Direct Magneto-Optical Observation of a Quantum Confined One-Dimensional Electron Gas

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The energy spectra of isolated one-dimensional (1D) electron channels have been studied by photoluminescence in zero and finite magnetic fields B. Arrays of periodic quantum wires (period = 290–400 nm, width = 150–170 nm) were etched from modulation-doped $Al_xGa_{1-x}As/GaAs$ heterojunctions, with special low-concentration Be δ doping in the buffer layer to increase the photoluminescence intensity. We were able to attain the 1D quantum limit, i.e., occupation of only the lowest 1D subband at $B=0$, and to measure, at small B, a characteristic quadratic B dispersion of the 1D subband edge.

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Molecular-beam epitaxy (MBE) has enabled the realization of two-dimensional (2D) structures with sharp interfaces [1] and high electron mobilities [2], producing much novel and unexpected physics. Recently, interest has turned to reducing the dimensionality still further in order to discover new or enhanced optical and transport phenomena. Improvements in lithographic and dry-etching techniques have now made the fabrication of quantum wires and boxes possible. Investigations of these structures have, so far, mainly concentrated on three areas: transport properties [3–5], far-infrared studies [6–8], and the optical properties of undoped systems [9–11]. Considerably less has been reported, to date, on optical measurements on modulation-doped 1D systems [12,13] and none at all, to our knowledge, in magnetic field.

In this Letter we report the results of magnetoluminescence experiments on deep mesa-etched [14] $Al_xGa_{1-x}As/GaAs$ heterojunction quantum wires, where the active layers have been etched through to produce completely isolated one-dimensional (1D) channels. We have realized and observed the 1D quantum limit, i.e., occupation of only the lowest 1D subband at zero magnetic field. The photoluminescence (PL) spectra directly reflect the 1D density of states while the 1D subband edge displays a characteristic quadratic magnetic-field dependence. With only one 1D subband occupied, self-consistent screening effects should be small [15], thus enabling us to analyze the magnetic-field dependence and hence to determine directly the 1D confinement energy and to estimate the width of the actual 1D confinement potential.

The quantum wires were prepared from $Al_xGa_{1-x}As/GaAs$ ($x=0.3$) heterojunctions which were grown by MBE with a δ layer of acceptors (Be) located in the GaAs at 25 nm from the interface to increase the PL intensity [16]. To prepare the wires, as depicted in the inset of Fig. 1, the sample was first covered with 100 nm of photoresist. The superposition of two expanded coherent laser beams from the 458-nm line of an Ar^+ laser was used to holographically expose the sample such that a periodic profile was produced after development. With an optimized reactive ion etching in $SiCl_4$ plasma, rectangular grooves of 92-nm depth were etched through the 10-nm GaAs capping layer, the 48-nm Si-doped AlGaAs, the 24-nm-wide AlGaAs spacer, and into the active GaAs to a depth of 10 nm, such that the free electrons were confined in 1D wires [14], while the Be δ layer and the 100-nm buffer layer remained intact. The periodicity and wire width were determined using a scanning electron microscope. On each quantum-wire sample a small part was kept unpatterned to obtain reference 2D spectra. The nonequilibrium carriers were created using an Ar^+ laser in multimode operation and the luminescence spectra were recorded in the Faraday configuration and analyzed using a double spectrometer with an overall spectral resolution of 0.5 meV. Measurements were taken in magnetic fields (B) up to 13 T using an optical fiber. In the 2D sample the optical transition investigated was that

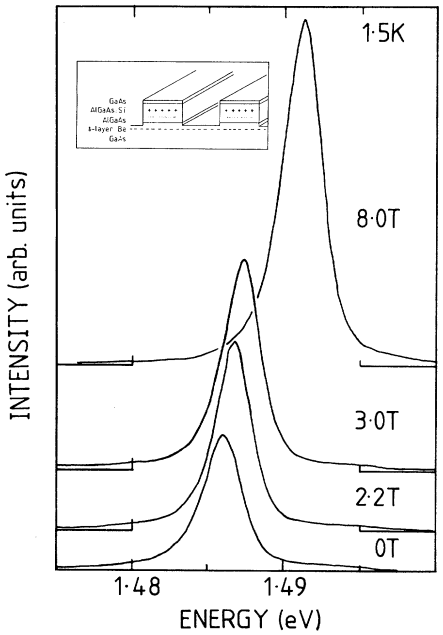

FIG. 1. Luminescence spectra at various magnetic fields for the quantum wires. The absolute intensity is about a factor of 100 smaller for the wires compared to that from the 2D reference. Inset: Schematic diagram of the quantum-wire heterostructure.

due to the free electrons confined at the interface recombining with photoexcited holes bound to acceptors from the δ layer. A series of gratings etched into Al_xGa_{1-x}-As/GaAs heterojunctions with grating periods $a=290$–400 nm and geometrical widths varying from $t=150$ nm to 170 nm showed essentially the same behavior. Here we give results from two samples, No. 1 and No. 2, both with $a=400$ nm and $t=160$ nm, as examples.

