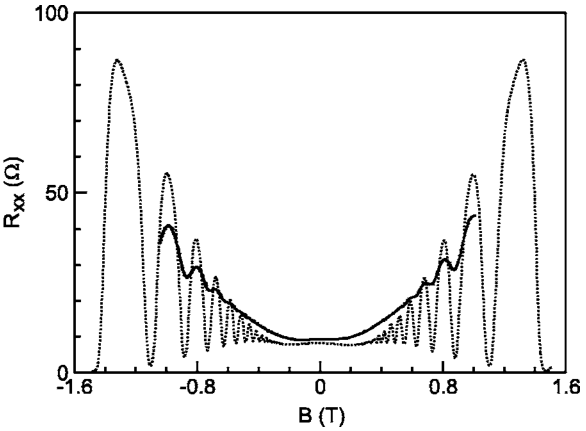

FIG. 1. Comparison of the magnetoresistance R_{xx} for $T=1.8$ K (dotted line) and $T=4.2$ K (solid line) at an electron density n_s of $2.13 \cdot 10^{11}$ cm^{-2}. The temperature sensitivity of R_{xx} can be exploited to detect heating of the electonic system due to resonant absorption.

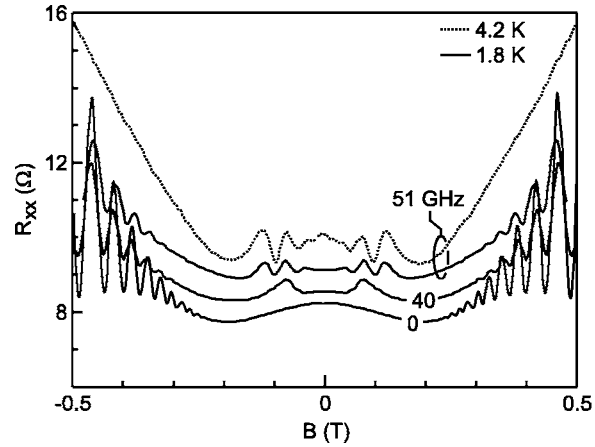

FIG. 2. The influence of 40 and 51 GHz microwave radiation on the magnetoresistance R_{xx}. Solid curves are taken at 1.8 K, the dotted curve at 4.2 K. For the sake of comparison, the R_{xx} trace in the absence of microwave radiation is also shown (bottom). Curves are offset for clarity. The microwave power at the entrance of the waveguide is 1 mW and the electron density equals $2.13 \cdot 10^{11}$ cm^{-2}.

spectrometer with a spectral resolution of 0.03 meV. A stabilized semiconductor laser served as a continuous wave excitation source. It was operated at a wavelength of 750 nm and delivered its power of approximately 0.1 mW onto the sample with the help of an optical fiber placed inside the microwave waveguide. After collecting luminescence spectra with the same fiber in the presence and absence of microwave radiation, the differential spectrum was obtained by subtracting these two spectra. It was previously demonstrated that the integral across the recorded spectral range of the absolute value of this differential spectrum is related to the microwave absorption strength.[4,6]

