Low size dispersion of InAs quantum islands emitting at 1.55μm on InP (001)

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We show that the size dispersion of InAs/InP(001) quantum islands emitting at 1.55μm can be reduced through the optimization of SSMBE growth parameters. In optimized growth conditions, i.e. high Tc ~520°C and low P_{As} = 2 10^{-6} torr leading to a 2D/3D growth mode transition measured by RHEED at 1.8 ML, photoluminescence spectra with a FWHMs as low as 68meV at 300K have been obtained for a 4ML InAs deposit. Photoluminescence measurements as a function of the excitation power show that the multi-component PL spectra can be understood in terms of fundamental and excited levels of InAs islands. The fundamental peak (FWHM equal to 22meV at 8K) reveals a very low island size dispersion. Plane-view TEM and AFM images show that InAs islands are quantum « sticks » aligned along [1-10], with flat top surfaces. Cross-section TEM imaging shows a very weak height dispersion attributed to the ability of the InAs/InP(001) system to allow island height variation by monolayer fluctuation.

I. Introduction

Highly compact microlasers, emitting in the 1.3-1.6μm range are important building blocks for optical interconnects applications in the next generation of integrated circuits. The compatibility of such devices with dense photonic integration implies in-plane emission and low threshold. 3D microcavities [1] and quantum dots [2], allowing to confine respectively both photons and electrons, can be efficiently associated to achieve these requirements. The relevant 1.3-1.6μm range, especially the 1.55μm telecommunication wavelength, can be reached with InAs/InP islands. Many works have been devoted to the fabrication of InAs/InP islands using the Stranski-Krastanov (SK) growth mode. Because of the low strain InAs/InP system (~3%) and As/P exchange reactions at the interfaces [3,4], the InAs island size dispersion is however naturally high. Full width at half maximum (FWHM) of photoluminescence (PL) spectrum, known as related to the island size dispersion, are typically 50-120meV [4-7], much higher than 15-50meV measured for InAs/GaAs islands [8,9]. The purpose of this work was to reduce the size dispersion of InAs islands grown on InP(001) by optimizing the MBE growth parameters of the InAs quantum island layers and the interface fabrication procedures. This was achieved by: i) increasing the growth temperature in order to lower the 3D growth mode onset (H_{3D}), ii) lowering the arsenic pressure during InAs growth in order to favor adatom surface diffusion and iii) reducing the InAs island exposure to phosphorus pressure before growth of the InP capping layer in order to reduce As/P exchange reactions.

II. Experimental

Samples were grown by Solid Source Molecular Beam Epitaxy (SSMBE) on epiready InP(001) wafers from InPact, in a RIBER 2300 reactor equipped with valved arsenic and phosphorus cracker cells. After thermal desorption of the native oxide, a 200nm-thick InP buffer layer is grown at 480°C. The sample temperature is then increased under 10^{-5} torr phosphorus pressure to the InAs growth temperature. After P/As flux switching, the surface is maintained 10 seconds under arsenic flux before starting the InAs growth. The InAs island layer is grown at 0.25μm/h and is annealed 10 seconds at growth temperature under arsenic pressure. The InP capping layer is then

immediately grown, after the As/P flux switching, with a 0.25μm/h growth rate and a 4.10^{-6} torr phosphorus pressure. During this InP capping layer growth, the sample is rapidly cooled to 480°C. After growing a 40nm-thick InP layer, the growth is interrupted during 5 minutes and then a 260nm-thick InP layer is grown with a 1μm/h growth rate and a 1.10^{-5} torr phosphorus pressure. The InAs 2D/3D growth mode transition is measured by reflection high-energy electron diffraction (RHEED). Samples without capping layers are grown for atomic force microscopy (AFM) imaging. For such samples, an arsenic to phosphor flux switching is necessary during sample cooling to avoid InAs island ripening. AFM measurements were carried out using a Park Scientific Instruments microscope operating in contact mode. Capped InAs islands were also characterized by plane-view and cross-sectional transmission electron microscopy (TEM) images using a TOPCON EM-002B microscope working at 200kV with 0.18nm point-to-point resolution. Cross-section TEM images were recorded using conventional dark-field images using (002) planes which allow a good composition contrast with low plane distortion influences. PL measurements have been performed at 300K using an AlGaAs laser diode emitter (λ=800nm) and at 8K using argon ion laser (514.5nm line).

III. Results

Figure 1 shows the dependence of the 2D/3D-growth mode transition versus the growth temperature T_g, as measured by RHEED, for InAs layers grown on InP.

