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Optical properties of self-assembled InAs quantum islands grown on InP(001) vicinal substrates

B. Salem,^{a)} J. Olivares, G. Guillot, and G. Bremond^{b)}

Laboratoire de Physique de la Matière-LPM, UMR CNRS 5511, INSA de Lyon, Bâtiment Blaise Pascal, 7 avenue Jean Capelle, F-69621 Villeurbanne cedex, France

J. Brault, C. Monat, M. Gendry, and G. Hollinger

Laboratoire d'Electronique-LEOM, UMR CNRS 5512, Ecole Centrale de Lyon, F-69131 Ecully, France

F. Hassen and H. Maaref

Laboratoire de Physique des Semiconducteurs-LPS, Faculté des Sciences de Monastir, 5000 Monastir, Tunisia

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We have investigated the effect of misorientated InP(001) substrates on the optical properties of InAs quantum islands (QIs) grown by molecular-beam epitaxy in the Stranski–Krastanow regime. Detailed temperature-dependent photoluminescence (PL), excitation density PL, and polarization of photoluminescence (PPL) are studied. PPL shows a high degree of linear polarization (near 40%) for the nominally oriented substrate n and for the substrate with 2° off miscut angle toward the $[110]$ direction ($2^\circ F$), while it is near 15% for the substrate with 2° off miscut angle towards $[010]$ direction ($2^\circ B$), indicating the growth of InAs quantum wires on nominal and $2^\circ F$ substrates and of InAs quantum dots on $2^\circ B$ substrate. These island shapes are confirmed by morphological investigations performed by atomic force microscopy. The integrated PL intensity remains very strong at room temperature, as much as 36% of that at 8 K, indicating a strong spatial localization of the carriers in the InAs QIs grown on InP(001). © 2001 American Institute of Physics. [DOI: 10.1063/1.1427742]

The self-organized formation of three-dimensional islands is considered to be one of the most promising methods to make quantum dot (QD) structures, which is of great importance for fundamental studies as well as for applications in novel semiconductor devices.^{1–3} Theoretical investigations have predicted that QD lasers should have higher gain, lower threshold currents, and higher temperature characteristics compared with quantum well lasers. Therefore, in order to achieve arrays of high quality QDs, several methods have been proposed to improve the QD self-organization. Among them, the growth on vicinal surfaces allows a lateral preferential growth at the surface step edges. Such QDs have been obtained with the InAs/GaAs and InP/InGaP material systems.^{4,5} Few studies of InAs QDs formation on misorientated (001)InP substrates have been reported.^{6–8} In this letter, we present the optical properties of InAs quantum islands (QIs) grown on nominally oriented, $2^\circ F$ and $2^\circ B$ InP(001) substrates via temperature-dependent photoluminescence (PL), excitation density PL, and polarization of photoluminescence (PPL) measurements. These results reveal the growth of isotropic QDs on $2^\circ B$ substrates and of quantum wires on nominal and $2^\circ F$ substrates.

The samples investigated in this study were grown by solid-source molecular beam epitaxy in a Riber 2300 reactor. InAs self-assembled QIs were grown on semi-insulating InP(001), simultaneously on nominally oriented, $2^\circ F$ and $2^\circ B$ substrates. 300-nm-thick InP buffer was grown at 480°C using a phosphorus pressure equal to 1×10^{-5} Torr,

then 3 monolayers (ML) of InAs were grown at 520°C with an arsenic pressure fixed at 4×10^{-6} Torr. The three-dimensional (3D) growth onset is observed by reflection high electron energy diffraction at 1.8 ML. Uncapped islands were imaged using *ex situ* atomic force microscopy (AFM), using a Park Scientific Instruments microscope, model CP, operating in the contact mode. To avoid the ripening of the uncapped islands during cooling under arsenic overpressure, an arsenic/phosphorus flux switch is done at 450°C . In order to characterize the carrier confinement in these quantum islands with PL measurements, the samples were capped with a 300-nm-thick layer of InP. The PL spectra were obtained in the 8–300 K temperature range. The PL was excited using the 514.5 nm line of an Ar⁺ ion laser or a 1064 nm line of a yttrium–aluminum–garnet (YAG) laser. The PL emission was dispersed by a spectrometer and detected by a 77 K cooled Ge photodetector using a conventional lock-in technique. The polarization measurements were performed on the PL emission normal to the surface via a Glan–Thompson near infrared polarizer at the entrance slit of the monochromator followed by a quarter wave plate in order to get the PL signal independent of any light polarization effect of the optical system response.

