Optical Fermi-edge singularities in a one-dimensional electron system with tunable effective mass

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We have investigated the dependence on the magnetic field of the optical absorption and emission of a one-dimensional (1D) electron gas in GaAs quantum wires with one occupied subband. Spectra show a strong Fermi-edge singularity that narrows as the Fermi energy in the wires is continuously reduced by the enhancement of the effective mass in a perpendicular magnetic field. At high fields, when the cyclotron energy is larger than the 1D subband spacing, the lowest optical transition splits into a doublet due to the spatial modulation of the Landau levels by the wire potential.

One-dimensional (1D) electron systems have been extensively studied in search of physics due to confinement and electron-electron interactions.[1–3] Characteristic many-body effects in the electron gas are the origin of the observed intrasubband and intersubband collective excitations,[4–8] and of the strong optical singularity at the Fermi energy.[9–22] In 1D systems (quantum wires) the optical Fermi-edge singularity (FES) is stronger than in 2D (Refs. 9, 12–15) and quasi-3D (Ref. 16) systems. This result has been attributed to the absence of hole recoil effects in 1D (Refs. 9 and 10) systems. Furthermore, the effect of a finite hole mass and the electron-electron interaction on the critical exponent of the 1D FES have also received attention.[22–24]

Many-body effects on the optical properties of the one-dimensional electron gas (1DEG) have been mostly investigated in quantum-well wires (QWW's) created by electrostatic confinement or by shallow processing of modulation-doped quantum wells. Among the latter, wires fabricated by low-energy ion bombardment have a moderate potential modulation,[4,5,9] which for sufficiently narrow wires results in one or two well-defined 1D subbands. Optical transitions in these shallow wires tend to be quasidirect in real space because of the weak potential modulation. This is the origin of the strong singularities observed in these systems.[9] In contrast, samples prepared by reactive ion etching[6,11] or by wet etching[7,25] have spatially indirect optical transitions as a result of the stronger potential modulation. Consequently, in these systems the wave-function overlap decreases, and the FES is not observed. One common and surprising experimental result in GaAs QWW's is the low intensity[9,10] or the total absence of a band-edge peak in the emission spectra resulting from the singularity in the 1D density of states. This fact has been attributed to wire-width inhomogeneities which result in fluctuations of the band-edge energy, while the Fermi level is fixed.[9]

In this article we report on the evolution with magnetic field of the strong optical FES of the 1D electron gas produced in shallow $GaAs/Al_xGa_{1-x}As$ quantum-well wires. The perpendicular magnetic field produces an enhancement of the electron effective mass that causes the continuous reduction of the Fermi energy in the quantum wires. This results in a narrowing of the FES which is still clearly observed for Fermi energies smaller than the inhomogeneous linewidth of the optical transition. In the mesoscopic regime, where the magnetic length becomes smaller than the wire width and the 1D electron system evolves into a quasi-2D structure,[9,26] the lowest optical transition splits into a field-independent doublet. This behavior is interpreted in terms of the spatial modulation of the lowest Landau level by the periodic wire potential. The present results are also relevant to determine the role played by hole localization[18,19] and by coupling to empty conduction subbands[20,21] on the FES intensity.

The sample has been processed from a modulation-doped, 250-Å-thick, single quantum well of GaAs by electron-beam lithography and low-energy oxygen-ion bombardment. The multiple QWW structure has 100-nm-wide lines repeated with a period of 200 nm. This fabrication procedure has been found to be effective in writing shallow QWW's that display strong FES at zero field.[9] The 1D intersubband spacing determined by inelastic light scattering of intersubband charge-density excitations[5] is $E_{01}=2.5$ meV. This value is consistent with a quantum-wire width of about 500 Å. The Fermi energy at zero field, obtained from the fit of the random-phase approximation (RPA) expression[4] to the dispersion of intrasubband excitations, is $E_F=2.0$ meV.[5] The same value is obtained from the width of the photoluminescence (PL) spectra[9] (see below). Therefore only the first 1D electron subband is populated with the Fermi level close to the next empty subband. Photoluminescence (PL) and photoluminescence excitation (PLE) measurements have been performed at temperatures between 1.4 and 24 K with the magnetic field perpendicular to the plane of the QWW's. The light source was a LD 700 dye

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laser with the intensity kept at about 20 μW. The emitted light was analyzed by a double monochromator with multichannel detection.

Figure 1 shows PL spectra of the quantum wires measured at 1.4 K and different magnetic fields. Below 1 T the FES appears as a relatively broad asymmetric band (labeled w) similar to those previously reported.[2,3,9] The Fermi energy is given by the energy difference between the low-energy PL threshold (the subband edge averaged over wire-width fluctuations) and the midpoint of the high-energy cutoff (the fixed Fermi level), as shown in the zero-field spectrum of Fig. 1. As the field increases, the PL band becomes narrower and more symmetric. This indicates a decrease of the Fermi energy, which is accompanied by a weak lowering of the Fermi level, shown by the small redshift observed below 1.7 T. At higher fields, when the cyclotron energy dominates over the 1D confinement, the PL peak shifts to higher energies and a second weak emission (labeled b) appears at 1.5 meV above the main peak.