In Fig. 1 we show luminescence spectra for the quantum-wire sample No. 1 at different magnetic fields B. Each spectrum consists of only one rather narrow peak whose position shifts with increasing B. To understand these spectra we compare them with 2D PL spectra from the as-grown reference heterojunction (Fig. 2). The 2D spectrum is very typical for one of these structures under laser illumination. The main luminescence signal is due to emission from the lowest subband. For 2D samples with a large electron concentration n_s the PL spectrum directly reflects the density of states (DOS) of the 2D system below the Fermi energy. The PL spectrum is essentially flat from the bottom of the conduction band E_0 up to the Fermi energy E_F [17]. (On a closer look, there is a small decrease in intensity to higher energies due to the recombination process being less efficient at larger wave vectors [16].) We can thus determine n_s via the 2D DOS from the width of the 2D PL spectra and also from the depopulation of the Landau levels with increasing magnetic field. For the sample in Fig. 2 we have hence evaluated a fairly low electron concentration ($n_s=2\times10^{11}$ cm^{-2}) and thus the flattening in this case is not really pronounced. The exact position of E_0, the bottom of the band, is strongly dependent on the carrier concentration which can be significantly altered by illumination [17]. The high-energy peak in Fig. 2 is due to the second subband which is barely occupied. That the latter is occupied at all is a result of the 2D intersubband spacing being severely reduced under illumination (to 8 meV in this case). The luminescence intensity of the quantum wires, shown in Fig. 1, is 2 orders of magnitude smaller than the 2D luminescence signal. The linewidth of the zero-field spectrum is significantly narrower than that of the lowest zero-field 2D luminescence line.

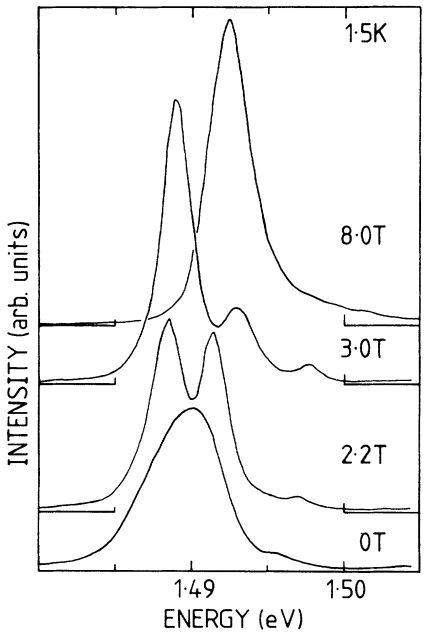

FIG. 2. Luminescence spectra at various magnetic fields for the as-grown heterojunction.

The peak energies as a function of magnetic field are plotted in Fig. 3 for both the 2D [Fig. 3(a)] and 1D structured [Fig. 3(b)] parts of the same sample. The 2D spectra show the well-known formation of Landau levels with a linear B dispersion, $E_n=E_0+(n+\frac{1}{2})\hbar\omega_c$, where E_0 is the effective energy gap between the 2D conduction-band edge and the energy position of the Be acceptors, $\omega_c=eB/m^*$ is the cyclotron energy, $n=0,1,2,\ldots$ is

