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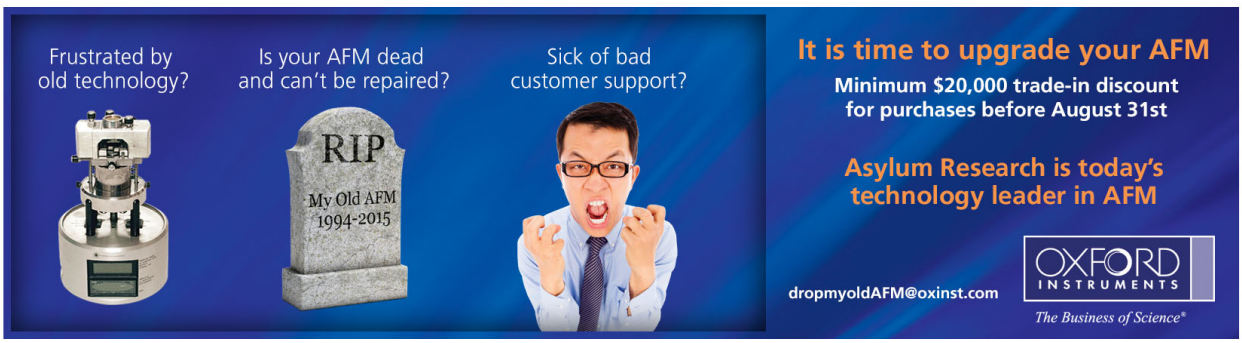

InGaAs/InP quantum wells with thickness modulation

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We investigated the optical properties of lattice-matched InGaAs/InP quantum wells grown by metalorganic molecular beam epitaxy on top of patterned InP buffer layers with elongated features along the $[0\bar{1}1]$ direction. The resulting quantum wells present a periodic thickness variation following the elongated features. Low temperature luminescence measurements exhibit double emission bands, attributed to distinct regions of the well. Temperature evolution of the photoluminescence spectra gives qualitative information about the effect of exciton localization.

Recently, an increasing interest has been devoted to study interface roughness in semiconductor heterostructures.[1–4] This attention has two basic motivations: to improve the interface quality which is a critical point to heterostructure devices and to use the interface control as a tool to design special new systems. In a recent work,[4] it was shown that the roughening process of (100) InP surfaces can generate periodic elongated features. The growth of thin InGaAs layers on top of these prepared InP surfaces gives rise to quantum wells (QWs) with periodic thickness variation. In the present work, we investigated the optical properties of a series of these specially modulated QWs.

The samples were grown by metalorganic molecular beam epitaxy using trimethylindium, triethylgallium, and cracked As_2 and P_2 as the material sources, and (100)InP:Fe substrates. The structure consists of an InP buffer layer, with thickness varying from 400 to 1000 nm, and a single lattice-matched InGaAs QW followed by a 25 nm InP top layer. As the growth of the InP film develops, roughness builds up in a pattern with sawtooth-like features elongated along the $[0\bar{1}1]$ direction. Figure 1(a) shows a scanning force microscope (SFM) image of an InP buffer layer with this pattern. The roughening effect is attributed to an anisotropic diffusion of In species along the crystallographic directions and it depends on the growth conditions such as growth temperature, group III and V fluxes and thickness of the InP film. The basic parameters that define the InP surface are the height and period of the features, with typical values of 4–7 nm and 100–300 nm, respectively. An additional important parameter is the surface roughness, with typical values of the order of 1 nm, and defined as the mean-square-root deviation of the film thickness measured by SFM in a 4×4 μm area. Figure 1(b) shows a schematic profile of an InGaAs QW grown on top of a patterned InP surface. The QW shows a thickness modulation following the sawtooth-like features. The width of the InGaAs film grown at the strongly tilted face is of the order of 1.5 times thicker than the width of the film formed at the less tilted face. The samples presented in this work were grown with a constant temperature (510 °C) and growth rate (1.6 μm/h), but varying the PH_3 flux and the thickness of the InP buffer layer in order to obtain different patterns for the InGaAs QW. This procedure avoids varia-

