Strong carrier confinement and evidence for excited states in self-assembled InAs quantum islands grown on InP(001)

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Photoluminescence (PL) and photoluminescence excitation (PLE) experiments are carried out in order to study the electronics states in self-assembled InAs quantum islands (QI's) fabricated on the InP(001) substrate by solid source molecular-beam epitaxy using the Stranski-Krastanov growth mode. The growth conditions of the InAs QI's have been optimized (high growth temperature, low arsenic pressure and growth rate) in order to minimize the island size dispersion. The low-temperature (8 K) PL spectrum of the InAs/InP(001) QI's is characterized by multicomponent transitions. From PLE spectroscopy, we have evidenced excited states associated with a single ground state in agreement with a unimodal size distribution. The full width at half maximum of the ground state PL peak is only 22 meV at 8 K, which reveals a narrow island size dispersion. The integrated PL intensities measured as a function of the temperature have shown a weak intensity decrease between 8 and 300 K. Intensity remains very strong at room temperature, as much as 49% of that at 8 K under nonresonant excitation and up to 90% under quasiresonant excitation. These results are indicating of a strong confinement and/or spatial localization of the carriers in such InAs/InP(001) QI's.

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INTRODUCTION

The self-organized growth of three-dimensional (3D) quantum islands (QI's) using the Stranski-Krastanov growth mode is considered to be one of the most promising methods to elaborate quantum dot (QD) or quantum wire (QWR) structures. Due to the small size of these QI's, they provide the ultimate quantum system with three- or two-dimensional carrier confinement resulting in 0D or 1D density of states. It is predicted that drastic improvement in laser characteristics such as an increase of quantum efficiency and thermal stability and a reduction of the threshold current can be reached with this unique feature of QI's. In this way, it has been experimentally shown that QD lasers have lower threshold current density and higher characteristic temperature in comparison to quantum well lasers.[1–3] Lasers containing InAs and InGaAs QD's embedded in a GaAs and AlGaAs matrix have been successfully fabricated as predicted.[4,5] However, the emitting wavelength for InAs/GaAs based QD's can scarcely exceed 1.3 μm,[6] which restricts the applications in optical fiber communication systems. In order to realize QD lasers within the spectral window of optical telecommunication interest at 1.55 μm, the growth of InAs QD's and QWR's on InP has been proposed.[7–13]

In this paper, we report on the electronic state spectroscopy and on the temperature-dependent photoluminescence (PL) properties of self-organized InAs QI's on InP(001) emitting around 1.55 μm at 300 K. By carrying out photoluminescence excitation (PLE) experiments, we analyzed in InAs/InP QI's the existence of exited states associated with only one ground state. This observation has been attributed to a unimodal size distribution of the InAs/InP(001) QI's.

EXPERIMENT

The sample investigated in this study was grown by solid-source molecular-beam epitaxy on semi-insulating InP(001) substrates. A 200-nm-thick InP buffer was grown at 480 °C at 1 μm/h growth rate using a phosphorus pressure equal to 1 $\times 10^{-5}$ Torr. Then, one plane of InAs islands was grown with optimized growth parameters in order to reduce the island size dispersion.[14] It consists of 4 ML of InAs grown at 520 °C under an arsenic pressure fixed at 2×10^{-6} Torr and with a reduced growth rate of 0.25 μm/h (0.22 ML/s). In these conditions, the 3D growth onset is observed by reflection high electron energy diffraction at 1.8 ML. Atomic force microscopy and transmission electron microscopy measurements have shown that the InAs QI's are quantum "sticks" aligned along the [1-10] direction, with a flat top surface.[14] These islands exhibit a truncated pyramid shape with typical widths of 17.5 ± 0.4 nm and almost identical height close to 2.4 nm. In order to characterize the carrier confinement in these quantum islands by PL measurements, the samples were covered with a 300-nm-thick InP layer. The PL spectra were recorded in the 8–300 K temperature range. The PL was excited using either the 514.5-nm line (2.41 eV) of an argon-ion laser (nonresonant excitation) or the 1064-nm line (1.165 eV) of a yttrium-aluminum-garnet (YAG) laser (quasiresonant excitation). The PLE was excited by a quartz-tungsten lamp dispersed through a 0.6-m double-grating spectrometer providing a tunable light source. The emission was dispersed by a spectrometer and detected by a 77-K cooled germanium photodetector using a conventional lock-in technique.

RESULTS AND DISCUSSION

Figure 1 shows the continuous wave (cw) PL spectrum of the sample at 8 K under high nonresonant excitation density (475 W/cm^2). The PL spectrum is characterized by several components that can be fitted with four Gaussian peaks labeled (a)–(d) with full width at half maximum $\approx$25 meV.

