Evidence for Exciton Localization in V-Shaped Quantum Wires

J. Bellessa (a), V. Voliotis (a), R. Grousson (a), X. L. Wang (b), M. Ogura (b), and H. Matsuhata (b)

(a) Groupe de Physique des Solides, CNRS, Université Paris VI et Paris VII, 2, place Jussieu, F-75251 Paris Cedex 05, France
Tel.: 33-1-44274632; Fax: 33-1-43542878

(b) Electrotechnical Laboratory, 1-1-4 Umezono, Tsukuba 305, Japan

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Crescent-shaped AlGaAs/GaAs quantum wires have been investigated using microscopic photoluminescence and photoluminescence excitation spectroscopy. The main photoluminescence line is split into sharp peaks of width less than 0.5 meV and separated by a few meV. They are attributed to exciton localized states in one monolayer deep quantum boxes present at the (001) top facet of the wire and larger than the exciton Bohr radius. Microphotoluminescence excitation reveals also a fine structure of the first excitonic transition formed by sharp peaks each one corresponding to sections of the wire with slightly different confining potentials.

Introduction. Recently, growth technology has been improved enough to lead to the fabrication of high quality one-dimensional (1D) semiconductor structures such as V-shaped quantum wires (QWR) [1 to 4]. The growth of heterointerfaces with controllability at an atomic scale remains however a real challenge since its quality influences drastically the optical properties of the one-dimensional structures. The development of microscopic photoluminescence (μ-PL) which consists in a highly spatially resolved PL experiment, has allowed to get a further insight into the optical properties of quantum wells or quantum dots [5, 6]. We present μ-PL and microscopic photoluminescence excitation (μ-PLE) studies of a single crescent-shaped Al0.3Ga0.7As/GaAs QWR at low temperature. The obtained results clearly show that fluctuations of the QWR confining potential occur and that excitons can be localized in one monolayer (ML) deep quantum boxes (QB).

Experimental. The QWRs were grown on a 4.8 μm pitch V-grooved GaAs substrate by flow rate modulation epitaxy, a modified metalorganic vapor phase epitaxy (MOVPE) [2]. The QWR thickness at the centre of the V-groove is about 5 nm. The Al concentration rate is 0.33 for the (001) mesa top facet. In order to enhance the PL signal of the QWR, the (001) flat region and a part of the (111)A sidewall AlGaAs barrier layers have been removed by wet chemical etching [2]. The sample has been characterized by classic PL and PLE experiments and presents good optical properties, for instance the full width at half maximum (FWHM) is only 8 meV and the Stokes
shift is 4 meV [7]. We have calculated the electronic transitions for the studied QWR by solving numerically the 2D Schrödinger equation based on a plane-wave expansion with periodic boundary conditions [8]. The description of the 2D potential was based on high resolution transmission electronic microscopy (HRTEM) photographs. In order to calculate properly the hole states, we have included the valence band mixing. It should be pointed out that one ML width fluctuation on the bottom of the V-wire shifts the first transition by 9 meV. If the lateral profile of the crescent is slightly changed, then the transitions shift by a few meV, which is not negligible. The quantum confinement along the growth direction is however predominant while the lateral confinement is only an additional effect.

Micro-PL and micro-PLE experiments have been performed using a titan–sapphire laser pumped by an argon laser at low temperature (10 K). The laser beam is focused on the sample by a microscope objective with a large numerical aperture (0.6). Since the laser spot size is 1 μm² and the QWRs are separated by 4.8 μm, we are certain to observe a single wire. The optimal spectral resolution is 50 μeV. Other experimental details can be found elsewhere [9].

Results and Discussion. Fig. 1 shows a typical μ-PL spectrum of the QWR. The μ-PL spectrum is formed by a line centered at 1.647 eV which is split into several (about ten) very sharp peaks having a width less than 0.5 meV, separated by 1 to 2 meV and distributed over about 10 meV. The spectral resolution in this experiment was about 150 μeV. As discussed in [9] the peak linewidth represents the homogeneous broadening of the transitions. The fine structure of the μ-PL line strongly depends on the observed wire and is also modified when moving the excitation spot along one wire. The sharp peaks on Fig. 1 are attributed to exciton fundamental states, localized in some monolayer-step islands at least as large as the exciton radius. This is a similar situation as in the case of a 2D quantum well [5]. These islands are due to one ML size fluctuations on the (001) top facet of the GaAs QWR. Let us also remark that the confinement energies of the localized states are distributed over 10 meV. This reflects the size distribution of the QBs which finally creates the inhomogeneous broadening of the PL line. The latter is thus a result of size fluctuations existing in one wire and not due to some size dispersion of the different wires.

