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Optical emission of a one-dimensional electron gas in semiconductor V-shaped quantum wires

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The optical emission spectrum of a one-dimensional electron gas has been studied in modulation-doped GaAs quantum wires grown by molecular-beam epitaxy on V-grooved substrates. At low temperatures the spectra are dominated by a strong Fermi-edge singularity, as in previously reported results for ion-milled quantum wires. The emission spectral shape and its temperature dependence are identical for both sets of wires, revealing a kind of universal behavior. Comparison with calculations based on the Fermi-liquid model indicate a significant coupling between the electron system and empty conduction subbands. [S0163-1829(98)03639-X]

I. INTRODUCTION

One-dimensional electron systems (1DES's) have been intensively studied during this decade because of the new basic physics expected from the special characteristics of the Coulomb interaction in one dimension. In principle, 1DES's are also interesting for optical and transport applications, due to their singular density of states (DOS) and their special screening properties. According to existing theories, electron-electron interaction in an ideal 1DES leads to a highly correlated system known as the Tomonaga-Luttinger liquid,[1] at difference with 2D or 3D systems, where electrons are well described as a Fermi liquid. Real 1DES's have been studied in doped semiconductor quantum wires (QWR's) fabricated by different methods.[2–8] In particular, optical emission[3] and inelastic light scattering measurements[4] of QWR's fabricated by electron-beam patterning and subsequent ion milling of a doped quantum well were found to be consistent with calculations based on the Fermi-liquid model. This can be understood because damping of virtual plasmons by impurity scattering and wire-width fluctuations restores the Fermi-liquid behavior in real 1DES's.[9] Their emission spectra are dominated by a strong singularity at the Fermi level (FES), with no traces of the density of states (DOS) singularity at the band edge. This *a priori* surprising result raises the important question of whether the observed lack of band-edge singularity in the optical emission is due to the presence of defects or inhomogeneities in the wires resulting from the particular fabrication process, or to intrinsic collective effects generally occurring in 1DES's. Many-body calculations based on both the Fermi liquid[10–13] and the Luttinger model[14–17] predict the existence of the FES with some differences, which have not led yet to an experimental exclusion of one of the models. The Fermi-liquid calculations for perfect wires do explain qualitatively the main FES characteristics, as its spectral shape and temperature dependence, even if they do not account for the observed lack of band-edge singularity. On this point, it has been reported that the 1D-DOS singularity is effectively suppressed by electron-hole correlation effects, both in the case of single excitons and in a two-component plasma.[18]

In this paper the optical emission spectrum of doped QWR grown on V-groove patterned substrates[19,20] is studied, with the aim to answer the above mentioned question. The present wires display well-defined 1D quantized transitions, and their emission spectral shape is practically identical to that of ion-milled wires reported previously.[2,3] They show also a strong FES with the same temperature dependence, in spite of the very different way in which both sets of wires were fabricated. This seems to indicate a universal behavior of the optical emission of 1DES. The FES temperature dependence can be understood assuming a Fermi-liquid model with coupling of the last occupied conduction subband to the first empty one. As far as we know there are no quantitative predictions of the Luttinger model for the FES temperature dependence. Such a calculation would be useful to decide if the observed optical properties of real 1DES can distinguish between the two models.

II. EXPERIMENT

Quantum wires of GaAs have been grown by molecular-beam epitaxy on V-groove patterned GaAs substrates. The substrate grooves were produced by optical lithography. They have a 250-nm period and 70-nm depth. A nominally 10-nm-thick GaAs layer was deposited between two short-period superlattices (40 periods of 4 ML of GaAs and 2 ML of AlAs) acting as potential barriers. The resulting V-shaped GaAs wires have been studied by transmission electron microscopy (TEM). Cross-section TEM (XTEM) sample preparation has been carried out by mechanical thinning and Ar^+ ion milling. XTEM studies have been performed with a Jeol

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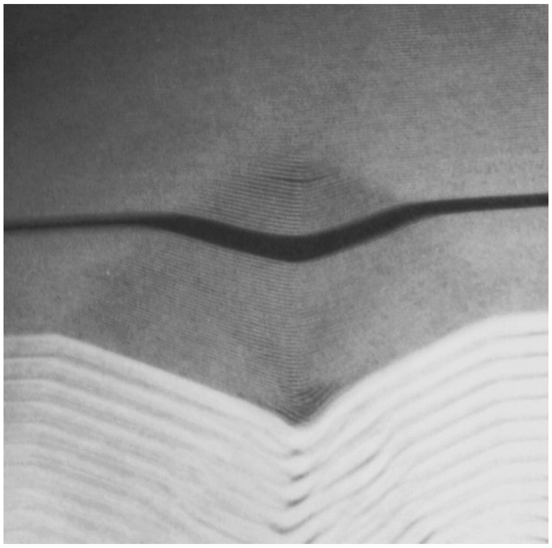

FIG. 1. (004) Dark field XTEM image of a defect-free quantum wire. The 1DES is located at the wider part of the GaAs well, shown by the dark stripe.