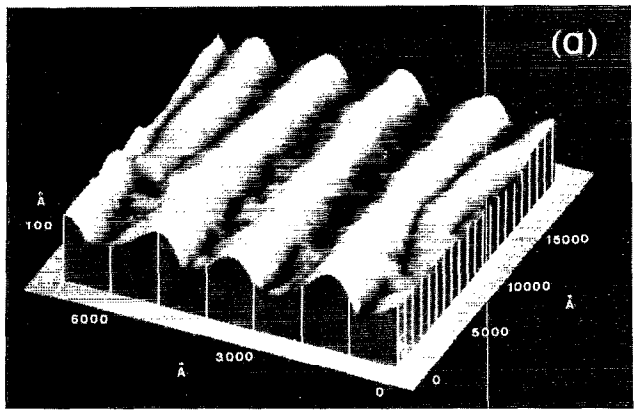

FIG. 1. (a) SFM image from the surface of an InP buffer layer with elongated features along the $[0\bar{1}1]$ direction. (b) Schematic profile of an InGaAs QW grown on top of the patterned InP surface.

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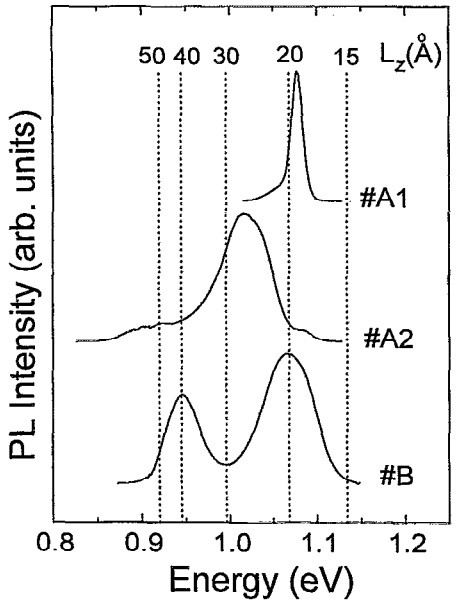

FIG. 2. PL spectra at 2 K from InGaAs/InP single QW samples grown on InP surfaces with different morphologies. Dashed lines correspond to the calculated energies for fundamental transitions of QWs with different thicknesses: L_z.

tions of the composition in the ternary alloy grown on nominal substrate. Samples **#A1** and **#A2** were grown simultaneously using singular and visinal (100) InP substrates, respectively. As a result of the growth conditions used in this case, the sawtooth features were not developed on sample **#A1**, but they just start developing on sample **#A2**, grown on the vicinal substrate. Sample **#B** was grown on a singular (100) InP substrate with slightly different conditions, so that the sawtooth features were well established.

Figure 2 shows the photoluminescence (PL) spectra at 2 K for samples **#A1, #A2**, and **#B**. Sample **#A1** has a distinct PL emission. It shows a single and relatively narrow PL peak, while the other samples show basically two broad bands. The observation of two emission bands from a single QW implies that there are two spatially distinct states, with different energies. We attribute these states to the QW regions with different thicknesses, as shown in Fig. 1(b). This interpretation is supported by the single PL emission from sample **#A1**, which does not present sawtooth-like features, and consequently, has no QW thickness modulation. An alternative explanation for the double bands is a fluctuation of the InGaAs composition. However, this would mean a variation of the order of 10% on the alloy composition, which is strongly unlikely. Finally, since the PL probes an area larger than the SFM resolution, an increase of the interface roughness measured by SFM should result in a broadening of the PL peak. In accordance, the interface roughness measured by SFM is significantly small for sample **#A1** (~0.2 nm) and has the biggest value for sample **#A2** (~2.0 nm).