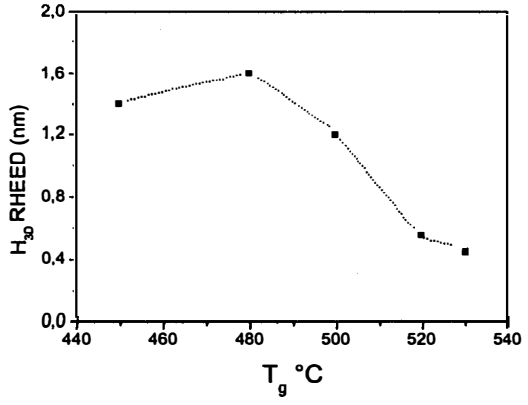

Figure 1: 2D/3D growth mode transition (H_{3D}) for InAs/InP(001) layers as a function of the growth temperature.

This clearly indicates that the 3D growth mode onset is strongly decreased down to 0.5nm when the growth temperature is increased to 520-530°C, comparing to 1.6nm measured at 480°C. Due to the low 3D growth mode onset in the 520-530°C T_g range, it becomes possible to fabricate small InAs islands which can emit around 1.55μm at 300K. We have then studied, in this T_g range, the effects of arsenic pressure and InAs deposit thickness on the emitting wavelength and on the PL peak FWHM at 300K. Figure 2 shows that lowering the arsenic pressure leads to a reduction of the wavelength as well as of the FWHM. Figure 3 shows that increasing the InAs deposit thickness leads to a wavelength increase and a FWHM reduction.

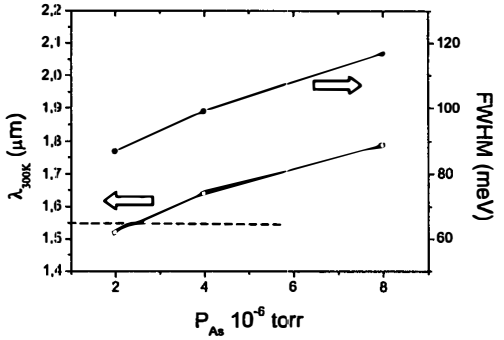

Figure 2: Emitting wavelength and FWHM at 300K as a function of the arsenic pressure (T_g=520°C, e_{InAs}=0.9nm).

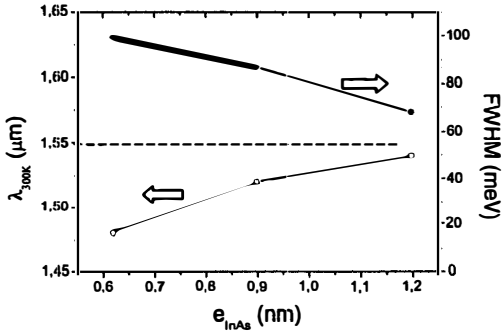

Figure 3: Emitting wavelength and FWHM at 300K as a function of the InAs deposit thickness (T_g=520°C, P_{As}=2 10^{-6} torr). The 3D-mode onset is measured by RHEED at 0.55nm.

It follows from these experiments that island size dispersion is minimized when the InAs deposit thickness is well superior to the 3D-growth mode onset and when the arsenic pressure is reduced. Using such conditions, FWHM as low as 68meV at 300K has been obtained for InAs islands emitting at 1.55μm when 1.2nm-thick InAs (4ML) has been deposited at 520°C with a 2 10^{-6} torr arsenic pressure.

Because of possible As/P exchanges within the InAs/InP interfaces [3], it was necessary to develop procedure to limit this phenomenon. In particular, we have prohibited the annealing of the InAs islands

under phosphorus pressure and the InP capping layer has been grown with a reduced phosphorus pressure.

Turning now to the low temperature PL study of these optimized InAs islands [10], the 8K PL measurements reveal a multi-component spectrum (Figure 4a) classically observed in the InAs/InP system. Five components can be detected. Two intense components at 0.845 and 0.875 eV and three weaker components at 0.825, 0.905 and 0.945 eV. More interesting are the PL measurements as a function of the excitation power (Figure 4b). When the power is increased, we observe a saturation of the 0.845eV peak intensity while the intensities of the three peaks at higher energy are continuously increasing. This behavior suggests that the higher energy components at 0.875, 0.905 and 0.945eV are transitions associated to excited levels (EL) and that the 0.845eV component is related to the fundamental level (FL). This attribution has been checked without any ambiguity by PL excitation and by time resolved PL [11]. Considering this peak assignment, the FWHM which has to be taken into account to characterize the InAs island size dispersion is that of the fundamental level transition (FL) at 0.845eV which is in fact very low, since measured at 22meV.

