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Spectrum of one-dimensional plasmons in a single stripe of two-dimensional electrons

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Microwave absorption spectra of a single, narrow stripe of two-dimensional electrons have been recorded with an optical detection scheme in order to investigate the dispersion of one-dimensional (1D) plasmons. For narrow stripes the dispersion of 1D plasmons is linear up to momentum values $K=1/W$, where W is the width of the stripe. The dependencies of the 1D plasmon velocity on electron density, length, and width of the stripe were measured. We also address the behavior of the 1D transverse and longitudinal plasma modes in a perpendicular magnetic field.

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The spectra of two-dimensional (2D) plasmons and magnetoplasmons in the two-dimensional electron system have been well established both theoretically[1,2] and experimentally.[3,4] Effects associated with edges and the finite size of the electron system as well as retardation phenomena have been addressed.[5,6] The situation for one-dimensional (1D) plasmons is more complex and far less satisfactory. Their spectrum was calculated two decades ago.[7–10] Experimental difficulties have, however, hindered a direct measurement of their dispersion. Theory has predicted a linear dispersion as the hallmark of 1D plasmons, with logarithmic corrections at small wave vectors. This contrasts with the well-known square root dependence for 2D plasmons. It is important to distinguish between 1D electrons and 1D plasmons. One-dimensional confinement of electrons can be achieved only in narrow quantum wires with a width comparable to the Fermi wavelength, which is typically on the order of 50 nm in GaAs/AlGaAs heterostructures. Such strong restrictions do not apply for observing the one-dimensional character of plasmons. We assert that it suffices to investigate a macroscopic stripe with a large length-to-width aspect ratio.

Several experimental attempts to study the dispersion of 1D plasmons have already been undertaken. One was based on the investigation of quantum wires using inelastic light scattering,[11] whereas another employed far-infrared absorption.[12] In both cases, not a single stripe or wire, but rather a superlattice of wires was investigated in order to enhance sensitivity. Interestingly, a 2D character of the plasmons was discovered instead[13] and numerical calculations confirmed that a strong coupling between the wires is responsible for this absence of 1D behavior.[14] Hence, in order to observe 1D plasmons the sample should consist of a single wire or a single stripe, narrow enough in comparison with its length. Also, measurements should be made at wave vectors smaller than the inverse width of the stripe. This condition was often not fulfilled for previous mesa geometries used in plasmon studies. In the present paper, we explore a single stripe of a two-dimensional electron system with a large length-to-width aspect ratio in the limit of small wave vectors. A linear dispersion indicative of the 1D character of the collective plasmon modes in this system is disclosed in this small wave-vector regime. The dependence of the velocity of these plasmons on the electron density, the dimensions of the stripe and the magnetic field has been determined, and these studies revealed some discrepancies with theory.

The work was performed on a set of high-quality GaAs/$Al_xGa_{1-x}As$ single quantum wells with well widths between 25 and 30 nm located approximately 200 nm below the crystal surface. The electron transport mobility μ ranged from 3 to 8×10^6 cm^2/V s at electron densities n_s between 0.4 and 2.6×10^{11} cm^{-2}. Stripe-shaped mesas with aspect ratios of 20:1 and 10:1 were fabricated from these heterostructures. The stripe terminates in an ohmic contact at both ends. Near these ohmics at a distance of 10 μm, metallic gate fingers, which run across the stripe, are deposited on top of the mesa (see the inset to Fig. 1 for a schematic drawing). They serve to excite the plasma waves. To detect the microwave resonances,[6] luminescence spectra were recorded with the help of a charge-coupled device (CCD) camera and a double-grating spectrometer, which offers a spectral resolution of 0.03 meV. A stabilized semiconductor laser operating at a wavelength of 750 nm and a power level of approximately 100 μW served as the cw-excitation source. An HP-83650B generator provided microwave radiation with frequencies from 0.01 to 50 GHz. The radiation was guided into the cryostat with a coaxial cable and transferred to the two-dimensional electron system via a coplanar waveguide transmission line. The central conductor of this waveguide is bonded to one of the gate fingers and the ground planes are connected to the adjacent ohmic contact of the stripe. The microwave power at the entrance to the coax cable was about 1–10 μW. In order to calculate a differential luminescence spectrum, spectra were recorded with and without microwave excitation. The microwave absorption amplitude is defined as the integral of the absolute value of the differential luminescence spectrum over the measured spectral range. It has been previously demonstrated that this technique offers excellent sensitivity.[6] Both frequency scans at a fixed magnetic field as well as magnetic field scans at a fixed frequency are possible in this arrangement. The cyclotron mobility μ_{CR} was extracted from the linewidth of the resonant

