Electron Gas in Semiconductor Multiple Quantum Wires: Spatially Indirect Optical Transitions

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In optical experiments with laterally patterned GaAs quantum wells we observe confinement of free carriers to motion in one dimension. Optical recombination of band-gap transitions shows that free electrons and holes are confined in spatially indirect type-II multiple quantum wires. Resonant-inelastic-light-scattering spectra show intersubband excitations of the one-dimensional electron gas. From the optical measurements we obtain the Fermi energy as well as subband spacings and determine the linear free-electron density.

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Advances in epitaxial growth and in nanometer-scale lithography have made it possible to fabricate semiconductor structures which exhibit one- and zero-dimensional properties. Semiconductor quantum wires and boxes have been found to exhibit new structure[1-4] or energy shifts[5,6] in their photoluminescence (PL) spectra which have been ascribed to excitonic confinement effects. Transport properties of modulation-doped quasi-one-dimensional structures such as electron waveguiding,[7] quantization of resistance,[8] and quenching of the Hall effect[9] have also been observed. Reed *et al.*[10] observed resonant tunneling into quantum boxes. Less work has been done on the optical properties of one- and zero-dimensional modulation-doped structures. Hansen *et al.*[11] and, more recently, Heitman *et al.*[12] have observed intersubband resonances in a quasi-one-dimensional electron gas by means of infrared absorption.

This Letter reports the observation of optical properties of a semiconductor one-dimensional (1D) electron gas that are markedly different from closely related two-dimensional (2D) systems. Band-gap optical absorption and emission in GaAs-(AlGa)As multiple-quantum-wire structures reveal properties of conduction- and valence-band states that are not obtainable from transport or infrared absorption measurements. Resonant inelastic light scattering is used to measure the energy spacings between the electron-gas states confined to one dimension. In these experiments we have determined that the lower states of electrons in conduction subbands and of holes in valence subbands show 1D confinement in adjacent, spatially separated quantum wires. We describe this behavior as a type-II multiple-quantum-wire heterostructure.[13,14]

Multiple quantum wires are fabricated from modulation-doped GaAs/AlGaAs single-quantum-well heterostructures grown by molecular-beam epitaxy on a GaAs substrate. The procedure is schematically shown in Fig. 1. The as-grown 2D electron-gas structure consists of a 250-Å-thick GaAs quantum well, separated from the surface by a 1000-Å-thick *n*-type delta-doped $Al_{0.3}Ga_{0.7}As$ layer and a 40-Å-thick GaAs cap layer. The 2D electron density and mobility are $n=2.9\times10^{11}/cm^2$ and 1.4×10^6 cm^2/Vs, respectively. 200-$\mu m\times5$-mm regions of the sample were patterned into 1000-Å lines with period $d=2000$ Å by means of electron-beam lithography.[15] Scanning-electron-microscope photos showed the lines to be uniform to within $\pm10\%$. The sample was then ion milled to selectively deplete the electron gas in the unmasked regions.[16,17] Similar structures were also fabricated by depositing a 1000-Å-thick layer of silicon nitride on the surface and then patterning lines into the silicon nitride by means of electron-beam lithography and reactive ion etching. The electron density was found to be substantially reduced under the silicon nitride and restored where it had been removed. In both types of samples the lateral modulation of the charge density induces a periodic lateral potential which confines the electron gas to one dimension.

The low temperature (~3 K) PL and inelastic-light-scattering spectra were excited with a cw infrared dye laser. A cylindrical lens was used to focus the laser to a 50-$\mu m\times4$-mm spot. Qualitatively similar spectra are observed in both samples. In the discussion that follows, we will therefore focus on the spectra of the ion-milled

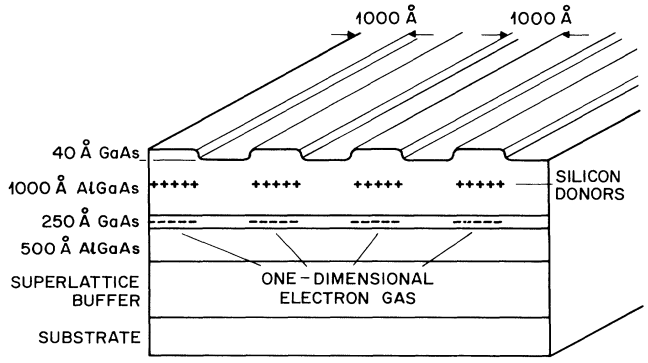

FIG. 1. Schematic diagram of the lateral multiple-quantum-wire heterostructure fabricated by selective ion milling as described in the text and Ref. 15.

wires.

The PL and photoluminescence excitation (PLE) spectra of the as-grown quantum well and of the ion-milled multiple quantum wires are shown in Figs. 2(a) and 2(b), respectively. The PL from the as-grown quantum well is similar to that of Pinczuk *et al.*[18] It exhibits an onset at 1.51 eV, peaks at close to the band gap of 1.514 eV, and then falls with increasing photon energy due to the Boltzmann distribution of the holes up to an abrupt cutoff at the Fermi level at 1.524 eV. The quantum efficiency of the PL from the quantum wires is comparable to that of the as-grown sample; however, the spectral line shape is dramatically different. It shows an onset at 1.512 eV, but, the PL intensity increases with increasing energy, reaching peak intensity at 1.521 eV, just below the cutoff due to transitions at the electron Fermi level at 1.523 eV. The peak at 1.514 eV is PL from the substrate.

