Edge magnetoplasmons in single two-dimensional electron disks at microwave frequencies: Determination of the lateral depletion length

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We present a new method to determine the lateral depletion length (LDL) at the boundary of a two-dimensional electron system (2DES). This approach exploits the fact that in high magnetic fields certain plasma excitations of the confined 2DES (edge-magnetoplasmons, EMPs) are sensitive to details of the density profile near the edge. Comparing the measured magnetic-field dispersion of EMPs in a circular mesa with existing classical theories, the LDL is found to be between 0.3 and 0.6 μm for an electron density of 3.0×10^{11} cm^{-2}. *© 1995 American Institute of Physics.*

The modification of the band structure at surfaces or interfaces constitutes a major issue in the physics of semiconductor devices. While the physics of two-dimensional (2D) surfaces of 3D bulk semiconductors is well established, much less is known about its lower dimensional analog, i.e., the 1D edge of the laterally confined 2D electron system (2DES) present in a modulation-doped semiconductor heterostructure or quantum well. Qualitatively, the situation is similar in both cases; the occupation of surface states leads to a region of carrier depletion near the surface. Quantitatively, however, the lateral or edge depletion length (LDL) differs from the 3D case because of the particular screening properties in lower dimensions. In devices whose operation relies on the presence of the edge of a 2DES,[1,2] the LDL plays a role of similar importance as the ordinary depletion length in a conventional 3D device. Information on the LDL is likewise important in the context of 1DES and 0DES. Such systems, which are currently a subject of great interest, are mostly fabricated by etching[3] or by means of a structured gate electrode at the surface.[4,5]

Choi *et al.*[6] have first obtained the LDL from magnetoresistance measurements in wire arrays, exploiting the theory of weak localization. Our experimental determination of the LDL relies on a completely different scheme. Employing rf transmission spectroscopy, we measure the magnetoplasma excitations in a finite size 2DES of circular geometry and compare the magnetic field dependence of the resonance positions with a classical theory that takes into account the electron density profile at the edge of the 2DES. In a magnetic field B, the spectrum of plasma resonances in a 2D electron disk[7–9] decomposes into cyclotron-resonance-like modes whose frequency increases with B, asymptotically approaching $\omega_c=eB/m^*$ and the so-called edge magnetoplasmons (EMPs), which decrease in frequency with increasing B. At large magnetic field, the EMP oscillations are localized at the edge of the 2DES, so that consequently the local electron density distribution in the vicinity of the edge influences the EMP frequency.[10] From recent calculations[11,12] is it known how the LDL explicitly enters the density profile. The LDL can thus be extracted from our experiment.

Sample preparation starts from a modulation-doped GaAs/Al$_x$Ga$_{1-x}$As heterostructure containing a 2DES with density $n_s=3.0\times10^{11}$ cm^{-2} and dc mobility $\mu=8\times10^5$ cm^2/V s at temperature $T=4.2$ K. The structure, grown by molecular beam epitaxy on a semi-insulating GaAs substrate, consists of a GaAs buffer layer, a 200-Å-thick Al$_x$Ga$_{1-x}$As spacer layer, a 400 Å Si-doped Al$_x$Ga$_{1-x}$As layer, and a 200 Å GaAs cap layer. Two circular disks with diameter $d=200$ and 40 μm were defined by optical lithography. Outside the disk pattern, the heterointerface was removed by chemically etching to a depth of about 2000 Å. Silver microstriplines with a thickness of 0.3 μm were subsequently evaporated on opposite sides of each disk. Their width (200 μm) was adjusted so as to obtain an impedance of 50 Ω for the given substrate thickness of 270 μm. Near the 40 μm disk, the striplines were also tapered down to a width of 40 μm. The spacing between the ends of the striplines and the mesa edges was chosen as $d/2$, close enough so that the rf power seen by the disk remains comparable with the direct crosstalk between striplines, but still far enough to leave the plasma oscillations undisturbed, to a good approximation. The sample is mounted in a LHe cryostat and connected by semirigid coaxial leads. We record the rf transmission either with the help of a rf synthesizer employing homodyne detection ($f<8$ GHz), or by means of a network analyzer ($f>8$ GHz). In the measurements where the magnetic field is swept while the frequency is held fixed, this setup allows a range from below 1 GHz up to ~70 GHz to be covered. In frequency sweeps at fixed B we are able to observe the disk resonances up to ~12 GHz.