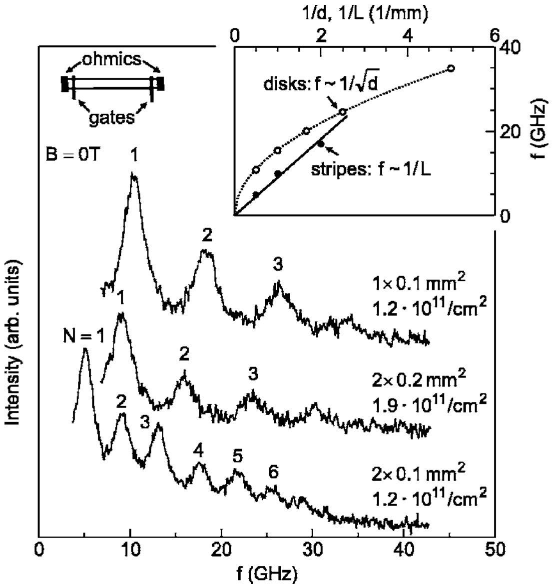

FIG. 1. Microwave absorption spectra measured at $B=0$ and 1.5 K on stripes with the following geometries and electron concentrations: 2×0.1 mm^2 and 1.2×10^{11} cm^{-2}; 2×0.2 mm^2 and 1.9×10^{11} cm^{-2}; 1×0.1 mm^2 and 1.2×10^{11} cm^{-2}. The inset plots the frequency of the fundamental mode for disk-shaped mesas as a function of the disk diameter d as well as for stripes with a width of 0.1 mm as a function of their length L at a density of 1.2×10^{11} cm^{-2}.

absorption peaks. It reached values from 2 to 5×10^6 cm^2/V s for the various samples and carrier densities. This sample quality level enables absorption studies of plasmons down to microwave frequencies of approximately 1 GHz.

In Fig. 1 we present typical absorption spectra measured on three stripes with different length, width, and electron concentration. A fundamental characteristic of these spectra is the periodic structure. Typically four to six absorption peaks are visible, spaced almost equidistantly on the frequency axis. These resonant peaks correspond to the excitation of dimensional plasma resonances, i.e., standing plasma modes along the length of the stripe with wave number $K=\pi N/L$. Here, L is the length of the stripe and the quantum number N equals 1,2,3,… . We note that according to the dipole approximation[17,18] a uniform microwave field can only excite modes with odd numbers. In the experimental arrangement here with a gate finger running across the stripe at a distance of 200 nm from the two-dimensional electron system, the spatial distribution of the electric field is however strongly inhomogeneous. Both odd and even modes are triggered, although odd modes indeed tend to be stronger. For example, the first mode in the data of Fig. 1 is more pronounced compared to all other modes and the second mode has an amplitude that is not larger but comparable in magnitude to mode 3. The observed periodicity is consistent with a linear dispersion, which points to 1D character of the plasmons.

