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Photoluminescence of one-dimensional electron gases in cleaved-edge overgrowth quantum wires

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We carried out micro-photoluminescence studies of doped multiple quantum wire structures grown by the cleaved-edge overgrowth technique in the GaAs/AlGaAs material system. The wires are defined in a quantum well whose potential is modulated by adjacent alternating negatively and positively charged layers. We observed strong band gap renormalization effects in the quantum wires indicating that they are densely populated. The measured recombination energies are in good agreement with a simple quantum mechanical calculation. Nevertheless, the design of the sample appears to be not suitable for light scattering studies of the one dimensional (1D) electron gas, for the 1D confinement strongly depends on photoexcitation.

1 Introduction

The cleaved-edge overgrowth technique [1] (CEO) has become an important tool for the fabrication of quantum wires (QWR) which features atomical precision, in contrast to procedures combining lithography and etching. The formation of one dimensional (1D) states [2, 3] and exitonic lasing [4, 5] have been observed in CEO quantum wire samples proving their high quality. Thus, by modulation doping the realization of 1D electron gases (1DEG) with exceptionally high mobilities and extremely narrow emission linewidths should be readily achieved, profiting from the atomical precision of the growth technique. This opens up new possibilities for studies of the many-body behavior of correlated electron systems in one dimension. It is generally accepted that an ideal 1D system of interacting electrons is best described by the Tomonaga-Luttinger liquid model [6]. There are contradicting opinions, however, about whether or not experiments on real quantum wire samples actually show such behavior [7]. Inelastic light scattering experiments on QWRs [8] prepared by electron-beam lithography and subsequent ion milling have been recently reinterpreted in the framework of the Luttinger model [9], in spite of the fact that the traditional Fermi liquid theory seems to apply as well [10]. Recently, transport measurements in coupled two-wire CEO structures [11] gave strong evidence for the existence of a Luttinger-liquid. Hence, several authors [7, 9] recommended to pursue inelastic light scattering experiments on 1DEG in semiconductor quantum wires grown by the CEO method, which might provide direct access to the elementary excitations of the electron system and possibly settle the question of its many-body properties. Such experiments are still lacking.

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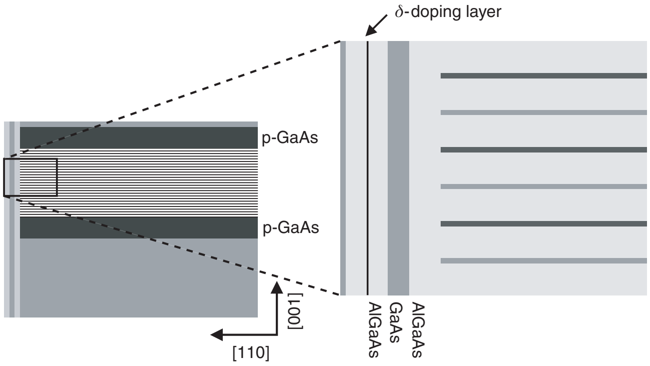

Fig. 1 Details of the sample design. The quantum wires form in the quantum well of the second growth due to the modulation of the electrostatic potential by nipi structure grown in the first run.

Here we present low-temperature results of micro-photoluminescence (μ-PL) measurements on a specially designed CEO multiple quantum wire structure, where the confining 1D potential is purely electrostatic. We found clear evidence for the formation of 1D states. Apparently this specific sample design is suitable for the creation of quantum wires filled with electrons, however, the 1D potential depends strongly on photoexcitation.

The samples (see Fig. 1) consist of an alternating n and p-doped (*nipi*) GaAs/AlGaAs multiple quantum well structure (QW) with 31 periods in [001] direction (first growth) and a single quantum well in the [110] direction separated from the cleaved edge by a thin AlGaAs barrier (second growth). The details of the first growth sequence are given elsewhere [12]. The doping layer of the second growth introduces electrons in the quantum well raising the Fermi level, such that the 2D electronic ground state of the quantum well is populated. The alternating n and p-doping layers are ionized and thus positively and negatively charged, respectively. These space charges of alternating sign create a spatial potential modulation along the first-growth direction (denoted z hereafter). Hence, electrons in the quantum well accumulate in several 1D channels. We have studied two similar samples that differ only in the set back of the doping layer from the quantum well – 20 nm and 40 nm –. This leads to two different electron densities in the quantum well of the second growth.