1200 EX transmission electron microscope. The wires have a maximum width of 12 nm in the growth direction at the bottom of the grooves. The GaAs layer thickness between wires is around 6 nm (see below). A δ-doping Si layer (10^{12} cm^{-2}) was deposited in the upper barrier to produce the 1DES in the wires. Part of the sample substrate was left unpatterned to keep a 2D reference for the electron system. The estimated electron concentrations are $n_{2D}=4\times10^{11}$ cm^{-2} for the unpatterned quantum well and $n_{1D}=9\times10^{5}$ cm^{-1} for the wires, respectively, as explained in the next section. They correspond to Fermi energies of 16 and 12 meV, respectively. Photoluminescence (PL) and photoluminescence excitation (PLE) spectra were excited at variable temperatures with a Ti-sapphire laser with 1 mW power and analyzed by a double spectrometer with photon counting detection.

III. RESULTS AND DISCUSSION

The cross-sectional TEM image shown in Fig. 1 corresponds to one of the fabricated wires. The dark stripe is the GaAs quantum well, with the wire formed at its wider part, in the center of the groove. The fine structures at both sides are the short-period superlattices acting as vertical barriers. The lateral confinement is provided by the narrowing of the GaAs layer away from the center of the groove.[19] Most of the wires observed by XTEM are defect free. However, a number of planar defects have been observed in the studied heterostructure. These planar defects emerge from the interface between the superlattice and the substrate. A weak beam TEM study of such defects shows that they are connected with the lateral walls of the V grooves. Also, some isolated dislocations have been detected in the top region of the epilayer.

The PL and PLE spectra of the reference quantum well are shown in Fig. 2(a), to be compared with those of the wires [Fig. 2(b)]. The 2D-PL spectrum has the usual shape for a two-dimensional electron gas, extending in energy from the band edge to the Fermi level. Its width, once corrected by the valence-band curvature factor $(1+m_e/m_h)$, where m_e and m_h are the conduction- and valence-band effective masses, respectively, corresponds to a Fermi energy of 16 meV approximately. Because of the finite hole mass and the low temperature (2 K), no FES is observed. The double structure at the onset of the PLE spectrum corresponds to transitions from heavy- and light-hole states to the Fermi level.

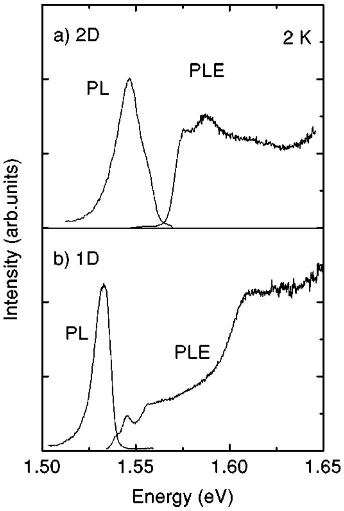

FIG. 2. PL and PLE spectra of the 2D reference (a) and the V-groove wires (b) at 2 K.

In the 1D PL spectrum shown in Fig. 2(b) the spectral weight is mainly at the Fermi level. The emission intensity decreases to lower energies without any visible feature at the band edge, as in the wires of Ref. 3. The Fermi energy of 12 meV is obtained from the difference between the Fermi level and the band edge, estimated by extrapolation to zero intensity of the low-energy side of the spectrum.[3] The PLE spectrum of Fig. 2(b) displays the 1D fine structure near the Fermi level. It can be observed only under carefully controlled conditions of illumination and cooling rate, probably because electron redistribution to interface defects takes place during the optical measurements, thus changing the lateral confining potential. The 1D intersubband spacing observed in Fig. 2(b) is 9 meV, so that only two 1D conduction subbands are occupied by electrons. The 1D spacing can be roughly estimated using a simple calculation based on a model potential for V-groove wires.[19–21] For the experimental value of 9 meV this model provides an effective lateral wire width of 20 nm, which is not inconsistent with Fig. 1. The broad step around 1.6 eV is attributed to the formation of a ''vertical'' well due to preferential Ga migration in the barriers.[22,23]

PL spectra of the present V-groove QWR taken at different temperatures are shown in Fig. 3(b). The PL intensity decreases very quickly as the temperature increases, as expected from theory,[10–13] due to the loss of coherency in the response of the electron system. Similar spectra of wires belonging to the same series as those reported in Ref. 3 are presented in Fig. 3(a). They were fabricated by electron-beam patterning of a modulation-doped quantum well, followed by ion milling. The resulting 1DES has a Fermi energy and 1D subband spacing of 3.5 meV and 5 meV, respectively.[3] The peak at 1.515 eV in the ion-milled sample

