Optical Properties of New V-Groove Quantum Wires: Towards Quasi-One-Dimensional Systems

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A new generation of V-groove GaAs/GaAlAs quantum wires is reported, studied by micro-photoluminescence imaging spectroscopy. These samples with an improved heterointerface quality give indications for quasi-one-dimensional (1D) behaviour. The imaging shows that the excitons are delocalized over mesoscopic distances up to about 1\,\rm \mu m so that the exciton states should form a quasi-1D continuum. As the exciton density is increased, red shifts of the transitions of a few meV are observed, which are attributed to band gap renormalization in the limit of a weakly interacting exciton gas. For higher exciton densities approaching one per excitonic Bohr radius, biexciton transitions and a slight blue shift appear, interpreted as the screening of the exciton binding.

Introduction

The optical properties of GaAs quantum wires (QWRs) are governed at low temperature by localization effects that are due to inhomogeneities of the size of the wire. Monolayer fluctuations of the interfaces of the wire generate a random potential leading to localization of the excitons, as in any one-dimensional (1D) system. This has been studied by local microscopy [1] or near-field microscopy [2]. It has been shown that for the previous generations of samples the wires can be considered from a local point of view as collections of quantum boxes and therefore have optical properties of a zero-dimensional (0D) system. Recent progress in growth techniques allows one to obtain much longer localization lengths in the new generation of wires, i.e. very long quantum boxes which can be seen as sections of ‘perfect’ QWR, as discussed below. The local study by micro-photoluminescence (\mu PL) of each of these wire sections shows new optical properties which are interpreted as a signature of their 1D character, as well as non-linear effects attributed to many-body Coulomb interactions between excitons.

Experimental

The nanostructures studied were 4.5\,\rm nm thick GaAs/GaAlAs V-shaped QWRs. The Al concentration in the barrier was 0.33. They were grown on a 4.8\,\rm \mu m pitched V-grooved GaAs substrate by flow rate modulation epitaxy which is a modified metalorganic vapour phase epitaxy technique. Details of the growth process and general characteristics of the V-shaped QWRs can be found in Ref. [1]. For the sample studied here the orientation of the V-groove prepared by photolithography is almost per-
fectly aligned along the [0–11] direction and the arsenic sources used for the growth were of a new kind, leading to an increased purity of the materials and a reduction of the non-radiative recombination at high temperature [3]. The sample was fixed on the cold finger of a helium cryostat and cooled at 10 K. The laser beam was focused on the sample by a microscope objective with a large numerical aperture (0.6), and the laser spot diameter was 1 μm. The excitation energy was 1.77 eV, which creates carriers resonantly in the wire transitions. As the different wires in the sample were separated by 4.8 μm, in our experiments only one single wire was excited over 1 μm. The excitation spot could then be translated with respect to the sample by moving the microscope objective with piezoelectric actuators with a precision better than 0.2 μm. The PL spectrum of the excited region was recorded at each position.

Results and Discussion  A μPL scanning image of a single wire of this sample is shown in Fig. 1. It shows that the density of emitting sites is of the order of 1 per μm corresponding to a typical extension of the states of about 500 nm which can reach more than 3 μm at some locations, e.g. at z = 5 μm in Fig. 1. The increase of the localization length from about 50 nm for the previous generation of samples [4] to 500 nm for this sample implies that the energy separation between the excitonic states confined in a localization site decreases from typically 2 meV in the former case to about 20 μeV in the latter case. The excitonic states do not behave any more as well-separated 0D states (0D regime QWR), but form rather a quasi-1D continuum (1D regime QWR).