The splitting between the absorption peaks depends on electron density as well as on the size of the stripe and is a measure of the plasmon velocity. Figure 2 plots the dispersion obtained from the absorption spectrum in the 2×0.1 mm^2 stripe with electron density of 1.2×10^{11} cm^{-2}. The plasmon wave vector was calculated from the mode number and the relationship $K=\pi N/L$. On the same plot, we draw for comparison the dispersion of 2D plasmons at the identical electron density. In the limit of small wave vectors $K<1/W=100$ cm^{-1} (W is the width of the stripe) the plasmon spectrum indeed deviates considerably from a square root dependence. It corresponds well to a linear dispersion with a velocity close to 1.8×10^7 m/s instead. We conclude that a macroscopic single, narrow stripe is suitable for the investigation of the spectrum of 1D plasmons and its modifications when the density or geometry are changed. Note that in the limit of large wave vectors $K\gg1/W=100$ cm^{-1} the plasmon dispersion is expected to approach that of edge plasmons with a frequency approximately equal to 0.9 times the square root dependent 2D plasmon frequency.[16] The slight but systematically observed reduction of the resonance frequency from the linear 1D plasmon dispersion for wave vectors close to $1/W$ (Fig. 2) is at least compatible with this limit. By analyzing the behavior of the fundamental mode ($N=1$) of stripes with different dimensions, our assertion of 1D character is strengthened further. The inset to Fig. 1 plots the frequency dependence of the fundamental mode as a function of the length of the stripe for $L\gg W$ and reveals linear behavior as anticipated for 1D plasmons. For the sake of comparison, the same dependence is plotted for the fundamental dimensional plasmon resonance mode in disk-shaped mesas and a square root dependence is found as these plasmons bear 2D character.

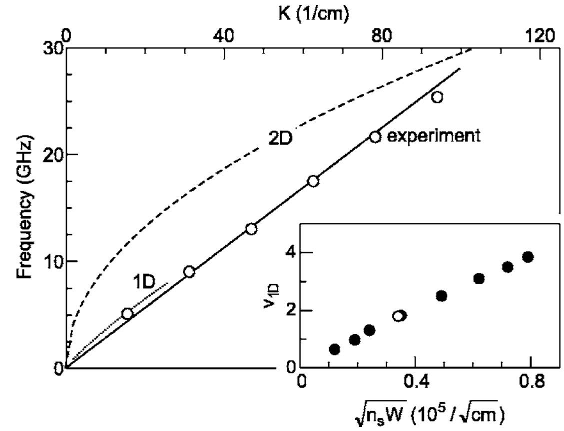

FIG. 2. The plasmon dispersion measured on a stripe with a length of 2 mm, a width of 0.1 mm, and an electron density of 1.2×10^{11} cm^{-2}. The dispersion of 2D plasmons and of 1D plasmons (in the limit of small wave vectors $KW\ll1$) predicted by theory are also shown for the sake of comparison. The observed linear dispersion points to 1D plasmon behavior with a velocity of 1.82×10^7 m/s. The inset depicts the dependence of the 1D plasmon velocity v_{1D} in units of 10^7 m/s on parameter $(n_SW)^{1/2}$.

The velocity of the observed 1D plasmons depends on the electron density and the width of the stripe, but not on the length of the stripe. An analytical expression for the 1D plasmon dispersion exists, but its validity is restricted to the limit $K\ll1/W$. It reads[9]

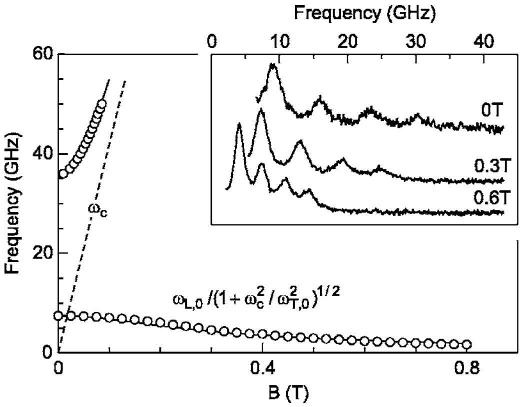

FIG. 3. Magnetic field dependence of the fundamental transverse and longitudinal plasma modes of a stripe of 2D electrons with a length of 2 mm, a width of 0.2 mm, and an electron density of 1.2×10^{11} cm^{-2}. The functional dependencies predicted with Eqs. (2) and (3) are plotted as solid lines. The dashed line represents the cyclotron frequency. The inset shows absorption spectra recorded at different magnetic fields (0, 0.3, and 0.6 T) for a stripe with the same dimensions but a larger electron density of 1.9×10^{11} cm^{-2}.