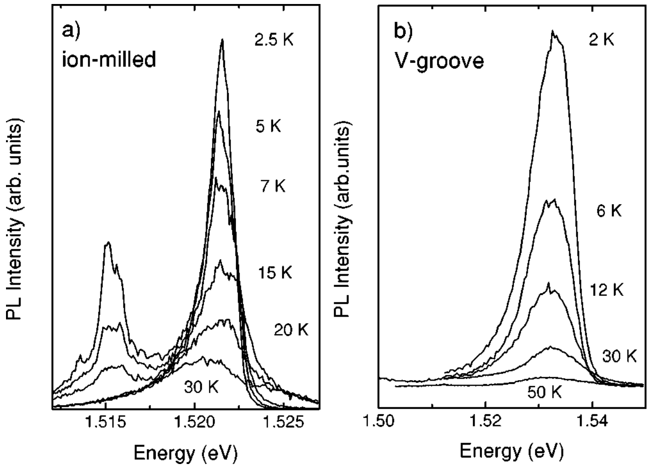

FIG. 3. PL spectra at different temperatures of the ion-milled wires (Ref. 3, a) and the V-groove ones (present work, b).

is due to the D^0-X bound exciton of the GaAs substrate. In contrast to the present V-groove wires, which are ''direct'' in real space, the ion-milled wires are ''indirect,'' as electrons and holes are spatially separated by the periodic lateral potential. In spite of the different characteristics of both kinds of wires, their PL spectra are remarkably similar. Even if the spectral positions and widths at low temperatures are different for the two sets of wires, due to the different wire dimensions and electron densities, the overall spectral shape and its evolution with temperature are practically identical in both cases.

The FES dependence on temperature is better observed in Fig. 4, where the PL maximum intensity for the ion milled wires (full dots) and the V-groove wires (open dots) are plotted versus temperature. The data are normalized to their value at the lowest temperature. This is to be compared with the PL exciton-emission intensity of similar undoped V-groove wires (dashed line), taken from Ref. 23, which is essentially independent of temperature in this range. The FES intensity and its evolution with temperature are strongly affected by conduction intersubband coupling.[11,24,25] In Fig. 4 we also present published theoretical results for spatially direct wires with one occupied conduction subband and no intersubband coupling[10] (open squares) and for spatially indirect wires with maximum coupling of the Fermi sea to the first empty conduction subband[11] (full triangles). The straight lines are drawn as a guide for the eye. They are not indicating a linear dependence of the FES intensity with temperature. One observes that the experimental data lie between the two theoretical predictions. This can be understood considering that some intersubband coupling is present in both sets of wires. The lateral inversion symmetry breaking, necessary for the coupling to exist,[11] is mainly produced by wire width fluctuations in the V-groove wires and by the spatially indirect character in the ion-milled ones.

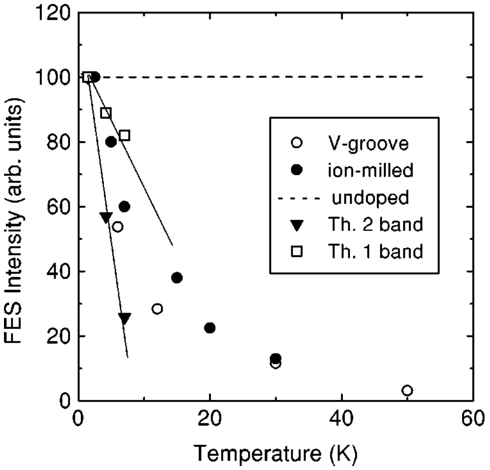

FIG. 4. FES intensity vs temperature for the ion milled wires of Ref. 3 (full dots), the present V-groove wires (open dots), undoped wires from Ref. 23 (dashed line), calculations with intersubband coupling from Ref. 11 (full triangles) and without coupling from Ref. 10 (open squares). The straight lines are drawn as a guide for the eye.

The close similarity of the PL spectra for ion-milled and V-groove wires, and their identical temperature dependence show that the coherent response of the electrons around the Fermi level leading to the appearance of a strong FES is a general characteristic of 1D electron systems, irrespective of the details of wire fabrication. The possibility of hole localization due to defects or wire inhomogeneities, which is known to enhance FES,[10–13] can certainly be present in both kinds of wires. The experimental lack of band-edge singularity can be attributed partially to disorder broadening, but we believe that it is mainly a consequence of intrinsic Coulomb correlation effects resulting in a vanishing oscillator strength for the band-edge transition (Sommerfeld factor),[18] which presumably occur also in single-component plasmas.

IV. CONCLUSIONS

Optical emission by 1D electron systems has been studied in V-groove GaAs quantum wires and compared with previously reported results on ion-milled wires. The emission spectra present general characteristic features, which are independent of the wire fabrication procedure. The spectra are dominated by collective phenomena resulting in a strong Fermi-edge singularity, and the lack of a visible DOS singularity at the band edge. While this lack can be attributed partially to disorder and to many-body effects, the FES and its temperature behavior can be understood on the basis of the Fermi-liquid model including conduction intersubband coupling. Calculations of the FES temperature dependence based on the Tomonaga-Luttinger model would be of interest to determine if experiments of this kind can distinguish between the two models.

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