Micro-PL measurements were performed in backscattering from the cleaved edge in [110] direction at 4 K with a Ti-Sapphire laser using a microscope setup. The laser spot is 2 μm in diameter, thus, about the same size as the whole *nipi*-structure. A $x-y$ drive allows for easy positioning of the laser spot on the (110) plane with sub-micrometer precision.

Figure 2 shows line scans in [001]-direction on the cleaved edge for both samples with a) low and b) high electron density depending on the thickness of the spacer layer for the doping. We first dis-

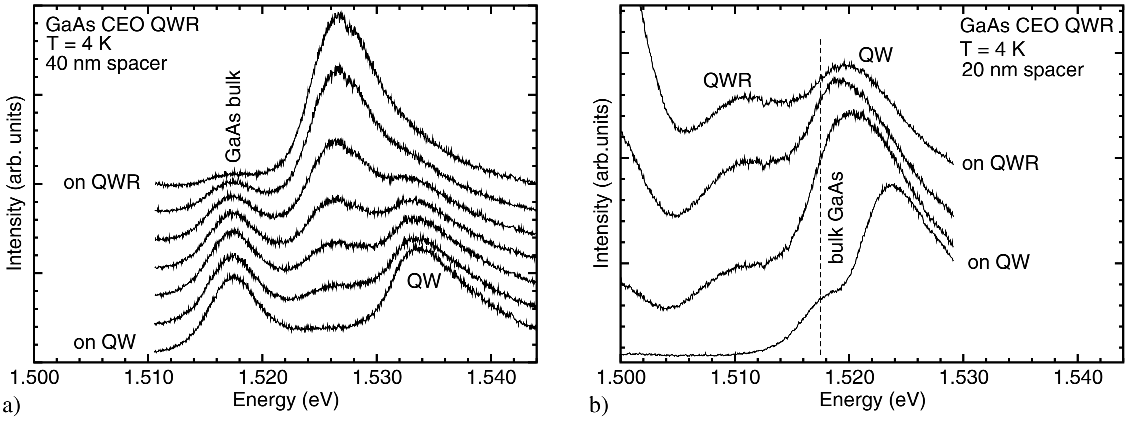

Fig. 2 Photoluminescence line scans on the cleaved edge in [110]-direction for the sample with a) low and b) high electron density.

cuss the low-density sample. Starting at the region along *z* below the *nipi* structure, the PL spectra exhibit two broad peaks originating from the ground state recombination of the unperturbed single quantum well (denoted as QW) and from the underlying bulk GaAs of the first growth. The total confinement energy for the ground state electron–hole pairs in a 15 nm wide quantum well is about 20 meV. Nevertheless, due to band gap renormalization effects [13–15], the energy of the quantum well ground-state emission is lowered by about 4 meV. We take this as evidence for the partial filling of the 2D subband, since we were not able to directly determine position of the Fermi edge in PL. When moving towards the multiple quantum wire (MQWR) structure, the QW luminescence peak shifts to lower energies because of further renormalization and vanishes. Centered on the MQWRs a new feature appears about 10 meV below QW peak. We attribute this emission to the spatially indirect recombination of electrons from the 1DEGs and photoexcited holes in the wires. The PL spectra of the high density sample look similar (Fig. 2b). Far from the MQWR structure both the QW luminescence, which shows stronger renormalization than in the low density sample, and the bulk GaAs luminescence peaks are apparent in the spectra. The QW luminescence is further red-shifted when scanning in *z*-direction but does not vanish, as in the spectra of the low density sample. The band gap renormalization for the QW ground state amounts to about 18 meV at the center of the MQWR structure. This is due to the larger 2D electron density that accumulates between the large *p*-doped, negatively charged layers at both sides of the *nipi* structure.