Figure 1 displays the rf transmission at $T=4.2$ K as a function of the perpendicularly applied magnetic field and the frequency. For each disk we observe two modes, having both negative magnetic-field dispersion (Fig. 2). They constitute the EMP modes $\omega_{1,-1}$ and $\omega_{1,-2}$ if the spectrum of an electron disk $\omega_{n,\pm m}$ is classified by the radial and azimuthal mode indices n and m, $n=1,2,...$, $m=0,1,...$. The 200 μm disk also exhibits the beginning of the cyclotron-resonance-like mode $\omega_{1,+1}$ with a positive magnetic-field dispersion.

We analyze the measured resonance positions within the framework of the classical theory of EMPs as worked out by

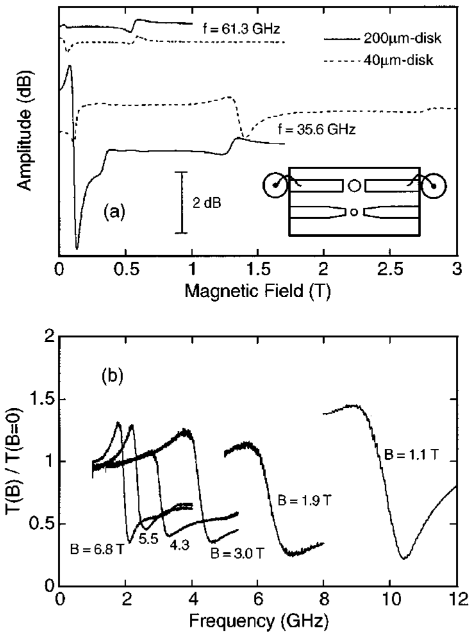

FIG. 1. (a) Transmitted microwave amplitude at fixed frequency f vs magnetic field for single electron disks. The solid (dotted) lines display the signal for the case that the coaxial leads are connected to the striplines leading to the 200 μm (40 μm) disk; the other disk is excited by crosstalk. The inset schematically shows the sample setup. (b) Normalized transmission amplitude vs frequency at fixed magnetic fields for the 200 μm disk.

Volkov and Mikhailov.[10] For a steplike density profile they obtain the resonance frequencies [real part of Eq. (41) of Ref. 10 with the wave-vector q discretized by the disk perimeter $P, q=2\pi m/P=2m/d, m\geqslant 1$]

$$\omega_{1,-m}=\frac{m\sigma_{xy}}{\varepsilon\varepsilon_0 d}\left(\ln\frac{d}{m|l|}+1\right), \tag{1}$$

where the modulus of the quantity

$$l=\frac{i\sigma_{xx}(\omega)}{2\varepsilon\varepsilon_0\omega} \tag{2}$$

can be identified with the width of the strip to which the charges and fields connected with the EMP are localized. Realistic density profiles, however, exhibit a continuous transition of the electron density from zero to the bulk value. Such profiles have been calculated by Chklovskii *et al.* [Ref. 11, Eq. (10); in the following referred to as "model A") and Gelfand *et al.* [Ref. 12, Eq. (7); "model B") and are of the form $n(x)=n_s f(x/h)$, where f is a function that rises from 0 to 1 essentially in an interval $|x|/h\approx 1$ at the edge and h is the lateral depletion length. As $|l|$ generally decreases with increasing magnetic field, one eventually reaches the regime $|l|\ll h$ where, instead of Eq. (1), the EMP dispersion is given by [Ref. 10, Eq. (71)]

$$\omega_{1,-m}=\frac{m\sigma_{xy}}{\varepsilon\varepsilon_0 d}\left(\ln\frac{d}{mh}+C\right), \quad |l|\ll h. \tag{3}$$