The values of the Fermi energy obtained from the PL data are shown in Fig. 2 (dots) as a function of magnetic field. The observed decrease of E_F is caused by the field-induced enhancement of the longitudinal electron mass in the quantum wires. For a thin electron slab, where the quantum wires are represented by an harmonic-oscillator potential, the Fermi energy given by[27]

$$E_F = \frac{E_F^0}{1+\omega_c^2/E_{01}^2} , \tag{1}$$

where ω_c is the cyclotron energy. The solid line in Fig. 2

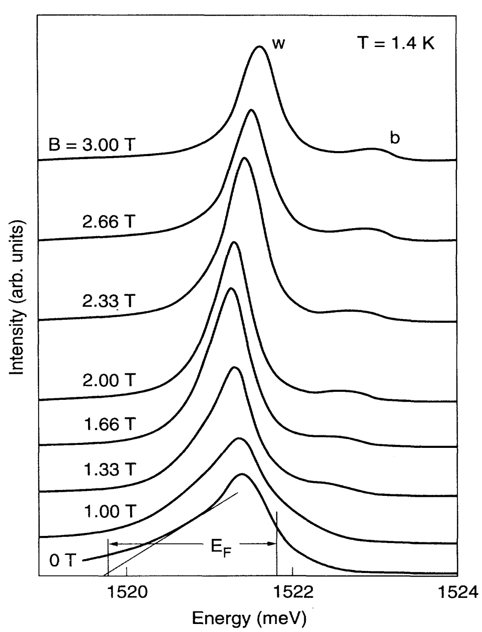

FIG. 1. PL spectra of the quantum wires with one occupied electron subband taken at 1.4 K for different magnetic fields. The Fermi energy is evaluated from the spectral shape as explained in the text.

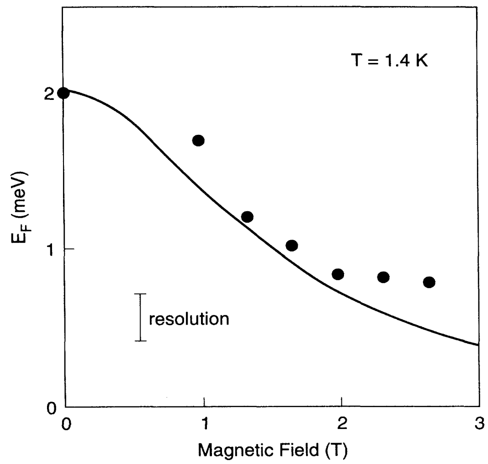

FIG. 2. Measured (dots) and calculated (solid line) dependences of the Fermi energy with the magnetic field. For the calculation, Eq. (1) has been used with $E_F^0=2$ meV and $E_{01}=2.5$ meV. The experimental resolution is indicated by the vertical bar.

represents the prediction of Eq. (1) using the experimental value of $E_F^0=2.0$ meV obtained from the zero-field data. The agreement with the measured energies is very good below 2 T. At higher magnetic fields E_F becomes smaller than the inhomogeneous broadening of the emission band ($\sim$0.8 meV), and cannot be determined from the PL spectral width.

With increasing magnetic field the 1D intersubband spacing, and therefore the energy difference between the Fermi level and the next empty conduction subband, increases in proportion to the cyclotron energy. In 2D systems a large enhancement of the optical FES is observed when the Fermi level approaches an empty conduction subband, which arises from the coupling of the electron gas to excitonic transitions from empty subbands.[10,14,20] For the quantum wires we find that the FES measured in optical emission changes remarkably little with the field. We thus conclude that the effect of coupling to higher subbands on the strength of the FES is not significant in the present 1D systems.

The PLE spectra for different magnetic fields are shown in Fig. 3. At 1 T a single peak is observed in the PLE spectra, which corresponds to the FES. Similar to that seen at zero field,[9] this peak exhibits a Stokes shift of 1 meV with respect to the PL emission band represented by the dotted line. Above 1.7 T the PLE emission splits into two peaks which coincide with the PL ones, whereas the Stokes shift between PL and PLE practically disappears. The absence of a Stokes shift is interpreted as an indication of a negligible localization energy for the holes,[28] even if they can have a large mass resulting from fluctuations in the wire width. With increasing magnetic field the peaks w and b measured in PL and PLE show a similar blue shift while keeping their energy difference of 1.5 meV essentially constant up to 11 T. Thus these optical transitions cannot be assigned to different electron subbands, as their energy difference would increase pro-

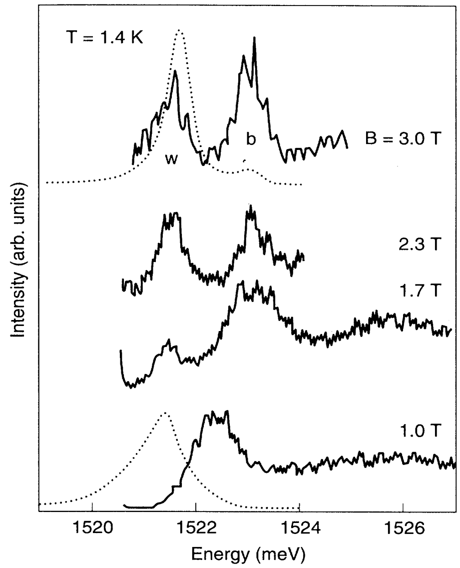

FIG. 3. PLE spectra (solid lines) taken at 1.4 K for different values of the magnetic field. PL spectra at 1 and 3 T are also shown (dotted lines).

portionally to ω_c with the field.