In Fig. 1, we show the magneto-resistance R_{xx} recorded on the Hall bar geometry at two different temperatures (1.8 and 4.2 K) for an electron density of $2.13 \cdot 10^{11}$ cm^{-2} and a mobility of $3.5 \cdot 10^6$ cm^2/Vs. The Shubnikov de Haas oscillations are strongly damped as the temperature is raised. In addition, at small magnetic fields ($B < 0.2$ T) where SdH oscillations are not yet resolved, the magnetoresistance displays a significant increase with temperature. This sensitivity of the magnetoresistance to electron heating[7] is exploited here to detect the resonant absorption of microwaves.[8,9] Figure 2 illustrates the influence of microwave radiation on the magneto-resistance for two different frequencies. For the sake of comparison, a transport curve is included when no microwave radiation is incident on the sample. A well-defined resonance develops for both orientations of the magnetic field at $B=75$ mT for a frequency of 40 GHz. The increase of the magnetoresistance at the resonance exceeds 5%. The resonance shifts to higher magnetic field values as the microwave frequency f is raised. When f is larger than 45 GHz, a second peak emerges. An example is shown for 51 GHz radiation for which two distinct resonances at 72 and 125 mT appear. The amplitude of the observed resonances is almost insensitive to a variation of the bath temperature from 1.8 to 4.2 K (see Fig. 2). Additional magnetoresistance traces collected at microwave frequencies between 30 and 75 GHz are depicted in Fig. 3. As many as three clear resonances can be discerned for the highest frequency. They correspond to different transverse magneto-plasma modes as shown below. Note that the mobility of the samples used in this work is insufficient to observe the recently discovered microwave induced zero resistance and $1/B$-periodic magnetoresistance oscillations.[10,11]

In order to identify the modes, we plot in Fig. 4 the magnetic field values at which resonances occur as the microwave frequency f is tuned (open symbols). These results were obtained on the same sample with a density $2.13 \cdot 10^{11}$ cm^{-2} and width $W=0.4$ mm. The data points fall on three lines. The three modes approach the cyclotron frequency in the strong magnetic field limit. When fitting the functional field dependence described by Eq. (2) to the data, these modes extrapolate to the following zero field plasma frequencies: $f_1(0)=26.1$ GHz, $f_2(0)=44.9$ GHz, and $f_3(0)=58.2$ GHz. The ratios $f_2(0)/f_1(0)=1.72$ and $f_3(0)/f_1(0)$

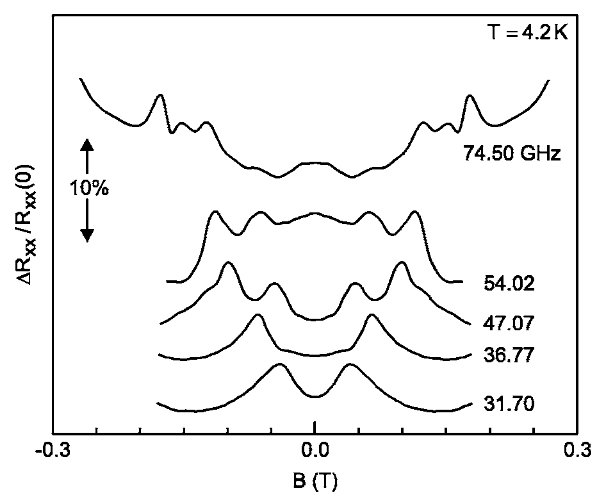

FIG. 3. Evolution of the microwave absorption resonances in the magnetoresistance with excitation frequency. The frequency range from 30 to 75 GHz is covered. The microwave power inserted into the waveguide is approximately equal to 1 mW, the electron density is $2.13 \cdot 10^{11}$ cm^{-2}.