We interpret our PL results of the CEO wires on the basis of simple quantum mechanical calculation. The carriers in the QW have translational symmetry only in [$\bar{1}$10] direction. In [110] direction the potential is given by the band offsets at the AlGaAs/GaAs/AlGaAs interfaces, whereas in [001] direction the potential is purely electrostatic and determined by the alternating space-charge layers of the *nipi* structure. Since the Schrödinger equation for this two-dimensional problem is separable in variables, we solve it for the potential in each direction and sum up the energy eigenvalues in order to obtain the energy levels according to

$$\left(\frac{p_x^2}{2m} + V_x(x)\right) u(x) = \varepsilon_x u(x)\,, \tag{1}$$

$$\left(\frac{p_z^2}{2m} + V_z(z)\right) v(z) = (E - \varepsilon_x)\, v(z)\,. \tag{2}$$

Figure 3 shows a sketch of the electrostatic potential created by the *nipi* structure along the QW of the second growth, as obtained by solving the 2D Poisson equation using the potential generated by a series of cylindrical wires with proper shape and charge, in order to mimic the edge of the *nipi* structure.

The amplitude of the potential modulation basically depends on the distance between QW and cleaved edge and on the charge of the np layers. The superimposed parabolic potential is a consequence of the charge of the *p*-doped layers at the top and the bottom of the *nipi* structure. The electrostatic potential has been set to zero at infinity. Assuming that the *np* layers are fully ionized and for a distance of 27.5 nm to the center of the QW, the calculation yields a modulation depth of around

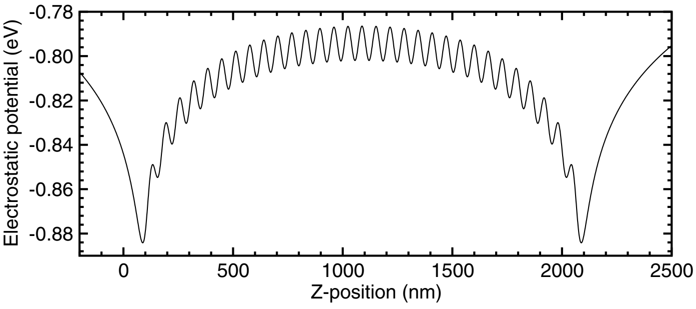

Fig. 3 Electrostatic potential created by the alternating space charge layers in [001] direction.

15 meV. The Schrödinger equation, however, was solved for a single wire whose potential was approximated by the following function: $U(x) = -U_0/\cosh^2 \alpha x$, where $\alpha \sim 1/d$, which has an analytical solution (see for example [16]). The solutions can be expressed in terms of the hypergeometric confluent function and their energies are given by

$$E_n = -\frac{\hbar^2 \alpha^2}{8m^*}\left[-(1+2n) + \sqrt{1 + \frac{8m^* U_0}{\alpha^2 \hbar^2}}\right]^2 . \tag{3}$$

For a peak-to-peak modulation of $U_0 = 15$ meV, an effective wire width of $d = 30$ nm and setting the zero of the potential energy at half maximum we obtain for the energies of the lowest electron and hole states $e_0^z = -4$ meV and $h_0^z = -6$ meV, respectively. The energy states in the potential perpendicular to the heterointerfaces have been calculated numerically by solving self-consistently the Poisson and Schrödinger equations of the modulation-doped GaAs quantum well of the second growth. This yields electron and hole ground-state energies of about $e_0^y = 17$ meV and $h_0^y = 3$ meV, respectively. Adding the energies obtained for both directions we finally get $e_0 = 13$ meV and $h_0 = -3$ meV with respect to the bulk conduction and valence band edges, respectively. The resulting band structure profile is sketched in Fig. 4. Note that even though the lowest electronic state of the wires is higher in energy than the top of the potential modulation, it still exhibits 1D character. Thus, the energy of the indirect recombination process within the MQWRs is expected to lie about 10 meV lower than the QW ground state recombination, in very good agreement with the redshifts observed in the experiments.

The recombination from the 1D states results in a rather broad band, which has possibly two reasons. One is the formation of a miniband due to tunnelling between the lowest 1D states in the conduction band. For the holes, having a larger effective mass, this is unlikely to happen, however, the valence band states are very dense, representing a quasi continuum. In the case of the high density sample, even the continuum electron states of the cosh potential in the conduction band seem to be populated, which explains the coexistence of the MQWR and QW peaks in PL.