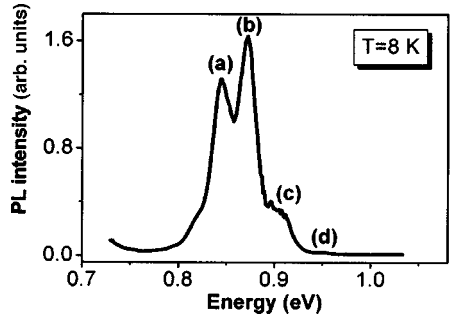

FIG. 1. PL spectrum at 8 K of InAsInP(001) QI's under high excitation density (475 W/cm^2). The different components are denoted by letters belonging to transitions states.

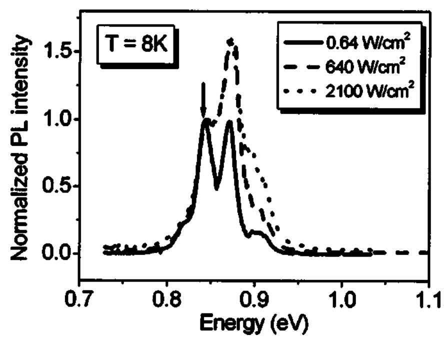

FIG. 2. PL spectra at 8 K of InAsInP(001) QI's with different excitation densities from 0.64 to 2100 W/cm^2 normalized from peak (a).

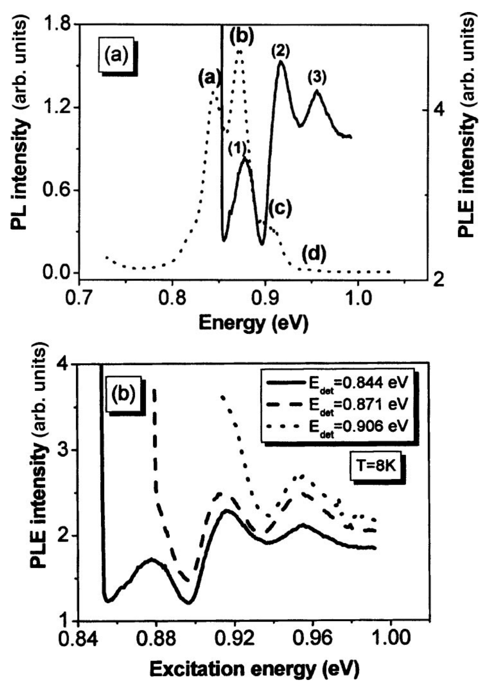

FIG. 3. (a) PL and PLE spectra at 8 K of the InAsInP(001) QI's. The PLE spectrum was detected at 0.844 PL peak. (b) PLE spectra at 8 K detected at 0.844, 0.871, and 0.906 eV.

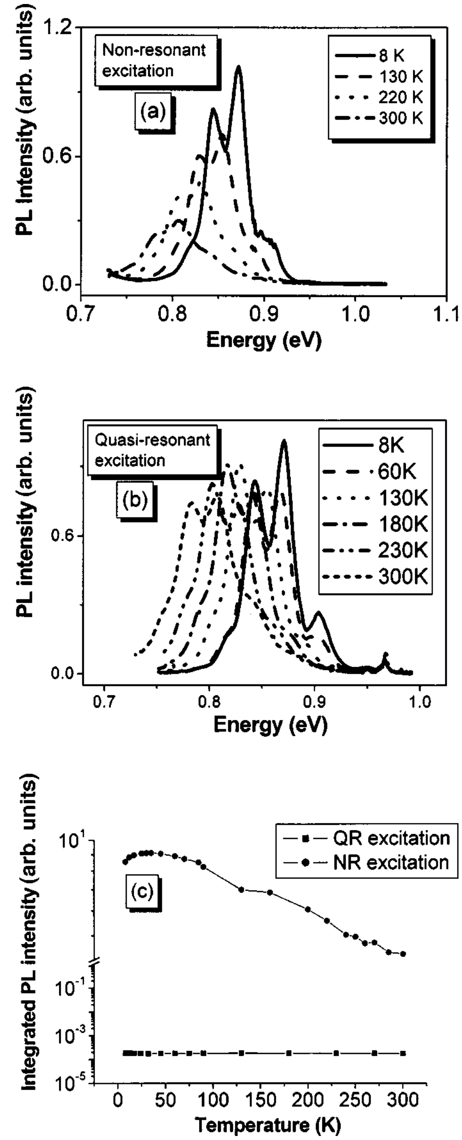

FIG. 4. (a), (b) Evolution of the PL spectrum with temperature under nonresonant (argon laser) and quasiresonant (YAG laser) excitations, respectively. (c) Integrated PL intensities as a function of the temperature.