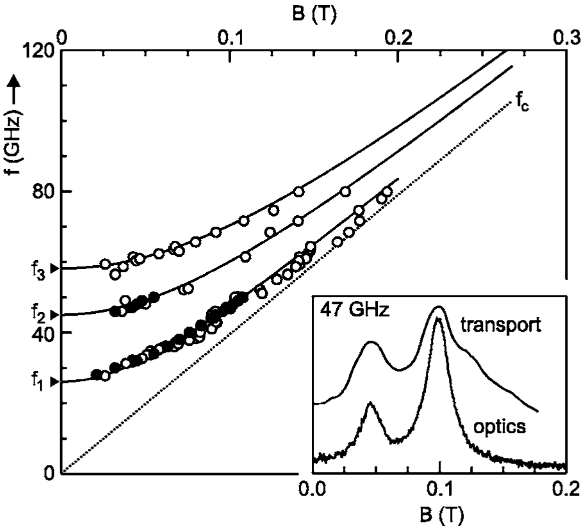

FIG. 4. The position of the microwave absorption resonance versus excitation frequency f. Open circles are data points collected from transport curves, whereas closed symbols represent data points acquired from differential luminescence spectra. The microwave power inserted into the waveguide is approximately equal to 1 mW. The electron density is $2.13 \cdot 10^{11}$ cm^{-2} in these experiments and the sample width is 0.4 mm. The dotted line marks the magnetic field dependence of the cyclotron frequency f_c assuming an electron effective mass of 0.071 m_0. The inset shows microwave absorption spectra measured simultaneously in a transport measurement and with the luminescence detection scheme. These curves were taken at 47 GHz and 4.2 K.

=2.23 are close to $\sqrt{3}$ and $\sqrt{5}$, respectively. Hence, these resonances can be assigned to standing bulk plasmon oscillations at odd multiples of the wave number defined by the Hall bar width W when considering that the plasma frequency obeys the dispersion described by Eq. (1). The wavenumber q takes on one of the values $\pi N/W$ with $N=1,3,5$. Under uniform electromagnetic radiation, the dipole approximation indeed predicts that only odd modes are excited.[12] The absolute values of the plasmon frequencies, obtained from fitting Eq. (2) to the experimental data, are however considerably smaller compared with the values determined from the expression for $\omega_p(q)$. For instance, for $f_1(0)$ this expression yields approximately 38 GHz instead of the fitted 26.1 GHz for the sample parameters at hand. We will demonstrate that this discrepancy is a consequence of retardation.[4] Retardation becomes prominent at high electron densities and for wide sample geometries. The cyclotron mass extracted from the asymptotic behavior of the lowest frequency mode equals $0.071m_0$, which is significantly higher than the frequently quoted value of $0.067m_0$ for GaAs. We assert that this discrepancy too stems from retardation. For wider samples and higher electron densities, the mass value extracted according to the same protocol can be as high as $0.1m_0$.[4] Hence, we exclude an explanation for the mass enhancement based on nonparabolicity and polaron effects. In the inset of Fig. 4, we compare a transport measurement with the absorption spectrum obtained from differential luminescence data. The position and width of the resonances are nearly identical. Resonances detected from optical luminescence are added as solid symbols in Fig. 4. Clearly, the optical studies yield the same information as the transport experiments. This confirms that the magnetoplasma resonances observed in transport essentially originate from the bulk.

The plasmon dispersion as described by Eq. (1) was derived within the quasi-electrostatic approximation.[1] At small wave numbers, electrodynamic effects such as retardation can however often no longer be ignored since the phase velocity of plasmons may approach the velocity of light. In previous studies[4] on disk-shaped mesas, it was demonstrated that at zero magnetic field retardation causes a strong reduction of the plasma frequency due to a hybridization between plasma and light modes. For disks with a radius R, the importance of retardation can be described by the dimensionless parameter $A=\omega_p\epsilon^{1/2}R/c$. It is equal to the ratio between the plasma frequency and the light frequency at wavenumber $q=1/R$. This parameter A grows with the density n_s as well as the radius R according to $A\propto(n_sR)^{1/2}$ and can in principal exceed unity in experiment. Retardation also strongly modifies the magnetic field dependence of the resonance frequency.[4] For instance, as opposed to the asymptotic behavior described by Eq. (2), the magnetoplasma mode may intersect the cyclotron resonance line at some finite magnetic field value. At small values of the retardation parameter ($A<0.2$), these changes to the magnetic field dependence just resemble an increase of the cyclotron mass of the electrons. The data in Fig. 4 is an example obtained on a rectangular Hall bar geometry instead of a disk-shaped mesa. The high field behavior is described well with Eq. (2) when assuming a larger effective mass of 0.071. At large A ($A>1$) the influence is more dramatic and modes become nearly independent of the applied magnetic field. In this regime, the photon contribution has turned dominant and the dispersion of light is obviously not sensitive to the applied magnetic field.