Figure 1 shows AFM images of the InAs QIs depending on the InP substrate nature. On one hand, on nominal and $2^\circ F$ InP substrates, the InAs islands have a wire shape oriented along the $[1\bar{1}0]$ direction [Figs. 1(a) and 1(b)]. The elongation of the wires is stronger on the $2^\circ F$ InP substrate. The height h of the wires ranges between 0.9 and 1.2 nm and the lengths are in the 100–200 nm range and in the 200–500 nm range on the nominal and $2^\circ F$ substrates, respectively.

^{a)}Electronic mail: bassem.salem@insa-lyon.fr

^{b)}Author to whom correspondence should be addressed; electronic mail: georges.bremond@insa-lyon.fr

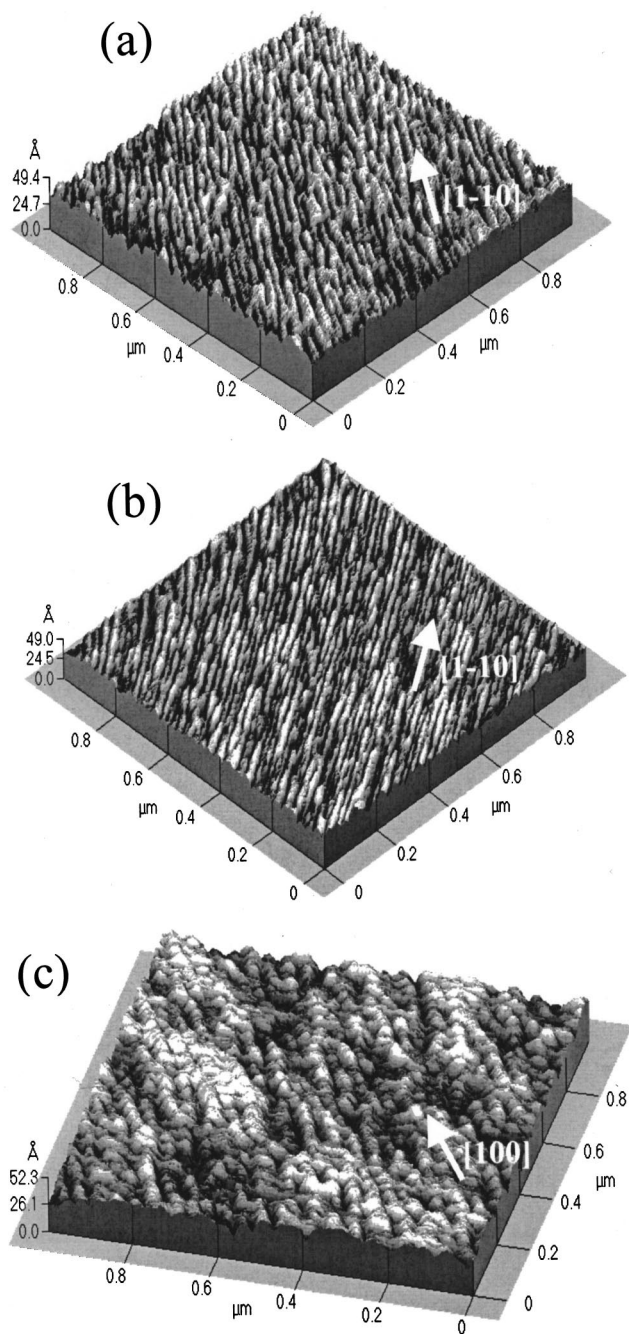


FIG. 1. AFM images of InAs QIs deposited on nominal (a), $2^\circ F$ (b), and $2^\circ B$ (c) InP substrates.

On the other hand, on the $2^\circ B$ InP substrate the islands have an isotropic dot shape with a typical density $\rho \approx 5 \times 10^{10} \text{ cm}^{-2}$ [Fig. 1(c)]. Dot-like island height and diameter are about 0.6 and 30–35 nm, respectively.