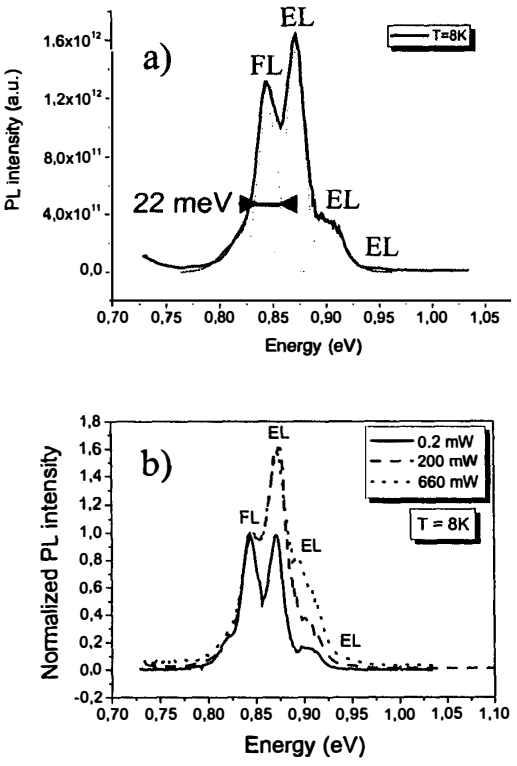

Figure 4: a) PL spectrum at 8K and b) evolution with the excitation power for optimized InAs/InP(001) islands (T_g=520°C, P_{As}=2 10^{-6} torr, e_{InAs}=1.2nm).

Figure 5 shows AFM and TEM images of the corresponding InAs islands. The AFM image (Figure 5a) clearly indicates that the InAs/InP islands have a stick-like shape with elongation in the [1-10] direction. Their lengths are in the 50-100nm range. From cross-section TEM (Figure 5b), it appears that these stick-like islands exhibit a truncated pyramid shape with typical widths of 17.5 ±04nm and almost identical heights close to 2.4nm. Both AFM and TEM images indicate a high island density, corresponding to an area coverage of about 90%.

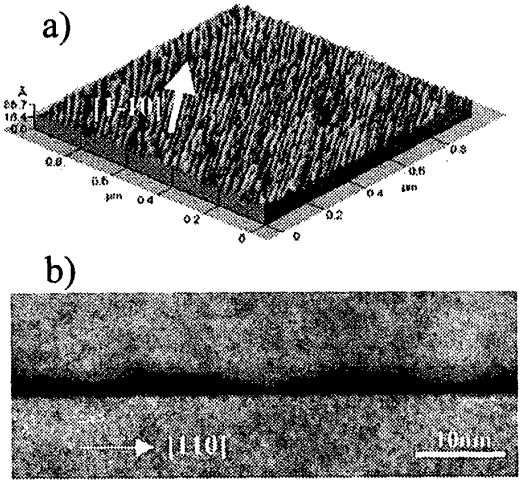

Figure 5: a) AFM image and b) Cross-section TEM image along [110] of optimized InAs/InP(001) islands (T_g=520°C, P_{As} 2 10^{-6} torr, e_{InAs}=1.2nm).

Finally, we note that the total island volume deduced from the TEM image corresponds to an equivalent InAs thickness of 5.7ML. This value is higher than the 4ML effectively deposited which seems to indicate the formation of additional InAs or InAsP. This could happen through P/As exchanges either at the InP buffer surface during the 10 seconds exposure to arsenic pressure before starting the InAs growth or when growing the capping layer.

IV. Discussion and conclusion

Our PL results clearly show that a low size dispersion can be obtained for self-organized InAs islands grown on InP(001) when growth parameters are optimized. This size dispersion becomes comparable to that obtained for the best InAs/GaAs islands.

The main characteristic of the optimized InAs islands are their truncated pyramid shapes, their identical heights (a monolayer fluctuation would give a PL shift higher than the 22 meV measured linewidth) and their relatively large sizes.

We think that we can achieve such a good order because we take advantage in the growth procedure of both thermodynamic and kinetic factors.

1) The high growth temperature leads to the nucleation of 3D islands after deposition of only a low quantity of InAs.
2) Additional deposition of InAs on these islands favors the island self organization. Adatoms tend to be incorporated at sites where the elastic strain energy is minimized (thermodynamics). This should lead to ideal periodic structures.
3) Reducing the arsenic pressure favors adatom surface diffusion (kinetics) and helps again self organization.

However, we think that the achievement of such low linewidth values is principally due to the ability of the InAs/InP (001) system to allow the fabrication of flat InAs islands. An interesting consequence of this flat shape is that the energy levels of the islands are governed by the height which is an integer number of monolayers. Whereas InAs/GaAs islands should have energy level varying continuously with their size, InAs/InP islands show discrete fluctuation associated to monolayer fluctuation Controlling the height at the monolayer level, with optimized growth conditions, allow immediately to reach very narrow level distribution.

To conclude, we have fabricated InAs quantum islands on InP(001) that are expected to give an active material exhibiting a spectral gain strong enough to demonstrate laser emission at 1.55μm. Works are in progress on that issue.

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