The dashed lines presented in Fig. 2 correspond to the fundamental transition energies for QWs with different thicknesses, L_z. The energies were calculated using the envelope function approximation for an ideal square (100) QW and considering a conduction band offset[5,6] of 0.4 Eg. This is probably a good approximation for the thin InGaAs regions whose lateral dimensions are of the order of 150 nm. However, in the case of the thick QW regions, with lateral dimensions of the order of 15 nm, it may be necessary to consider lateral confinement. Nevertheless, the present calculation can be used as a rough estimation of the QW widths. As shown in Fig. 2, the high energy bands correspond to QWs with thicknesses of the order of 20 Å, which is in reasonable agreement with the 11 Å value obtained by transmission electron microscopy (TEM) measurements, considering the large error of both the theoretical model and the TEM measurements for these relatively thin QWs. The low energy bands should correspond to the thick QW regions, and the ratio between the thicknesses of the two regions is close to the 1.5 value estimated by TEM measurements.

The temperature evolution of the PL emission from sample **#B** is presented in Fig. 3(a). As the temperature increases, the low energy band becomes relatively stronger as compared to the high energy one. At room temperature the low energy band is dominant and the high energy band has almost vanished. All spectra shown in Fig. 3(a) are normalized. The total integrated PL intensity decreases with increasing temperature. This effect is attributed to the thermal emission of photogenerated carriers to the InP barriers followed by nonradiative recombination. The inset of Fig. 3(a) shows the logarithmic of the ratio between the intensity of the high energy band (I_H) and the total integrated emission (I_T) as a function of the reciprocal temperature. The ratio remains almost constant from 2 to 50 K and decreases for higher temperatures, indicating an increase of the recombination probability through the levels corresponding to the low energy band. This result indicates that the exciton is localized and has to overcome a certain energy barrier to be able to migrate from the thin QW regions (high energy levels) to the thick QW regions (low energy levels).

The localization of excitons has been observed by other authors and has been interpreted as the binding energy of excitons to local fluctuations of the potential, created by microscopic variations of the well width and the alloy composition.[6–8] The microscopic fluctuations at the interfaces break the in-plane symmetry, so that the two-dimensional (2D) plane-wave-like states are replaced by a set of states modulated by the microroughnesses. Since the microroughness is relatively small, the states are closely separated in energy and actually form a band of localized states. The lower the energy of the state, the more its wave function perceives the attractive-like fluctuations and the more the state is localized. As we consider states with higher energies, they become less localized, barely discerning the fluctuations, and tend to recover the ideal 2D-like behavior. This simple picture can explain our observations. At low temperatures, once electrons and holes are photoexcited to high energy states, their wave functions are extended over the entire interface plane and they quickly relax to the low energy states by phonon emission. As they relax into states with different spatial modulation randomly distributed over all the QW plane, further phonon emission becomes more difficult and can only be achieved by tunneling. The formation of