PL spectra at 8 K from samples grown on nominal and misoriented InP(001) substrates are shown in Fig. 2. The PL spectra of InAs QIs consists of several lines. The measured linewidths of such individual lines are about 45 meV. No PL intensity transfer has been observed from low to high energy peaks versus the excitation power density. So these individual lines have been attributed to the size fluctuation of the InAs QIs. This fluctuation seems to be less on the $2^\circ F$ substrate, where the full width at half maximum (FWHM) of the total peak is 75 meV, rather than on nominal and $2^\circ B$ substrates where the FWHM is about 115 meV. No emission

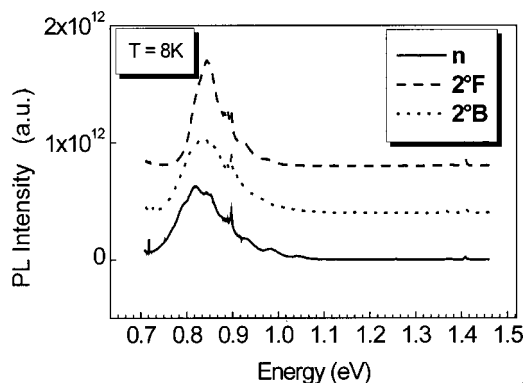


FIG. 2. 8 K PL of self-assembled InAs QIs, grown on nominal, $2^\circ F$, and $2^\circ B$ substrates excited with an argon ion laser.

from the wetting layer is observed, indicating that carriers photogenerated from the wetting layer diffuse quickly to the adjacent InAs QIs. The weaker peak around 1.41 eV is due to recombination in the InP barrier.

The variation of PL integrated intensities as a function of the temperature of the three samples is shown in Fig. 3. The PL intensity remains very strong at room temperature, as much as 36% of its value at 8 K for the $2^\circ B$ sample and around 30% for the $2^\circ F$ and n samples. This behavior suggests that the photogenerated carriers recombine mostly in the QIs without escaping to the barrier layer even at room temperature. As compared to the InAs/GaAs and InAs/InGaAsP/InP QDs for which the room temperature PL intensity drops, respectively, to 0.1% and 20% of its 10 K value,^{9,10} this suggests that the InAs/InP QIs have more favorable characteristics for optoelectronic devices operated at room temperature.

This strong maintenance of luminescence versus the temperature can also be explained¹¹ by a low stress-related defect density at the InAs/InP QI interfaces, as indicated by the linear dependence of the PL intensity with the excitation density, in the range of 0.6–3150 W/cm², that we have observed at $T=8$ K for the three samples.

Additional information about exciton localization in InAs/InP QIs can be extracted from the temperature dependence of the PL peak position (Fig. 4). For comparison, the bulk InAs band gap variation with temperature is also plotted (dotted line) in Fig. 4. We observe that below 70 K, the PL peak position remains quite stable, showing that the exciton

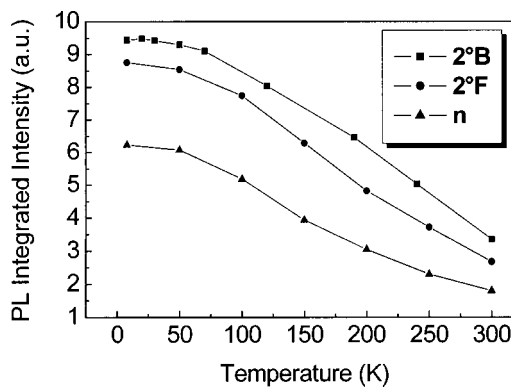


FIG. 3. Temperature dependence of the integrated PL intensity energy for the nominal, $2^\circ F$ and $2^\circ B$ samples under an excitation power of 630 W/cm².