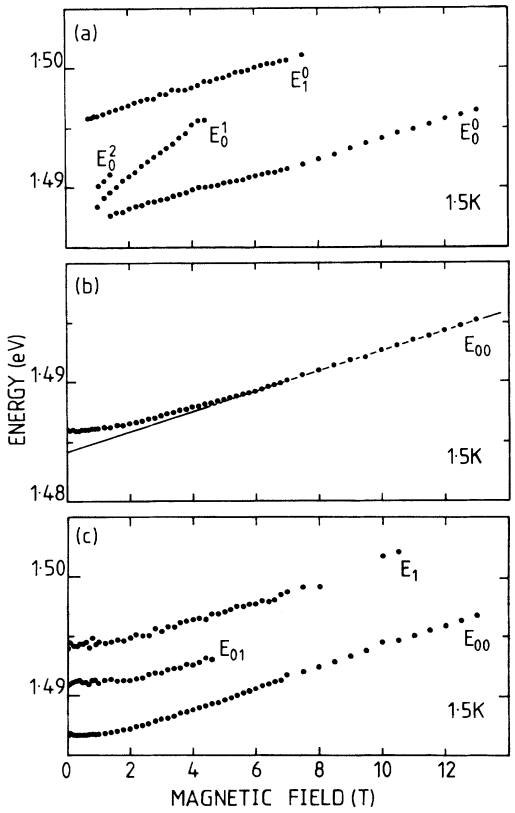

FIG. 3. Luminescence peak energies as a function of magnetic field for (a) the as-grown heterojunction and (b) the quantum wires of sample No. 1 and (c) a different quantum-wire sample No. 2. (a) The formation of Landau levels in the first, E_0^0, E_0^1, E_0^2, and second 2D subband, E_1^0, of the 2D sample; (b) a quantum-wire sample with only one occupied 1D subband; (c) a quantum-wire sample with two occupied 1D subbands, E_{00}, E_{01}, and luminescence from the second 2D subband, E_1, in the wire.

the Landau-level index, and m^* is the effective mass ($0.067m_0$ for GaAs in the following) [18]. As has been discussed above, Figs. 2 and 3(a) demonstrate that 2D PL spectra on modulation-doped heterostructures with acceptors directly display the density of states and the dispersion of the energy levels. Application of this method to the quantum wires of Fig. 1 should thus directly give the 1D density of states.

The lineshape of the 1D zero-field luminescence peak is significantly different from the 2D spectrum and one is tempted to speculate that the asymmetric high-energy tail reflects the expected $1/\sqrt{E}$ dependence of the 1D density of states. Most important, and in contrast to the 2D system, the 1D spectra in Fig. 1 show a characteristic nearly parabolic dispersion at small values of B. This is exactly what one expects for additional confinement, i.e., the magnetic field has no effect on the energy levels as long as the magnetic energy $\hbar\omega_c$ is small compared to the confinement energy. We thus interpret the line in the quantum-wire PL spectrum in Figs. 1 and 3(b) as the luminescence from the lowest quantum-confined 1D subband. The occurrence of only one peak indicates that we have realized in our sample under these illumination conditions the 1D quantum limit, i.e., occupation of only one 1D subband. In most of the studies on modulation-doped quantum wires so far several 1D subbands were occupied [6–8,12,13]. In that case the subband spacing is strongly governed by self-consistent screening effects, as shown by numerical subband calculations by Laux, Frank, and Stern [15]. These calculations also show that for only one occupied subband and a small number of electrons, as in our experiment, the confining potential has a nearly parabolic shape, $V(x)=\frac{1}{2}m^*\omega_0^2x^2$. For this parabolic confinement it is possible to solve analytically the one-electron Schrödinger equation and find the energy levels in a magnetic field [3],

$$E_n=E_0+(n+\tfrac{1}{2})[(\hbar\omega_c)^2+(\hbar\omega_0)^2]^{1/2}.$$

Below $B\approx 4$ T the experimental dispersion in Fig. 3(b) can indeed be fitted very well by the B-dependent part of this theoretical dispersion (for $B>4$ T see discussion below). Within this approximation of a parabolic confinement potential, we can determine a confinement energy, $\hbar\omega_0=4.6\pm 0.2$ meV. If we define the "electronic" width, i.e., the effective confinement width of the parabolic potential, by the extent of the harmonic-oscillator wave function [$w=2(2n+1)^{1/2}(\hbar/m^*\omega_0)^{1/2}$], we find with $n=0$ for one occupied subband, $w=31$ nm, which implies a lateral edge depletion of $w_d=(t-w)/2=64$ nm on each side of the wire. This seems reasonable since the existence of any free electrons at all is only due to laser illumination; in such narrow wires as these, the lateral depletion in the dark is larger ($w_d\approx 100$ nm) and all electrons are trapped in etching-induced surface states [14].