The energy spacing between these peaks is roughly constant ($\approx$30–40 meV). Similar behavior has already been observed in InAs/GaAs and InGaAs/GaAs QD's.[15,16]

In order to identify the origin of these peaks we have carried out PL experiments as a function of excitation densities. Figure 2 depicts the normalized PL spectra at 8 K of InAs/InP(001) QI's when the power excitation density is increased from 0.64 to 2100 W/cm^2. We observe a relative saturation of the peak (a) at 0.844 eV as compared to higher-energy peaks at 0.872 eV (b), 0.906 eV (c), and 0.945 eV (d). This behavior can be a first signature for excited levels [(b), (c), and (d) peaks] related to a ground state [peak (a)]. Indeed, it is expected in such low-dimensional structures that excited states are filled at higher excitation densities when the fundamental one is saturated.[17] It is worth noting that the excited states are observed even at very weak excitation power. Although this effect can be attributed to the fact that the ground state may be partially occupied with carriers as a consequence of the nonintentional *n* doping of the InP layers, it was necessary to confirm the existence of these excited states.

A powerful tool for the investigation of the excited-state absorption spectrum of QI's is the PLE spectroscopy.[18] The PLE spectrum for peak (a) shown in Fig. 3(a) clearly reveals three absorption peaks labeled (1), (2), and (3) at energies about the same that of the (b), (c), and (d) peaks of the PL spectrum. Actually, (b), (c), and (d) peaks can be attributed to three excited states related to a ground-state peak (a). As mentioned above, the spectrum discloses however a small apparent energy shift between the (1), (2), and (3) PLE and the (b), (c), and (d) PL peaks, respectively. This energy shift can have several explanations. On one hand, owing to the discrete nature of the energy levels in a 3D-confined quantum structure, this energy shift is not a true Stokes shift.[19,20] On the other hand, the ground state (a) of the InAs QI's cannot be probed by PLE measurements due to the lack of nearby continuum states. Indeed, the process of the absorbing and emitting lights to and from the same quantum state can be viewed as photon scattering. Consequently, for QI's, the energy of the outcoming photons is close to that of the exciting light and the luminescence will be resonant with the incident beam. As a result, and as already observed for In(Ga)As/Ga(Al)As QD's,[19] the ground state cannot be observed. Finally, the PLE spectra measured with different detection energies [Fig. 3(b)], which do not shown energy shift between the PLE spectra, is demonstrating of the same origin for all components and strengthen the excited state attribution.

To measure the temperature-dependent luminescence properties of InAs/InP QI's at high excitation intensity in order to probe the excited states, the PL measurements were performed under nonresonant (NR) and quasiresonant (QR) excitations. Figures 4(a) and 4(b) show the PL spectra at various temperature under NR and QR excitations, respectively. We can point out that no emission from the wetting layer (expected around 1.25 eV) is observed, indicating that carriers photogenerated from the wetting layer probably transfer rapidly to the adjacent InAs QI's and then recombine inside. The variation of the integrated PL intensity as a function of the temperature is shown in Fig. 4(c). First, we note that the integrated PL intensity remains very strong at room temperature, as much as 49% of that at 8 K under NR excitation and 90% under QR excitation. This difference of the temperature dependence of integrated PL intensities is attributed to the quality of the InP barriers which are elaborate at 520 °C. Second, under NR excitation we observe a weak anomalous enhancement of the PL intensity in the 8–75 K temperature range. We tentatively attributed this weak enhancement to the presence of traps in the InP barriers that would capture excitons at low temperatures and release them at higher temperatures. It is well known that released excitons from such traps can take part in the radiative recombination within the dots, resulting in a small change of the PL intensity contrary to what happens for intrinsic levels.[21] So, we assume that these traps are point defects, more precisely phosphor vacancies in the upper InP barrier just above the InAs QI's, which was grown at high temperature (520 °C). The fact that we do not observe any PL intensity enhancement when the InP barriers are grown at 480 °C confirms our assumption. Beside, when the temperature is rised up to 75 K, the integrated PL intensity weakly decreases. This decrease at higher temperature is related to exciton dissociation and the consequent escape of electron-hole pairs from the QI's. However, the remarkable stability of the integrated PL intensity as a function of the temperature is indicating of a strong carrier confinement and/or spatial localization, which, to our knowledge, has never been obtained for InAs QI's grown on InP(001).

In summary, with PLE measurements, we have evidenced excited states in high-quality InAs QI's self-organized on InP(001). We demonstrate a strong carrier confinement in these islands through the integrated PL intensity which was nearly stable in the 8–300 K temperature range under nonresonant excitation and quite stable under quasiresonant excitation. Finally, we have analyzed the unusual temperature dependence of the integrated PL intensity in the 8–75 K temperature range. The abnormal intensity enhancement is attributed to the presence of traps associated with phosphorus vacancies in the InP barrier elaborated at 520 °C.

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