$$\omega^2 = (2n_S We^2/\epsilon^* m_e)K^2[\ln(8/KW) - 0.577]. \tag{1}$$

Here, n_S and m_e are the electron concentration and effective mass, and $\epsilon^* = (1+\epsilon_{GaAs})/2$ is an effective dielectric constant (the average between vacuum and GaAs). This formula contains a logarithmic correction to the linear proportionality between frequency and wave vector. The dispersion relation of 1D plasmons as predicted by Eq. (1) is plotted in Fig. 1 in the limit of very small wave vectors ($K \ll 1/W$). The experimental data hardly deviate from a linear dependence at the smallest momenta and suggest that the logarithmic correction becomes only relevant at even smaller wave vectors not accessible in this experiment. Others have omitted the logarithmic term altogether[10] and replaced it with a constant as we find here for the wave vector range covered in experiment. In the inset to Fig. 2, the dependence of the 1D plasmon velocity v_{1D} is plotted as a function of the parameter $(n_S W)^{1/2}$. In agreement with the dominant term in Eq. (1), v_{1D} is linearly proportional to $(n_S W)^{1/2}$. Moreover, the measured velocities are captured well by Eq. (1) when replacing the factor containing the logarithmic term with a constant value of approximately 1.7–1.8.

In addition to the longitudinal modes described above, there are also transverse plasma modes, which correspond to plasma oscillations across the narrow stripe. We have investigated the fundamental transverse modes by placing the same samples in a microwave waveguide and sweeping the magnetic field as described in Ref. 6 (rather than sweeping the frequency as for the longitudinal modes described above). Both the transverse and longitudinal plasma modes are strongly modified when applying a perpendicular magnetic field. In Fig. 3 we plot the measured magnetic field dependence for both fundamental modes. We will still refer to these modes as transverse and longitudinal modes even though strictly speaking, a nonzero magnetic field mixes the x and y motions. In zero magnetic field, a large gap separates the transverse and longitudinal plasma modes. This gap is an immediate consequence of 1D quantization of the plasmon spectrum. The magnetic field dependence of the transverse mode in a single stripe follows the formula

$$\omega^2 = \omega_{T,0}^2 + \omega_c^2. \tag{2}$$

In this expression, $\omega_{T,0}$ is the lowest transverse plasma frequency for wave vector value $K=\pi/W$. An approximate analytical expression yields $(2\pi^2 n_S e^2/\epsilon^* m_e W)^{1/2}$ for $\omega_{T,0}$. More accurate numerical calculations correct this expression by a numerical factor of approximately 0.85.[17] The cyclotron frequency ω_c equals eB/m_e. The value of $\omega_{T,0}$ at $B=0$ T and its magnetic field dependence predicted by theory are in good agreement with the data, as well as previous experimental data.[15] As evident from Fig. 3, the frequency of the transverse plasmon rapidly increases with B field and approaches the cyclotron frequency already at B fields of 0.1–0.2 T. Conversely, the longitudinal plasma mode drops in frequency as the magnetic field is raised. This mode can be detected up to 0.8 T. According to theory,[9] the magnetic field dependence of the longitudinal plasma mode in a stripe is given by