Fig. 1. QWR μ-PL excited with the Ti–Sa laser at 1.689 eV under 1 μW excitation power.
Fig. 2 represents a $\mu$-PLE spectrum superimposed to a $\mu$-PL spectrum. Both have been recorded at the same position on a given wire. The detection energy of the $\mu$-PLE spectrum (1.6493 eV) corresponds to a sharp peak on the $\mu$-PL line. Four features are predominant on the $\mu$-PLE spectrum. Near the detection, at 1.66 eV, a first line is observed which is attributed to the first excitonic transition of the QWR labelled $e_1-h_1$. Inside this line some peaks can already be distinguished. At 10 meV higher in energy, a second line appears, attributed to the $e_1-h_2$ excitonic transition, which could become allowed because of the asymmetry of the QWR potential. At 1.698 and 1.724 eV the $e_2-h_2$ and $e_3-h_3$ are observed, respectively. These higher energy transitions do not show any particular fine structure even at low excitation power. All the above described transitions are in very good agreement with the classic PLE experiments performed by Wang et al. [7] and with our calculations.

Fig. 3, curves a and b represent typical $\mu$-PLE spectra recorded on another QWR under lower excitation power than in the previous situation (Fig. 2). The first excitonic $\mu$-PLE line, $e_1-h_1$, is now resolved and several sharp peaks, as narrow as 0.2 meV, can be observed. The $\mu$-PLE peaks are attributed to QWR exciton states corresponding to wire sections with slightly different confining potentials. In Figure 3, curve a the detection energy is set at 1.65 eV, on one $\mu$-PL peak. We can distinguish three resonances on the curve. The first one lies at 5 meV above the detection energy; the second one at 6.5 meV and the third one at 15 meV above. In this situation, we believe that the two first peaks are $e_1-h_1$ states related to two different QWR sections separated in energy by 1.5 meV. The last peak is attributed to the $e_1-h_2$ transition. Then from the energy difference between the detection and the first $\mu$-PLE peak we may estimate the QB width. Assuming that its potential is one ML deep, we find 20 nm. Nevertheless, QBs excited states can be observed in $\mu$-PLE. This situation is represented in Fig. 3, curve b where the excited states are labelled with ticks. The first (second) peak lies at 1.9 (3.6) meV above the detection energy. From the
energy separation between those levels, we may estimate the QB width. In this case it will be about 80 nm. The higher energy peaks correspond to $e_1-h_1$ and $e_1-h_2$ wire states as discussed above. It is worthwhile noticing that the $\mu$-PLE sharp peaks when changing the detection energy, appear at different energy positions, each emitting QB being related to a different wire section or to several wire sections.

The variations of the wire confining potential are due to size inhomogeneities created on one hand, by the ±1 ML thickness fluctuations at the center of the crescent and on the other hand by the thickness fluctuations on the (311)A heterointerface [10]. Since the first electronic wavefunction is mainly concentrated at the center of the V-wire, then the $e_1-h_1$ exciton will be mainly influenced by the thickness variations along the growth direction. However, higher energy excitons like $e_2-h_2$ or $e_3-h_3$ will be more affected by the fluctuations on the (311)A heterointerface because the corresponding electronic wavefunctions are mainly distributed over the (311)A sidewalls as confirmed by our calculations and discussed in [7]. Qualitatively, the QWR can be represented as segmented into extended sections of hundreds of nm with slightly different confining potentials. Inside these sections, one ML deep QBs are present, with different lengths typically of the order of magnitude of the exciton Bohr radius. Recent AFM observations [11] could support our conclusions, although the growth conditions of the samples were different. In [11], the (001) facet at the V-groove bottom of GaAs QWRs was found to be almost flat along the wire direction with monolayer step-terraces inside.

**Conclusion.** By performing $\mu$-PL and $\mu$-PLE spectroscopy on a single V-shaped QWR, sharp excitonic resonances have been observed. The $\mu$-PL line corresponds to exciton localized states in one-ML deep QBs present on the (001) top facet of the crescent. The confinement energies in the boxes are distributed over 10 meV and thus the broadening of the PL gives the size distribution of the boxes. The sharp resonances observed in $\mu$-PLE are attributed to sections of the wire with slightly different potentials. The energy dispersion of the $\mu$-PLE peaks (about 4 meV) is narrower than that of $\mu$-PL, suggesting that the size distribution of the wire sections is narrower. The typical length of the wire sections is of the order of magnitude of 100 nm.

**References**