The "form factor" C, a dimensionless constant of the order of 1, depends on the specific form of the density profile

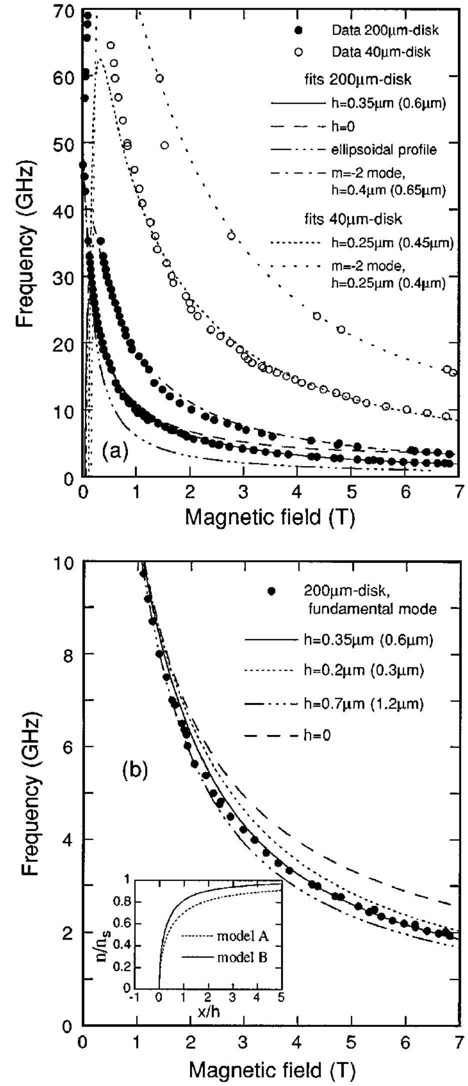

FIG. 2. (a) Positions of the observed magnetoplasma resonances for two disk diameters together with magnetic-field dispersions calculated from Eqs. (1) and (3) using the lateral depletion length h as fit parameter. The two different values of h are obtained for model A (model B), respectively. Also shown are dispersions for an abrupt and for an ellipsoidal density profile. (b) Enlarged view of the low-frequency part of the fundamental EMP mode for the 200 μm disk together with fits using different values of h. The inset shows calculated density profiles for both models.

$$C=-\gamma+\int_{-\infty}^{\infty}d\xi\frac{df(\xi)}{d\xi}\ln\frac{1}{|\xi|}, \tag{4}$$

where γ=0.577... is Euler's constant. Thus, for $|l|\ll h$, the EMP frequency is given in terms of edge profile parameters, in particular the LDL.

We now compare the experimental resonance positions of the two disks with the theoretical dispersion [Eqs. (1) and (3)] for both models of the density profile[13] and determine h from a best fit to the data (Fig. 2). The form factor is calculated as $C=\ln 4-\gamma=0.809$ for model A and $C=2-\gamma=1.423$ for model B. With the Drude expression for the conductivity tensor σ using the carrier density and dc mobility of the sample and the effective mass $m^*=0.067m_e$ and with $\varepsilon=(1/2)(\varepsilon_{\mathrm{GaAs}}+1)=6.8$, we thus find for the LDL h=0.35 μm (model A) or h=0.6 μm (model B). These values are obtained from the fit of the fundamental EMP of the 200 μm disk. The fit to the $m=-2$ mode yields comparable results. The 40 μm disk yields slightly lower values, which may be due to the necessary thermal cycle between the two series of measurements. In Ref. 6 it was pointed out that different cooling rates from room temperature to cryogenic temperatures are believed to be the main cause for fluctuations in the LDL. The theoretical dispersion displayed in Fig. 2 is obtained by suitably interpolating between Eqs. (1) and (3) in the regime $|l|\approx h$ (for our sample parameters $|l|=0.5$ μm at $B=1.7$ T). We emphasize, however, that the determination of h relies on the fit at high B, i.e., for $|l|\ll h$, where Eq. (3) holds. Note that for low magnetic fields the above analysis is no longer valid if $|l|$ becomes comparable with the disk diameter d.