For some other samples and under certain illumination intensities we could observe higher-energy luminescence peaks in the 1D sample spectra as shown in Fig. 3(c) for sample No. 2. We assign the higher resonances in Fig. 3(c) to the first excited 1D subband E_{01}, and the second 2D subband E_1. For two occupied 1D subbands PL spectroscopy gives us the unique possibility to determine directly the 1D subband spacing which in this case is 4.2 ± 0.2 meV. Because of the increasing energy separation and, also, the increasing 1D density of states with increasing B, this second 1D subband becomes depopulated at $B\approx 4$ T. Evaluation of the B dispersion within the parabolic confinement gives for the lowest 1D subband $\hbar\omega_0=3.5\pm 0.2$ meV. The difference between this value and the directly determined subband spacing of 4.2 meV indicates that the confinement is not strictly parabolic. In particular, the weaker dispersion of the second 1D subband E_{01} suggests that the actual potential has "harder" walls compared to that of parabolic confinement. If we adopt the limit of a square-well potential within finite potential walls, we evaluate from the energy difference of the two lowest-energy levels in this model, $E_{01}-E_{00}=3\hbar^2\pi^2/2m^*w^2=4.2$ meV, an "electronic" width $w=63$ nm, which again is reasonable for narrow modulation-doped wires under illumination. Self-consistent effects may also influence the actual shape of the potential. For the case of two occupied 1D subbands we can also estimate the 1D electron density N_{L00} and N_{L01} in the two 1D subbands. From the integrated PL intensity we estimate a ratio $r=N_{L01}/N_{L00}=0.25$. From the 1D density of states one then can determine $E_F=\Delta E/(1-r^2)=4.48$ meV, where $\Delta E=4.2$ meV, the experimental spacing between the two 1D subbands [Fig. 3(c)], and this then gives $N_{L00}=0.57\times 10^6$ cm^{-1} and $N_{L01}=0.14\times 10^6$ cm^{-1}.

We have purposely not etched into the Be δ-doped layer. We are therefore confident that the PL process is the same in the 1D structures as in the 2D reference samples, i.e., radiative recombination of free electrons with holes bound to the Be acceptors. This is further confirmed by the fact that a high B, where the magnetic energy is larger than the confinement energy and thus the system effectively becomes 2D-like, the wires and 2D samples show the sample B dispersion and increase in intensity. We also rule out any excitonic effects, since these have never been observed in the 2D reference heterojunction samples and we see no reason to suppose that they should be present in the wires. In any case, the diamagnetic shift we observe is 2–3 times steeper than that expected for excitonic behavior. We can also rule out bulk transitions as the origin of resonances since, when the 1D sample is photoexcited with laser light of photon energy smaller than the GaAs bandgap, the bulk luminescence lines observed do not coincide with the energy position of the lowest 1D line [18] and the other lines observed do not increase in intensity with magnetic field, as expected for bulk transitions.

The energetically highest luminescence peak in Fig. 3(c) arises from the second 2D subband. That luminescence from this subband is still present in the quantum-

wire spectra and at roughly the same energy position as in the 2D sample could be due to the greater extent of its electronic wave function compared to that of the lower 2D subband. This would make it less sensitive to the 1D profile which is only etched to a depth 10 nm deeper than the $Al_xGa_{1-x}As/GaAs$ interface. Hardly noticeable within the experimental accuracy, this subband also seems to exhibit a parabolic dispersion at small B. Using the parabolic confinement model again, we estimate a confinement energy of $\hbar\omega_0=0.7$ meV. This very small value indicates that 1D quantization is weak in this case and even, perhaps, that we may not be observing a single subband but rather, due to inhomogeneous broadening, a number of unresolved 1D states. From 2D samples it is known that, due to the better overlap of the wave function, luminescence from the second 2D subband is significantly stronger than that from the first. The second 2D subband luminescence for the wire sample here is very weak. This implies that the actual electron population in the second 2D subband is very small and it is not clear whether it is in equilibrium or not.

Our observations of the 1D density of states and our determination of the 1D energy levels and 1D confinement energies give much more direct information on the 1D system than previous investigations of quantum wires. In far-infrared [6–8] and Raman [12,13] experiments only transition energies between 1D subbands are measured, which for many occupied 1D subbands are strongly governed by collective effects. These shift the resonance energies away from the 1D subband spacing. (Spin-density excitations in Raman spectra are influenced by excitonic effects which, so far, have not been calculated for 1D systems.) The method of magnetic depopulation of 1D subbands [3], which is very often used to characterize 1D systems, can obviously not be applied if only one 1D subband is occupied. Even to evaluate energy levels and other quantities of the 1D electronic system for several occupied 1D subbands requires a detailed, only numerically accessible, knowledge of the self-consistent potential.