The temperature dependence of the PL spectrum at 3 T is shown in Fig. 4. The strong decrease in intensity of the main PL peak is a signature of the many-body character of the FES.[9] In contrast, peak *b* changes its intensity only slightly upon heating. This speaks against the possibility that peaks *w* and *b* originate from different hole states. If this were the case, both peaks would have a similar many-body enhancement and display a similar temperature dependence, as reported for heavy and light holes at zero field.[9] Moreover, the temperature dependence of peak *b* is inconsistent with the Boltzman population distribution of two hole states separated by 1.5 meV.

The splitting of the lowest optical transition is interpreted as the consequence of the spatial modulation of the electron Landau levels by the periodic 1D potential. Such modulation occurs in a 2D electron gas when a small periodic electrostatic potential is superimposed on the perpendicular magnetic field.[29,30] This leads to the formation of energy minibands because the energy of the Landau states depends on the orbit-center coordinate. In our case this effect is produced by the wire potential, and thus the energy of the lowest conduction state will be spatially modulated, having peaks in the density of states (DOS) at the energy minima and maxima, as indicated schematically in Fig. 5. The minima at the center of the wires are populated by electrons, and the maxima at the interwire barriers are essentially empty. Optical transitions from the minima to the first hole state result in peak *w*, while the much weaker *b* emission originates from residual (or hot) electrons at the interwire maxima. As the electrons are concentrated in the wires the many-body effects that give rise to the FES are present only in the low-energy peak (w). The estimated amplitude of the wire potential of around 5 meV (Ref. 31) is larger than the observed splitting (1.5 meV) of the optical transition. This might result from a difference in binding energy between the FES and the excitons formed by hot electrons in the barriers. As the same electron subband is at the origin of the two observed peaks, one can understand that both have the same energy dependence on the magnetic field.

In conclusion, this work shows the evolution of the optical FES in a 1D electron system when its Fermi energy is continuously reduced by a magnetic field. Such measurements probe the mesoscopic regime where the magnetic length is comparable to the wire width. We find that the optical transitions associated with the 1D Fermi

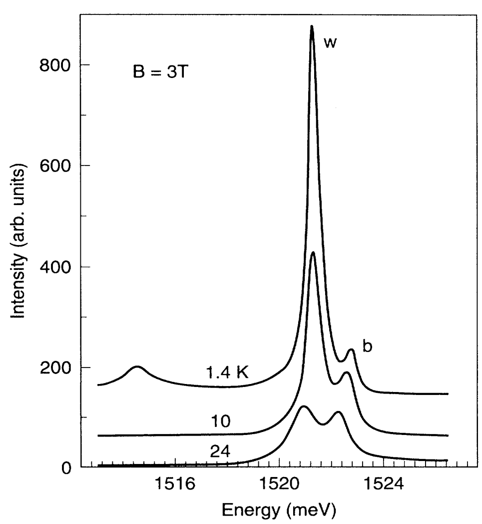

FIG. 4. PL spectra of the quantum wires for 3 T and different temperatures.

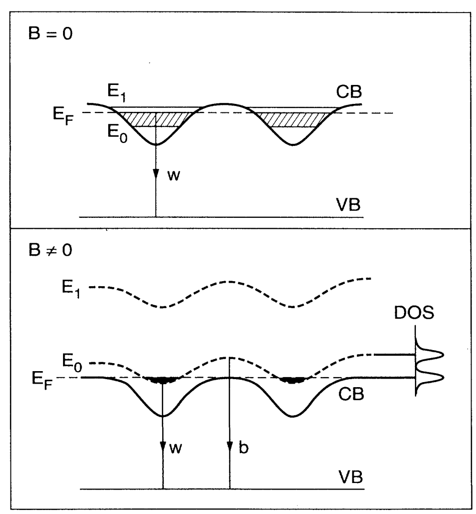

FIG. 5. Schematic representation of the energy diagram of the QWW in the magnetic field showing the modulation of the Landau levels, the resulting density of states, and the transitions associated with peaks *w* and *b*.

sea retain their many-body character even in the limit when the Fermi energy is lower than the inhomogeneous excitonic width. The spatial modulation of the lowest Landau level by the wire potential is revealed in the optical spectra by a nearly field- and temperature-independent splitting of the main emission band. Coupling of electrons in the occupied conduction subband to empty ones plays a minor role on the FES intensity in our quantum wires.

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