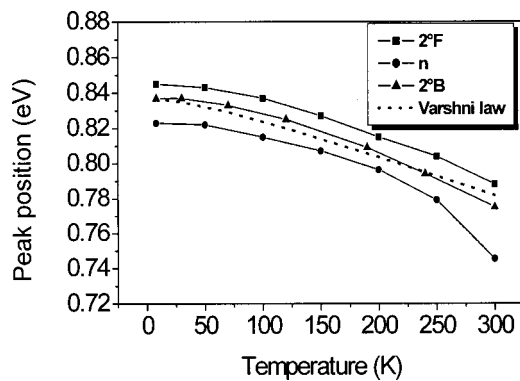


FIG. 4. Temperature dependence of the PL peak energy for the nominal, $2^\circ F$ and $2^\circ B$ samples. The dotted line is calculated according to the Varshni law using the bulk InAs parameters.

is localized in a potential minimum. In the range of 70–190 K, the energy shift follows the Varshni law.¹² But when the temperature is raised further, the redshift is a little faster than the InAs band gap variation. The same behavior is seen for InAs/InGaAs/GaAs QDs.¹³ In the 8–300 K temperature range, the energy shifts only by 61, 67, and 78 meV for the $2^\circ B$, $2^\circ F$, and n samples, respectively. It is far less than the usually reported value of about 200 meV for InAs/GaAs QDs.^{9,14,15} Besides, it is generally believed that the redshifts can be attributed to the redistribution of carriers in QDs^{10,16} and that the large redshifts are an indication of more inhomogeneous QD size distributions. Therefore the smaller redshifts with the temperature increase shown by our results indicate a good size distribution of InAs QDs in our samples.

The PPL measurements were performed in the linear regime. No PL polarization anisotropy was observed on InAs/InP(001) quantum wells (checked but not shown here). On the nominal and $2^\circ F$ samples, a strong anisotropy was observed. In fact, the PL peak intensities observed in the $[110]$ direction of the polarizer are twice smaller than that observed in the $[1\bar{1}0]$ direction.

The degree of linear polarization P of the emitted light is classically defined by the following equation:

$$P = \frac{I[1\bar{1}0] - I[110]}{I[1\bar{1}0] + I[110]}, \quad (1)$$

where $I[1\bar{1}0]$ and $I[110]$ are the PL intensities along the two orthogonal directions $[1\bar{1}0]$ and $[110]$. The degree of linear polarization for the two previous samples (n and $2^\circ F$) are near 40% [Figs. 5(a) and 5(b)]. In fact, these results indicate the signature of quantum wires. We also observed that the degree of linear polarization gradually decreases with the increase of photon energy. This suggests that large size QIs have stronger optical anisotropy than small ones as was also evoked for InP/InGaP and InAs/GaAs(311) QDs.^{17,18} On the other hand, the degree of linear polarization of the $2^\circ B$ sample is only 16% [Fig. 5(c)]. These results reveal that 2° off miscut angle toward the $[010]$ substrate leads to the growth of very slightly elongated self-assembled InAs/InP QDs.

In conclusion, this letter has reported the effect of the misoriented InP (001) substrate on the optical properties of InAs quantum islands using PL and PPL spectroscopies. PPL

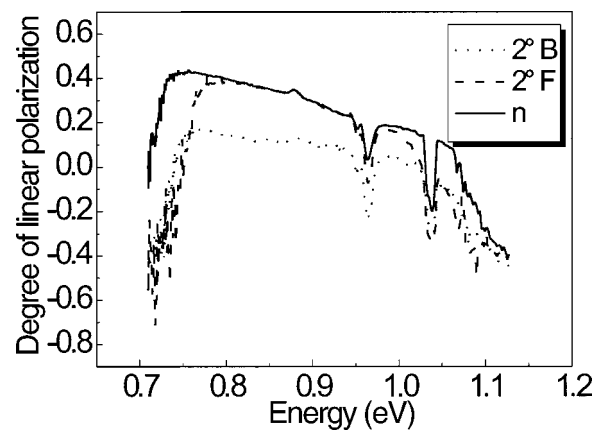


FIG. 5. Polarization PL spectra at 8 K and degree of linear polarization for the nominal, the $2^\circ F$, and the $2^\circ B$ samples.

results give evidence of InAs quantum wires using nominally and 2° off miscut angles toward $[110]$ substrates, while isotropic InAs quantum dots are obtained using a 2° off miscut angle toward the $[010]$ substrate. These results are in good agreement with InAs island morphologies deduced from AFM observations. Therefore these results point out that the use of PPL spectroscopy is a very convenient way of characterizing the shape of QIs with a fast and a nondestructive experimental approach. We also show that we have a great stability of the PL intensity in the 8–300 K temperature range according to a strong localization of photocarriers in the InAs QIs grown on the InP(001) substrate.

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