$$\omega^2 = \omega_{L,0}^2/(1+\omega_c^2/\omega_{T,0}^2), \tag{3}$$

where $\omega_{L,0}$ denotes the lowest longitudinal plasma mode in the stripe. The measured magnetic field dependence on a stripe of 2×0.2 mm^2 in Fig. 3 is fitted to Eq. (3). The best agreement is obtained when adopting a value of 90 GHz for $\omega_{T,0}$. This value of $\omega_{T,0}$ from the fit is almost three times larger in comparison with the resonant frequency $\omega_{T,0}$ measured directly in the small magnetic field limit (Fig. 3). Equation (3) has been derived for a semielliptical profile of the electron density in the stripe. This is an incorrect description of the density profile in stripes with a width of 0.1–0.2 mm, in which the electron density is uniform everywhere except near the mesa edge, where it decreases abruptly over a depletion length of less than a micron. This difference between the density profile used to derive the analytical expressions in Ref. 9 and the actual density profile likely accounts for the discrepancy between the measured value of $\omega_{T,0}$ and the fit value in Eq. (3). The inset to Fig. 3 depicts absorption spectra taken at several values of the magnetic field for a fixed but larger electron density of 1.9×10^{11} cm^{-2}. The reduction of the frequency of the fundamental mode with magnetic field is also apparent from this data at higher density. Particularly noteworthy is, however, the narrowing of the linewidth with increasing B field. A narrowing with magnetic field is a characteristic feature of edge magnetoplasmons.[9,16] Hence, the narrowing of the resonance width confirms that longitudinal plasma modes become strongly localized near the edges of the stripe as the field is raised and so it should come as no surprise that details of the density profile near the edge determine the magnetic field dependence of the longitudinal plasma mode.

In Fig. 4, the magnetic field dependence is plotted not only for the fundamental mode but also for higher order longitudinal plasma modes. These measurements were carried out on a stripe with a size of 2×0.2 mm^2 and an electron density of 1.2×10^{11} cm^{-2}. The higher order modes ex-

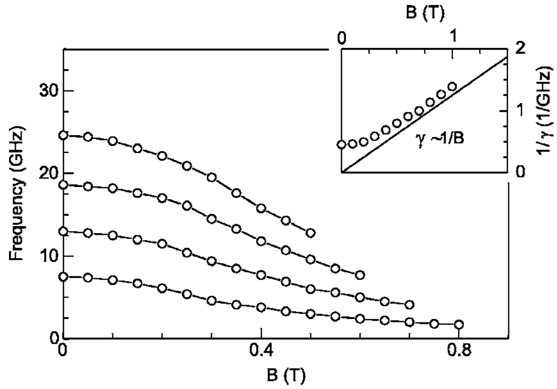

FIG. 4. Magnetic field dependence of the fundamental and higher order longitudinal 1D plasma modes of a stripe with a length of 2 mm, a width of 0.2 mm, and a density of 1.2×10^{11} cm^{-2}. The inset plots the magnetic field dependence of the linewidth of the fundamental mode.

hibit a similar B-field dependence. They can be fitted equally well to Eq. (3) with values for the fitting parameter $\omega_{T,0}$ in the range 90–110 GHz. The inset of Fig. 4 depicts the linewidth (γ) as a function of the perpendicular magnetic field. Its magnetic field dependence is described by

$$\gamma^2 = \gamma(0)^2/(1 + \omega_C^2/\omega_{0T}^2). \quad (4)$$

Here, $\gamma(0)$ is the width measured at zero magnetic field. The value of $\omega_{T,0}$ is again treated as a fit parameter. We obtain, consistent with the previous fits, a value close to 110 GHz. Note that the observed $1/B$ dependence of $\gamma(B)$ contradicts the predicted $1/B^2$ dependence in Ref. 9. This discrepancy may presumably in part also be ascribed to the in that work adopted semielliptical density profile. For a steplike density profile, closer to the experimental situation at hand, a functional dependence of $\gamma(B)$ of the form $1/\ln(B)$ or $1/B$ has been predicted in different limits.[16]

In conclusion, we have investigated the microwave absorption spectra of a single stripe of two-dimensional electrons. We have identified resonant modes with a linear dispersion characteristic of 1D plasmons. The dependence of the 1D plasmon velocity on the electron density, the geometry of the stripe and a perpendicular magnetic field have been determined. Most observations can be accounted for by existing theory except for the behavior of the linewidth of the transverse and longitudinal modes with magnetic field and the B-field dependence of the frequency of the longitudinal mode. These discrepancies may at least in part be resolved by considering the appropriate density profile for these stripes in the theory.

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