The excitation spectrum of the as-grown sample is shown in Fig. 2(a). It exhibits an onset at the Fermi energy, followed by two broad peaks due to transitions from the lowest heavy-hole (H_0) and light-hole (L_0) subbands to the Fermi level (E_F) located within the lowest conduction subband L_0. Four sharper peaks are observed at higher energies due to excitonic transitions between the valence bands and higher-energy conduction subbands. The sharpness of these peaks is indicative of the high quality and uniformity of the sample. The excitation spectrum of the quantum wires is shown in Fig. 2(b). The absorption edge and the L_0E_F and H_0E_F transitions are shifted to lower energy than those of the as-grown sample, whereas, the higher-lying transitions are blueshifted and broadened.

Depolarized light-scattering spectra of the quantum wires are shown in Fig. 3. In Fig. 3(a) a peak at about 2.2 meV is seen when the laser photon energy is in the range of H_0C_1, the transition to the first excited conduction subband. As the photon energy is increased, the peak increases in intensity and shifts to about 2.6 meV [Fig. 3(b)]. As the incident photon energy is increased still further [Fig. 3(c)] the peak becomes weaker and a second peak appears at 4.6 meV. When the focal spot is shifted off the wires the peaks disappear. Similar structure is seen in polarized spectra.

The PL spectrum of the quantum wires can be understood as follows. The periodic lateral modulation of the doping induces a corresponding lateral modulation of the potential, shown schematically in Fig. 4(a). This potential confines the electrons and holes in laterally spatially separate regions of the sample, forming a type-II lateral multiple-quantum-wire heterostructure. As shown in Fig. 4(a) the lowest-energy recombination transitions will occur at energy less than the band gap because of the lateral band bending. Their intensity is weak, however, because the electrons and holes are well confined in spatially separate regions. There is more spatial overlap between the higher-energy, less confined, subbands and so the luminescence intensity increases at higher energy.

The sharp onset of the absorption edge indicates that the spatial overlap between the hole wave functions and electron wave functions at the Fermi energy is quite large, implying that the height of the lateral conduction-band potential is comparable to the Fermi ener-

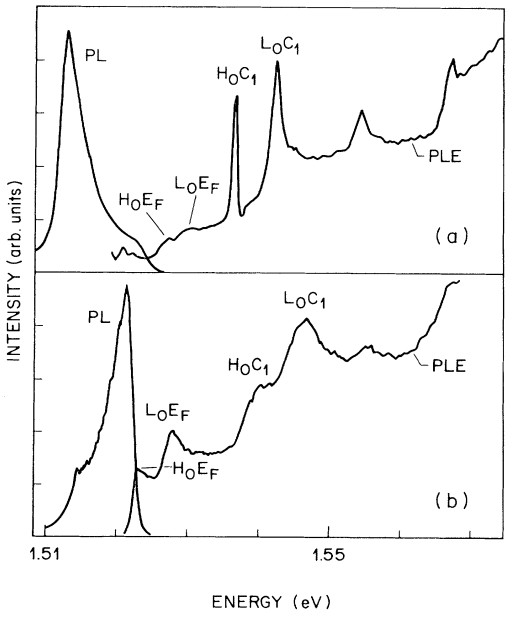

FIG. 2. Photoluminescence (PL) and photoluminescence excitation (PLE) spectra for (a) the as-grown single-quantum well and (b) quantum wires fabricated by selective ion milling.

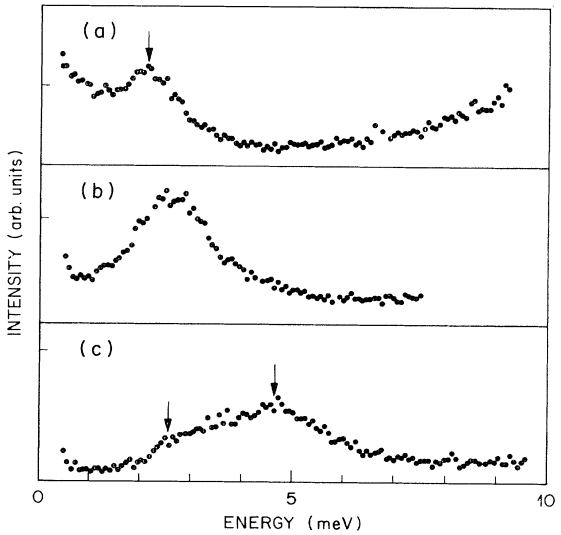

FIG. 3. Inelastic-light-scattering spectra of quantum wires obtained with incident photon energies of (a) 1.5383 eV, (b) 1.5402 eV, and (c) 1.5422 eV.