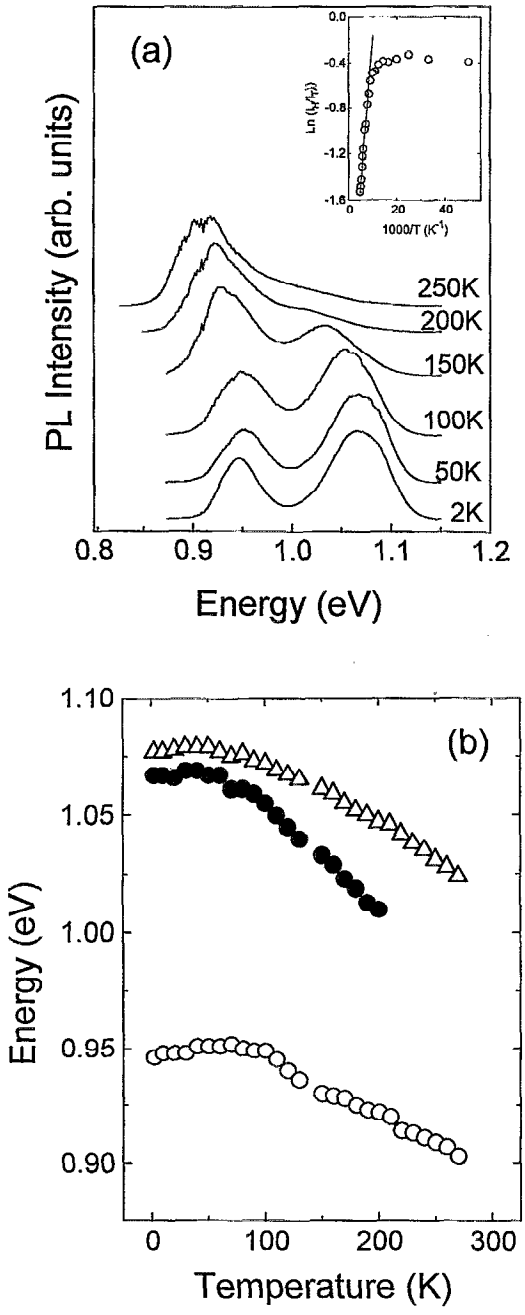

FIG. 3. (a) Temperature evolution of the PL emission from sample **#B**. The inset shows the logarithmic of the ratio between the intensity of the high energy band (I_H) and the total integrated emission (I_T) as a function of the reciprocal temperature. (b) PL peak energy from sample **#A** (△) and **#B** (● and ○) as a function of the temperature.

excitons from closely localized electrons and holes followed by radiative recombination is therefore favored. The low temperature PL shape can then be viewed as a rough estimate of the density-of-states for the localized states. By increasing the temperature, the phonon population increases and the electron-phonon interaction can detrap the carriers by scattering them into delocalized states, so that they can diffuse in the QW plane. They may be then captured by nonradiative centers. However, it is reasonable to suppose that these centers are randomly distributed over all QW regions and this should not affect the PL intensity ratio. Concurrently, the carriers from the high energy band can diffuse and relax into states corresponding to the low-energy band, increasing its intensity against the high-energy band.

It is hard to estimate the binding energy of the localized exciton due to difficulties in modeling the microscopic fluctuations at the interface and to its high sensitivity to the growth parameters. However, this binding energy can be estimated from an Arrhenius plot of the data presented in Fig. 3(a). The fitting to the data in the temperature range from which the ratio of intensities shows an exponential behavior gives an "activation energy" of 25 meV. This value is higher than those presented in the literature.[6,7] This is probably due to a significant interface roughness as compared to a sample with a smooth interface, since the special conditions used to obtain our samples result in a quasi-3D growth.

The variation of the PL peak energy as a function of temperature is presented in Fig. 3(b). Both sample **#A** and the low energy band from sample **#B** show a temperature dependence that agrees with the band-gap energy variation of the well material. In contrast, the position of the high energy band from sample **#B** shifts to lower energies faster than the band-gap energy. This is compatible with our model of exciton localization. Two reasons favor the excitons which are in the high energy side of the localized band to be detrapped earlier from the microscopical fluctuations: (i) they need less energy to scatter into a delocalized state, so that more phonons are energetically available to the process; (ii) they are less localized in space, which increases their probability to interact with phonons. As the temperature increases, the PL intensity of the high energy band reflects the density-of-states of the localized band weighed by the carrier distribution in the band. Since the carriers in the high energy side of the band are faster detrapped, the PL peak shifts to low energies with increasing temperature with a faster rate than the host material energy gap, as it was observed.

In summary, we have investigated InGaAs/InP QWs with periodic variation of the thickness in the form of wires. PL results indicated that there are spatially localized states associated with the sawtooth features with energies smaller than the basic QW state. At low temperature, the excitons are bound to local fluctuations of the potential at the interface. The binding energy was estimated to be of the order of 25 meV.

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