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Planarization of InP pyramids containing integrated InAs quantum dots and their optical properties

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Position-controlled InAs quantum dots (QDs) are integrated into planar InP structures by employing selective area growth of InP pyramids and regrowth by metalorganic vapor-phase epitaxy. A smooth surface morphology is obtained at elevated regrowth temperature due to suppression of three-dimensional growth on the pyramids. The height differences are less than 30 nm after nominal 700 nm InP regrowth at 640 °C. Most important, the integrated QDs maintain good optical quality after regrowth for the realization of integrated nanophotonic devices and circuits operating at telecom wavelengths. © 2010 American Institute of Physics. [doi:10.1063/1.3491025]

I. INTRODUCTION

Photonic integration shows a clear exponential increase in component density similar to Moore's law in electronics.¹ For further increase, in particular, quantum dot (QD) gain material is appealing due to low transparency currents, very broad gain spectra, and the possibility of deep etching without device degradation. Extended cavity Fabry-Pérot QD lasers have already been demonstrated based on established Butt-joint active-passive integration technology.² Pushing photonic integration technology to the fundamental limits regarding component size, complexity, and power consumption will require position control of QDs in small numbers, down to a single QD and novel integration techniques allowing device operation at the few/single electron and photon levels. Among the various approaches for QD position control based on growth on patterned substrates^{3–6} and selective area growth^{7–13} we have chosen the latter. The deposition of QDs on selectively grown pyramids allows not only QD position and number control but also the control of the QD distribution through the pyramids base shape¹² for matching it, e.g., to the optical mode of a particular photonic crystal nanocavity.

Here we demonstrate the integration of position controlled InAs QDs embedded in submicron-size InP pyramids into planar structures by regrowth of InP in metalorganic vapor-phase epitaxy (MOVPE). Growth conditions are first optimized for nominal 250 nm InP regrowth and then transferred to thicker layers for large-scale regrowth. A smooth surface morphology is obtained at elevated regrowth temperature due to suppression of three-dimensional growth on the pyramids. The height differences are less than 30 nm after optimized nominal 700 nm InP regrowth at 640 °C and there is no growth on the pyramids top. Most important, good optical quality of the integrated QDs is maintained for the realization of integrated nanophotonic devices and circuits operating at telecom wavelengths.

II. EXPERIMENTAL DETAILS

For substrate patterning a 100 nm SiN_x mask layer was deposited on the InP (100) substrates by plasma-enhanced chemical-vapor deposition. A field of openings in the mask was processed by electron beam lithography and reactive ion etching. The center-to-center distance of the openings was

FIG. 1. (Color online) AFM images of (a) truncated pyramid with QD on top, (b) CP, and (c)–(h) RPs with regrowth temperatures of 550 °C, (e) 585 °C, (f) 600 °C, (g) 615 °C, and (h) 630 °C. Diameter of the circular mask opening is 700 nm.

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FIG. 2. (Color online) (a) AFM line profiles taken along $[01\bar{1}]$ and $[001]$ of the CP and RPs for different regrowth temperatures, offset by the thickness of the planar layers around the pyramids. The vertical solid, dotted, and dashed lines indicate the pyramids center, edge, and the planar areas. (b)–(d) Temperature dependence of the (b) regrown layer thickness at the pyramids center, edge, and of the planar layers aside, (c) extension of the laterally grown layers around the pyramids along $[01\bar{1}]$ and $[001]$, and (d) angle of the sidewalls in the $[01\bar{1}]$ and $[001]$ directions between the laterally and planar grown layers.

10 μm . For selective area growth and regrowth, first, truncated InP pyramids were grown at 610 $^{\circ}\text{C}$ by selective area MOVPE using tertiary butyl phosphine and trimethyl indium as precursors. Then the temperature was lowered to 500 $^{\circ}\text{C}$ for growth of a GaAs interlayer (tertiary butyl arsine, trimethyl gallium), and the InAs QDs (TBA, TMI). The GaAs interlayer tunes the QD emission wavelength into the 1.55 μm wavelength region.¹⁴ After QD formation, an 8 nm InP capping layer was grown at 500 $^{\circ}\text{C}$, then the temperature was raised to 610 $^{\circ}\text{C}$ and another 40 nm InP cap layer was deposited. The detailed growth parameters can be found in Refs. 12 and 13. The SiN_x mask was then removed and regrowth of 250 or 700 nm InP was performed at temperatures between 550 and 640 $^{\circ}\text{C}$. The surface morphology of the uncapped InAs QDs on the InP pyramids top, the fully capped pyramids (CPs), and the regrown pyramids (RPs) was examined by atomic force microscopy (AFM). The optical properties of the regrown InP and the capped and regrown QDs were studied by microphotoluminescence (micro-PL) spectroscopy with a spatial resolution of ~ 0.5 μm and the samples mounted in a He-flow cryostat. The PL was excited by the 632.8 nm line of a He–Ne laser through an optical microscope objective, which also served

to collect the PL. The PL was dispersed by a single monochromator and detected by a cooled InGaAs linear array detector.