Within the remaining space we would like to discuss briefly some further findings. In Fig. 3(b) there is a very slight flattening of the slope of the energy dependence between 4 and 6 T. Similar, more pronounced, behavior is also observed in 2D samples and was found to be most probably due to g-factor enhancement which sets in at filling factors below $\nu=2$ and increases until $\nu=1$ [18]. For the 1D systems we observe that, as in 2D, the weaker the laser intensity, the greater this flattening. It thus raises the interesting question of g-factor enhancement in 1D systems. Comparing Figs. 1 and 2 we observe that at zero magnetic field the lowest 1D subband lies at lower energy than that from the 2D spectra. This is not expected if one assumes that the confinement can be simply explained within a harmonic-oscillator potential theory. However, we also know from 2D samples that the effective gap energy E_0 depends very sensitively on n_s. Thus we cannot expect that E_0 is the same in the etched quantum-wire samples as in the 2D sample. It is also interesting to note that if the second subbands for the 1D and 2D parts of the sample are superimposed one finds that the 1D subband lies above the 2D lowest Landau level in energy as expected for additional 1D confinement.

In summary, we have directly observed quantum confined one-dimensional electron systems in heterojunction quantum wires at zero magnetic field. We could realize systems in the 1D quantum limit, directly observe the 1D density of states and the energy dispersion in magnetic field, and have determined the 1D confinement energy $\hbar\omega_0$ from these magneto-optical experiments. We find typical values of $\hbar\omega_0=3$–5 meV which are consistent with the rather narrow channel width.

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[1] K. Ploog, A. Fischer, L. Tapfer, and B. F. Feuerbacher, Appl. Phys. A **52**, 135 (1989).

[2] L. N. Pfeiffer, K. W. West, H. L. Störmer, and K. W. Baldwin, Appl. Phys. Lett. **55**, 1888 (1989).

[3] K.-F. Berggren, T. J. Thornton, D. J. Newson, and M. Pepper, Phys. Rev. Lett. **57**, 1769 (1986).

[4] B. J. van Wees, H. van Houten, C. W. J. Beenakker, J. G. Williamson, L. P. Kouwenhoven, D. van der Marel, and C. T. Foxon, Phys. Rev. Lett. **60**, 848 (1988).

[5] D. A. Wharam, T. J. Thornton, R. Newbury, M. Pepper, J. E. F. Frost, D. G. Hasko, D. C. Peacock, D. A. Ritchie, and G. A. C. Jones, J. Phys. C **21**, L209 (1988).

[6] W. Hansen, M. Horst, J. P. Kotthaus, U. Merkt, Ch. Sikorski, and K. Ploog, Phys. Rev. Lett. **58**, 2586 (1987).

[7] Ch. Sikorski and U. Merkt, Phys. Rev. Lett. **62**, 2164 (1989).

[8] T. Demel, D. Heitmann, P. Grambow, and K. Ploog, Phys. Rev. Lett. **64**, 788 (1990).

[9] D. Gershoni, H. Temkin, G. J. Dolan, J. Dunsmuir, S. N. G. Chu, and M. B. Panish, Appl. Phys. Lett. **53**, 995 (1988).

[10] M. Tsuchiya, J. M. Gaines, R. H. Yan, R. J. Simes, P. O. Holtz, L. A. Coldren, and P. M. Petroff, Phys. Rev. Lett. **62**, 4668 (1989).

[11] M. Kohl, D. Heitmann, P. Grambow, and K. Ploog, Phys. Rev. Lett. **63**, 2124 (1989).

[12] J. S. Weiner, G. Danan, A. Pinczuk, J. Valladaras, L. N. Pfeiffer, and K. West, Phys. Rev. Lett. **63**, 1641 (1989).

[13] T. Egeler, G. Abstreiter, G. Weimann, T. Demel, D. Heitmann, and W. Schlapp, Phys. Rev. Lett. **65**, 1804 (1990).

[14] T. Demel, D. Heitmann, P. Grambow, and K. Ploog, Appl. Phys. Lett. **53**, 2176 (1988).

[15] S. Laux, D. J. Frank, and F. Stern, Surf. Sci. **196**, 101 (1988).

[16] I. V. Kukushkin, K. v. Klitzing, K. Ploog, and V. B. Timofeev, Phys. Rev. B **40**, 7788 (1989).

[17] I. V. Kukushkin, K. v. Klitzing, K. Ploog, V. E. Kirpirchev, and B. N. Shepel, Phys. Rev. B **40**, 4179 (1989).

[18] A. S. Plaut, I. V. Kukushkin, K. v. Klitzing, and K. Ploog, Phys. Rev. B **42**, 5744 (1990).