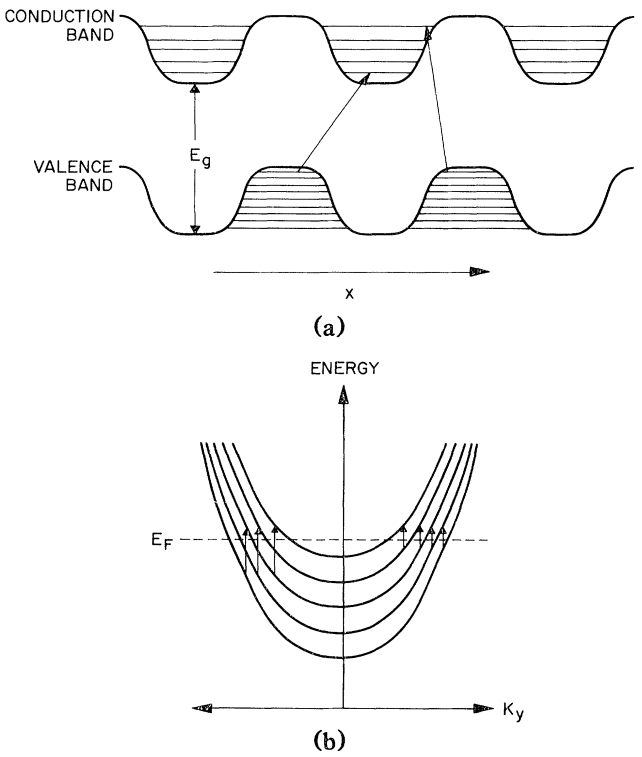

FIG. 4. (a) Schematic representation of the lateral potential induced by the lateral spatial modulation doping. (b) Schematic representation of 1D subbands as a function of wave vector parallel to the quantum wires (K_y). The arrows represent vertical 1D intersubband transitions which can contribute to the inelastic light scattering.

gy. The redshift of the absorption edge in the quantum wires is due to the decreased band gap of the spatially indirect transitions. The reduced electron-hole overlap tends to decrease the exciton binding energy. This could explain the broadening and blueshift of the higher-energy excitonic peaks in the PLE spectrum.

We interpret the light-scattering peak near 2.2 meV as due to the lowest-energy 1D intersubband excitations. We rule out grating assisted coupling to 2D plasmons[19] because for the grating wave vector ($2\pi/d$) and electron density of our system this would occur at a plasmon energy of about 9 meV. There is little difference in the peak position between polarized and depolarized spectra. This implies that collective interactions within the electron gas are small in this energy range, and that peak energies are close to spacings between adjacent 1D subbands. As shown on the right-hand side of Fig. 4(b) several different vertical transitions between adjacent 1D subbands can contribute to the light scattering. This would tend to broaden the lines. The observed linewidths are about 1.5 meV, which implies that the 1D subbands are almost equally spaced. The peak which appears at 4.6 meV is assigned to the higher-energy 1D intersubband transitions shown on the left-hand side of Fig. 4(b). It is resonantly enhanced at higher incident phonon in a way similar to that observed in electronic Raman scattering in 2D systems.[20] We note that in some of the PL spectra of the wires there is a hint of structure with 2-meV spacing which may be due to the additional lateral confinement.

The light-scattering spectra of the quantum wires also exhibit peaks in the range of the intersubband excitation between C_0 and C_1 subbands of the as-grown sample (25–30 meV). The splitting of the subbands by the quantum-wire potential broadens and shifts these excitations. In the quantum wires we find that the onset of the C_0 to C_1 excitations is ~ 1 meV below that of the as-grown sample. As the incident photon energy is increased, peaks are observed at increasing energies in a manner similar to that of Fig. 3(b). We attribute this behavior to transitions between different 1D subbands derived from the C_0 and C_1 states. In agreement with this interpretation, excitations are found to cover a range of ~ 8 meV, comparable to the 1D Fermi energy.

We estimate the 1D subband spacings in the following manner. The lateral confinement potential is represented by a 1000-Å finite square well with barrier height equal to the Fermi energy. Using a transmission-resonance model[21] we calculate the energy spacing of the first two subbands to be 1.3 meV. This model would tend to underestimate the level spacing since self-consistent calculations[22] show that the potential at the electron gas due to a narrow gate is neither parabolic nor square, but, something in between; hence, this is consistent with the spacing of 2.2 meV that we observe.

Our results lead to a unique determination of the 1D electron density. The shift between the onset of the PL and the absorption edge gives the Fermi energy of the electron gas. Using electron and hole effective masses of $m_e = 0.068 m_0$ and $m_h = 0.39 m_0$ and correcting for the curvature of the valence band[18] gives $E_F = 9$ meV. Assuming equal subband spacing, we estimate that five 1D subbands are occupied. We calculate a linear carrier density of $N_{1D} = 2.6 \times 10^6$/cm. Assuming that the confinement region is $L = 1000$ Å wide, the areal density is $N_{1D}/L = 2.6 \times 10^{11}/\text{cm}^2$, which is consistent with the carrier density of the as-grown quantum well.

In conclusion, our optical measurements reveal new behavior of free carriers in a type-II quantum-wire heterostructure. These results show that optical methods have a fundamental role in studies of the electron gas in novel semiconductor nanostructures.

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