III. RESULTS AND DISCUSSION

Figure 1 shows the AFM images of the uncapped InP pyramids and CPs before and after InP regrowth. The round shaped mask opening has a diameter of 700 nm. Figure 1(a) reveals a single InAs QD on the InP pyramid close to pinch-off, Fig. 1(b) the CP after capping the QD, and Figs. 1(c)–1(h) the RPs after deposition of nominal 250 nm InP at the growth temperatures of 550 $^{\circ}\text{C}$, 585 $^{\circ}\text{C}$, 600 $^{\circ}\text{C}$, 615 $^{\circ}\text{C}$, and 630 $^{\circ}\text{C}$, respectively. Figure 2(a) depicts the corresponding line profiles taken along $[01\bar{1}]$ and $[001]$, offset by the thickness of the planar layers around the pyramids. The vertical solid black, dotted red, and dashed blue lines indicate the pyramids center, edge, and the planar areas. In Fig. 2(b) the regrown layer thicknesses at the pyramids center, edge, and of the planar layers aside are plotted as a function of regrowth temperature; in Fig. 2(c) the extension of the laterally grown layers around the pyramids along $[01\bar{1}]$ and $[001]$, and in Fig. 2(d) the angle of the sidewalls in

FIG. 3. (Color online) AFM image of the optimized large-scale RP with base size of $1.5 \mu\text{m}$ together with the line profile, including that of the CP. Inserted arrow indicates the profile place and direction.

the $[01\bar{1}]$ and $[001]$ directions between the laterally and planar grown layers. Before regrowth, the height and diameter of the CP are 510 nm and 850 nm, respectively. After regrowth, with increasing temperature from 550 to 630 °C:

- The regrown layer thickness at the pyramid center reduces from 460 to 0 nm.
- The layer thickness at the pyramid edge decreases from 930 to 260 nm.
- The thickness of the planar layer around the pyramids increases from 0 to 230 nm, close to the thickness at the pyramid edge.
- The extensions of the laterally grown layer around the pyramid along $[01\bar{1}]$ and $[001]$ reduce and become equal.
- The angles of the sidewalls in the $[01\bar{1}]$ and $[001]$ directions between the laterally and planar grown layers reduce and become equal.

Therefore, with increase in the regrowth temperature there is a clear transition from three-dimensional asymmetric growth entirely on the pyramid to two-dimensional symmetric lateral and planar growth around the pyramid leading to planarization.

The growth rate enhancement at the pyramid edge is attributed to adatoms migrating from the pyramid side facets to the planar area and is reduced when planar growth dominates. The strong asymmetry of the three-dimensional growth at low temperature is due to the different growth rates on the pyramid facets. The growth rate on the $(111)\text{B}$ facets is the largest, leading to strong extension along $[01\bar{1}]$, most probably due to its surface energy being the lowest.¹³ This growth asymmetry is also reflected in the different and relatively steep sidewall angles of the laterally grown layer around the pyramid. At high temperature, faceting becomes less pronounced and symmetric lateral and planar growth dominate, which is also seen in the almost identical and reduced sidewall angles.

To perform larger-scale regrowth, the nominal InP layer thickness is increased to 700 nm and the growth temperature to 640 °C. Figure 3 shows the AFM image of the regrown structure around a pyramid with base size of $1.5 \mu\text{m}$ together with the line profile, including that of the CP. There is no growth on top of the pyramid. The growth rate enhance-

FIG. 4. (Color online) (a) Micro-PL spectrum of an integrated single QD after regrowth. (b) Excitation power dependent micro-PL spectra. $P_0 = 13.6 \text{ nW}$. Resolution of monochromators is indicated. (c) Temperature dependent micro-PL spectra and (d) plot of the QD PL peak position and FWHM vs temperature.

ment at the pyramid edge is reduced to 30 nm which is the same as the height difference of the laterally and planar grown layers. The extension of the laterally grown layer is increased to $5 \mu\text{m}$ with an overall very smooth surface morphology. The PL efficiency of the regrown InP is high, com-

parable to that of planar layers. This confirms good crystal quality and indicates a low level of nonradiative recombination centers which is required for low absorption of the passive structures in photonic integrated circuits.

Figure 4 shows the micro-PL spectrum of an integrated single QD after regrowth taken at 5 K with 13.6 nW laser excitation power. The PL peak is centered at 0.8478 eV (1462 nm) with a full-width at half maximum (FWHM) of 308 μ eV (0.5 nm). This is close to the resolution limit of our setup and most probably larger than the intrinsic linewidth due to pronounced broadening and redshift with excitation power already observed in this regime, as shown in Fig. 4(b). When the excitation power is increased from 13.6 nW up to 136 μ W the PL linewidth increases up to 6 nm and the PL peak shifts from 1462 to 1456 nm. This excitation power dependence is typical due to fluctuating charge distributions around the QD statistically shifting its energy levels, in particular to lower energies due to the quantum confined Stark effect. Unfortunately the measurement sensitivity does not allow us to further reduce the excitation power below the 13.6 nW.

To definitely make sure that the emission stems from a single QD, temperature dependent PL spectra are taken, shown in Fig. 4(c). The excitation power is 136 μ W in order to trace the emission up to sufficiently high temperatures. With increasing temperature the PL peak redshifts from 1456 nm at 5 K to 1478 nm at 120 K, plotted in Fig. 4(d), following the bandgap, typical for single QDs. The FWHM does not change much below 50 K (from 6 to 7 nm), while there is a strong increase for higher temperatures. This again is typical for single QDs also on planar substrates due to the change over from acoustic to optical phonon scattering.¹⁵

IV. CONCLUSIONS

We have demonstrated the planarization of selectively grown submicron size InP pyramids containing integrated InAs QDs by regrowth of InP in MOVPE. Taking advantage of the two-dimensional lateral and planar growth around the pyramids at elevated growth temperatures, a smooth surface morphology is obtained. The height differences are less than

30 nm after optimized nominal 700 nm InP regrowth at 640 °C and there is negligible growth on the pyramids. Most important, good optical quality of the integrated QDs is maintained after regrowth paving the way for the realization of integrated nanophotonic devices and circuits operating at telecom wavelengths.

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