The influence of retardation on plasma modes in the stripe geometry was addressed theoretically by Mikhailov and Savostianova.[12] For our Hall bar with width W, the retardation parameter can be estimated from[12]

$$A=\sqrt{\frac{n_se^2W}{2\pi\epsilon_0m^*c^2}}. \tag{3}$$

For $W=0.4$ mm and $n_s=2.13\cdot10^{11}$ cm^{-2}, the retardation parameter A is approximately equal to 0.24 and hence modifications of the magnetic field dispersion of plasma modes are expected and seen in the experiment of Fig. 4. To enhance the influence of retardation, we have investigated samples with larger widths and increased densities. The inset to Fig. 5 illustrates the dependence on the electron density of the zero field frequency of the lowest mode measured for a stripe with a width $W=0.4$ mm. The frequencies are normalized to f_0, a rough estimate of the zero field plasma frequency based on Eq. (1) ignoring retardation: $2\pi f_0=\sqrt{\frac{\pi n_se^2}{2m^*\epsilon_0\epsilon W}}$. More accurate calculations of the zero field plasma frequency in the absence of retardation yield $0.85f_0$.[12] For $A\rightarrow0$ the measured resonance frequency is indeed very close to $0.85f_0$. By increasing the electron density (or A) the zero-field plasma frequency systematically drops compared with f_0. This behavior is

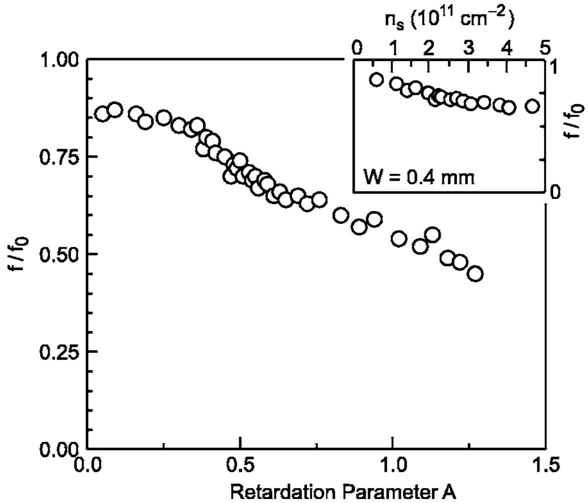

FIG. 5. The dependence of the resonance frequency f at zero magnetic field of the lowest plasma mode on the retardation parameter $A=\sqrt{\frac{n_s e^2 W}{2\pi\epsilon_0 m^* c^2}}$. Frequencies have been normalized to the value predicted by theory when ignoring retardation effects f_0. The inset plots f/f_0 as a function of electron density n_s for a stripe with $W=0.4$ mm.

similar to the one for 2D disks.[4] The main graph of Fig. 5 depicts resonance frequencies as a function of the retardation parameter A. These frequencies are also normalized to f_0. The data have been obtained on structures with different widths as well as carrier densities. Again the frequency at small A starts at approximately $0.85 f_0$ and then drops with increasing values of the retardation parameter. For fixed values of the stripe width and of the electron density an influence of the length of the stripe on the retardation effects was not detected in our experiment in spite of the fact that the length was considerably larger than the width of the structures. For example, a variation of the stripe length in the range 1–3 mm did not affect the transverse resonant plasma frequency for a fixed stripe width W of 0.2 mm and a density of $6.6\cdot 10^{11}$ cm^{-2}. This should come as no surprise. The plasma modes excited along the length of the stripe occur at much lower frequencies and have one-dimensional character. These modes posses a linear dispersion and their velocity is considerably smaller than the speed of light.[13]

In conclusion, we have investigated resonant microwave absorption with optical and transport techniques in stripes containing two-dimensional electrons. Several plasma modes excited across the stripe were simultaneously detected with both experimental methods. We have demonstrated that at high electron densities and large widths of the stripe retardation becomes important. Retardation affects the frequencies of all plasma modes, their magnetic field dependence as well as the relative absorption strength of the modes.

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