To assess the sensitivity of the above procedure, we show in Fig. 2(b) curves for different values of the LDL. From such fits we estimate the accuracy of the determination of h—for a given model—to be of the order of 20%. Figure 2(a) displays in addition the dispersion obtained numerically for a rectangular profile,[8] i.e., $h=0$ [whose high B side thus coincides with Eq. (1)] and the dispersion $\omega=(\omega_c^2/4+\omega_0^2)^{1/2}-\omega_c/2$, valid for an ellipsoidal density profile.[7] These approximations, which have earlier been employed in the analysis of EMPs, clearly deviate from the experimental data at high B.

The differences in the functional form *f(x/h)* of the density profile arise from specific assumptions of the extension of the edge surface charge. In model A the edge of the 2DES is supposed to originate from a negatively biased gate, so that the external charge seen by the 2DES is distributed over the gate, whereas model B assumes a line charge at the side of an etched mesa in the plane of the 2DES. The resulting profiles are shown in the inset of Fig. 2(b). The faster rise of the density in model B as compared to model A leads, via Eqs. (4) and (3), to larger values of C and h. In other words, the differences in the determination of the LDL arise because the EMP experiment essentially measures the width of the region of inhomogeneous density near the edge, which for a given LDL is smaller in model B than in model A. Since the precise surface charge distribution for an etched edge is not known at present, the values for h obtained in the two models represent a lower and upper bound. With an improvement of the theory of edge electrostatics, the accuracy of our method could therefore be substantially enhanced. Our results are in agreement with the work of Choi *et al.*[6] who have obtained values between 0.3 and 0.8 μm for the LDL in their samples. In comparison to their technique, our method possesses the advantage of avoiding sub-μm lithography and millikelvin temperatures. On the other hand, it requires high frequency equipment and high magnetic fields.

The validity of the Drude approximation entering the above analysis is rather unexpected for the high-magnetic-field regime addressed here, but is justified experimentally by the absence of oscillations in the dispersion as well as in the linewidth (not shown here). Presumably, the inhomogeneous density distribution at the edge averages out any oscillatory character of the magnetoconductivity. To our knowledge, previous investigations of EMPs, where the dispersion and linewidth were found to oscillate with the magnetic field, have either been performed at lower frequencies[14] such that $\omega\tau\ll 1$, or with samples having lower densities.[15] In these cases, the length $|l|$ can assume values larger and smaller than h depending on whether the filling factor is noninteger or integer (or fractional at low temperatures). For our choice of experimental parameters, on the other hand, $|l|$ is always smaller than the lateral depletion length (for the magnetic fields in question) so that a detailed knowledge of σ_{xx} is in fact not needed for the analysis of the dispersion $\omega(B)$.

Apart from the determination of the LDL, our experiment opens the route to the millimeter wave spectroscopy of single mesoscopic electron systems approaching the quantum-dot size. In contrast to arrays of dots, required in conventional transmission setups in order to obtain sufficient signal strength, resonances in single dots can be studied without effects of inhomogeneous broadening or interdot interaction.[16] The necessary shift of the frequency range of the present setup to the millimeter regime can be achieved by using waveguide instead of coaxial leads. The problem of increasing crosstalk between the sender and detector stripline at the dot at higher frequencies could be diminished by scaling down the stripline geometry and working with a triplate (screened) stripline. Other promising approaches to the problem of the spectroscopy of single dots may involve the use of cavities, diaphragms, or planar antennas.

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