A striking result concerns the dependence on laser excitation power of the QWR luminescence, which is illustrated in Fig. 5 again for both samples. The laser spot is centered on the MWQRs. The main peak in Fig. 5a, which corresponds to the QWR emission, shifts to higher energies with increasing excitation power. This is also true for the high-density sample, where the QWR peak shifts upwards until it merges at high power levels together with the broad QW line. The latter, in contrast, remains peaked at 1.52 eV independently of the laser power. We explain this behavior as being caused by screening of the electrostatic potential by the photoexcited carriers generated at the *nipi* structure, which neutralize the ionized dopants, thus, reducing the space charge. This implies that in light scattering experiments which generally need laser powers a factor of 100 higher than for luminescence measurements, the formation of the 1DEGs will be prevented by the cancellation of the potential modulation. In fact, light scattering studies on these samples have not revealed any signs of the existence of a 1D gas. In contrast, they showed strong signals originating from two-dimensional hole gases confined in the *nipi* structure in the first growth [12].

In summary, we have studied an alternative design of a GaAs multiple quantum wire structure fabricated by the cleaved-edge overgrowth method by means of μ-PL measurements. The quantum wires are well defined through a lateral potential modulation of a single quantum well produced by an

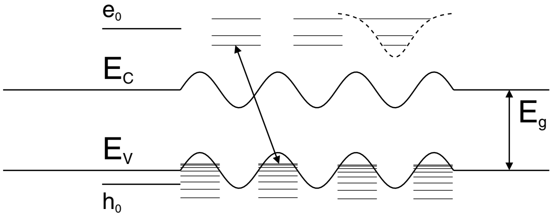

Fig. 4 Sketch of the electronic band structure in the region of the electrostatic potential modulation defining the quantum wires. The electronic states are calculated by approximating the potential with a $1/\cosh^2 x$ function (dotted line).

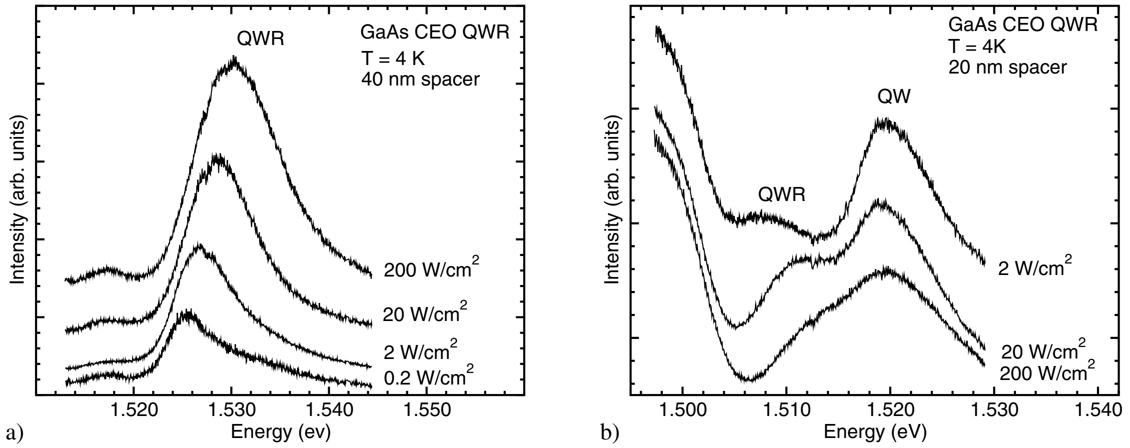

Fig. 5 Micro-PL spectra for various laser excitation powers of the sample with a) low and b) high electron density.

adjacent *nipi* structure. Luminescence data give clear evidence for the formation of 1D electron gases. The ground state recombination from the quantum wires is about 8 meV lower in energy than the quantum well emission. The observed peak energies are in good agreement with the results of a simple quantum mechanical calculation after band-gap renormalization effects were taken into account. Unfortunately, the design of the samples appears to be not suitable for inelastic light scattering experiments, as the potential is flattened by photoexcited carriers, destroying the one-dimensional confinement.

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