The optical properties of this sample are qualitatively different from those obtained for 0D regime QWRs and confirm the assumption of a quasi-1D system, as shown in Fig. 2. In this experiment carriers are created resonantly in the wire transitions using a tunable dye laser. The black circles represent μPL spectra of a given point of the sample as a function of the excitation power ranging from 0.1 to 14 μW, which corresponds to an estimated average number of excitons in the excited spot ranging from about 0.3 to 56. At low excitation power two lines are observed, corresponding to spatially distinct emitting sites. It should be noted that the shape of the lines is Lorentzian (full curves) at low-power excitation (Fig. 2a) and their widths are 0.8 and 1.8 meV, corresponding to very short dephasing times of 1.6 and 0.7 ps, respectively. The homoge-
neous character of the transition confirms the absence of any disorder in the structure, even on a micrometre scale: each μPL line corresponds to a section of ‘perfect’ wire. For higher pump power (Figs. 2b–e) there is a small deviation from the Lorentzian shape in the low-energy tail of the spectrum that can be qualitatively compared to recent theoretical results [5].

All of the μPL lines show a continuous shift to the red by about 1 meV as the excitation power density is increased. This effect is attributed to many-body Coulomb interactions between excitons, as explained below. This is not the case in 0D regime QWRs, where no shift of the μPL lines is observed and a very broad background over the whole spectrum appears as the excitation power density is increased. This is attributed to the presence of an electron–hole plasma in the wire [6]. For larger exciton densities the lines shift slightly to the blue (0.5 meV) and a low-energy line grows non-linearly. These shifts are the signature of Coulomb interactions between excitons. In the first density regime between 0.1 and 10 excitons in the localization site the excitons form a weakly interacting gas and the red shift is interpreted as the modification of their self-energy due to exchange correlations known as band gap renormalization. As the power is increased the distance between excitons becomes comparable to the excitonic Bohr radius, leading to a screening of the excitonic binding by the exciton gas as well as the appearance of a line associated with biexcitonic transitions.

The role played by Coulomb interactions in these effects is confirmed by the second set of experiments, the results of which are shown in Figs. 2a and c. Here, an additional

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Fig. 2. μPL spectra (black circles) as a function of the power of the laser resonantly exciting the QWR. The estimated numbers of excitons are indicated. Lorentzian fits are shown as solid curves. Grey dots represent μPL spectra at the same excitation power under a weak HeNe laser excitation of 5 nW. **
HeNe laser excites simultaneously with the dye laser the same spot of the sample with a much smaller excitation power (5 nW) and at a higher energy (grey circles). It creates carriers in the QWR that only weakly contribute to the luminescence, but mostly carriers in the vertical quantum well (VQW) surrounding the QWR [5]. When a few excitons (about 10) are present simultaneously (Fig. 2c), this very weak radiation induces a blue shift of the line. The new energy position is the same as that in Fig. 2a, which corresponds to a very low excitation power and for which there are no interactions between excitons. Indeed no shift is observed in this regime when a weak HeNe laser beam is added (Fig. 2a). This indicates that the photocarriers generated in the VQW screen the Coulomb interaction between the excitons present in the wire.

These Coulomb effects have been studied in QWRs both theoretically and experimentally. They result from the competition between two different interactions: (i) band gap renormalization, due to Coulomb exchange correlations inducing a red shift; and (ii) the screening of the exciton binding, inducing a blue shift. Theoretical models are still under debate since blue, red and zero shifts are predicted depending on the model and the parameters [5]. Concerning the experimental data obtained by photoluminescence, zero shifts [7] and blue shifts [8] have been observed but it should be noted that the samples studied were in the 0D regime, where exciton transitions are not expected to shift until excitons are ionized in an electron–hole plasma.

**Conclusions** We have demonstrated through the μPL imaging technique the delocalization of the excitons over mesoscopic distances (1 μm) in this latest generation of QWRs, which indicates that these QWRs are the first reported wires in the 1D regime. Each emitting site can be considered as a section of ‘perfect’ QWR and the corresponding transition is homogeneously broadened. Shifts of the μPL lines are observed as the exciton density increases, attributed to Coulomb interactions between excitons. Band gap renormalization and screening of the exciton binding have been observed in two distinct exciton density regimes below and above $10^5$ cm$^{-1}$, respectively. This indicates that the cancellation of these two contributions is not total and depends on the exciton density. These results are in qualitative agreement with recent theoretical calculations that predict small energy shifts of the excitonic transition.

**References**