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InAs/InGaAsP sidewall quantum dots on shallow-patterned InP (311)A

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Highly strained InAs quantum dots (QDs) embedded in InGaAsP are formed at the fast-growing $[01-1]$ mesa sidewall on shallow-patterned InP (311)A substrates by chemical beam epitaxy. Temperature dependent photoluminescence (PL) reveals efficient carrier transfer from the adjacent dashlike QDs in the planar areas to the larger sidewall QDs resulting in well-distinguishable emission around 80 K. The large high-energy shift of the PL from the sidewall QDs as a function of excitation power density is ascribed to the screening of the internal piezoelectric field. The linear polarization of the PL from the sidewall QDs is reversed compared to that of the quantum dashes in the planar areas due to the more symmetric shape and possible nonuniform strain in the sidewall QDs. © 2006 American Institute of Physics. [DOI: 10.1063/1.2345045]

I. INTRODUCTION

Epitaxial growth on patterned substrates has been widely studied for the formation of quantum wires (QWRs) and quantum dots (QDs) with precisely controlled position and emission energy for optoelectronic devices. Being complementary to the growth on V-groove and ridge-patterned substrates^{1–6} we have developed a technique for formation of quasiplanar sidewall QWRs and QDs on shallow $[01-1]$ mesa-patterned GaAs and InP (311)A substrates.^{7–10} QWR and QD formations rely on the preferential adatom migration from the mesa top and bottom towards the fast-growing sidewall in the sector towards the next (100) plane.¹¹ The direction of adatom migration is, thus, opposite to that on patterned (100) substrates for formation of V-groove or ridge-type QWRs which are bound by slow-growing side facets. High-quality, weakly strained InGaAs QWRs embedded in InGaAsP on shallow-patterned InP (311)A substrates have been demonstrated with strong emission up to room temperature in the technologically important 1.55 μm wavelength range for telecom applications.¹⁰

Here we report the growth and optical properties of highly strained InAs/InGaAsP sidewall QDs on shallow-patterned InP (311)A. Larger and more symmetric InAs QDs are formed at the fast-growing $[01-1]$ oriented mesa sidewall compared to the shallower, dashlike QDs, elongated along $[-233]$, in the planar areas. With the increase of the sample temperature, the photoluminescence (PL) intensity of the sidewall QDs rises with respect to that of the quantum dashes in the planar areas due to thermally activated carrier transfer, leading to well-distinguishable emission in the temperature range around 80 K. As a function of excitation power density, the emission from the sidewall QDs reveals a large high-energy shift due to screening of the internal piezoelectric field by photogenerated carriers. Strikingly, the linear polarization of the PL from the sidewall QDs along $[01-1]$

is reversed compared to that of the PL from the quantum dashes in the planar areas, polarized along $[-233]$, which is attributed to the more symmetric shape and possible nonuniform strain in the growth plane perpendicular to the sidewall in these sidewall QDs formed on shallow-patterned InP (311)A.

II. EXPERIMENT

The InAs sidewall QDs were grown by chemical beam epitaxy (CBE) on a shallow-patterned InP (311)A substrate using trimethylindium (TMI), triethylgallium (TEG), AsH₃, and PH₃ as precursors. The AsH₃ and PH₃ gases were thermally decomposed in a high-temperature injector at 900 °C. The InP (311)A substrates were patterned into $[01-1]$ oriented mesa stripes with 2 μm width, 4 μm pitch, and ~ 30 nm height by conventional photolithography and wet-chemical etching in the HCl:H₃PO₄ (1:10) solution with etching rate of 50 nm/min. The substrates were mounted by In on a Mo block and degassed in the buffer chamber at 200 °C for 30 min before being transferred into the growth chamber. The layer structure commenced with a 20 nm InP plus 20 nm lattice-matched In_{0.73}Ga_{0.27}As_{0.59}P_{0.41} buffer with band gap at 1.3 μm (Q1.3 InGaAsP), which is our standard waveguide core material for photonic devices. The buffer layer was followed by 2.5–3.2 ML (monolayer) InAs for QD formation in different samples, capped by 50 nm In_{0.73}Ga_{0.27}As_{0.59}P_{0.41} after 5 s growth interruption, and a second 2.5–3.2 ML InAs QD layer on top for structural analysis by atomic force microscopy (AFM) in air. The growth temperature was 500 °C and the growth rates were 0.40 ML/s for InAs and 0.52 ML/s for InGaAsP. For PL, the sample presented here with 2.5 ML InAs for QD formation was placed in a He-flow cryostat and excited by the 532 nm line of a Nd:YAG (yttrium aluminum garnet) laser at temperatures between 5 K and room temperature, and excitation power densities between 1 and 100 W/cm². The PL was dispersed by a single monochromator and detected by a cooled InGaAs charge-coupled device. A linear polarizer fol-

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FIG. 1. (Color online) AFM image of the sidewall QDs and quantum dashes in the vicinity of the fast-growing mesa sidewall on shallow-patterned InP (311)A substrate. The scan field is $1 \times 1 \mu\text{m}^2$ and the full color height contrast is 10 nm.

lowed by a quarter-wave plate was inserted in the detection path directly after the sample to analyze the linear polarization of the PL from the sample surface. For micro-PL, the 632.8 nm line of a He-Ne laser with power of $10 \mu\text{W}$ was used as excitation source. The PL was excited and collected through an optical microscope objective providing a spatial resolution of $2\text{--}3 \mu\text{m}$.

III. RESULTS AND DISCUSSION

Figure 1 shows the AFM image of the surface morphology of the top InAs QD layer in the vicinity of the fast-growing mesa sidewall. The scan field is $1 \times 1 \mu\text{m}^2$ and the full color height contrast is 10 nm. In the planar areas on the mesa top and bottom, the typical dashlike surface morphology is found, which is due to strain induced growth instability during deposition of InAs on InP (311)A (Ref. 12) or (In,Ga)As on GaAs (311)A.^{13–15} The dashes are elongated along $[-233]$. At the mesa sidewall, on the other hand, larger and higher InAs QDs are formed with a more symmetric shape. On planar InP (311)A substrates, nucleation of larger InAs QDs on top of the dashes occurs for deposition of InAs above 4 ML.¹² This confirms the strong selective In adatom migration towards the fast-growing mesa sidewall on the shallow-patterned InP (311)A substrate. No large QDs are observed at the opposite slow-growing mesa sidewall, which is solely covered by dashes.

The temperature dependent PL spectra from the mesa-patterned areas between 5 and 140 K are shown in Fig. 2. The excitation power density is 10 W/cm^2 . At low temperature, only the PL from the quantum dashes in the planar areas is observed. With increase of the temperature a clear peak from the InAs QDs at the fast-growing mesa sidewall arises, which is redshifted by 50 meV with respect to the PL peak from the quantum dashes. The spatial origin of the emission of the sidewall QDs is confirmed by the micro-PL spectra taken at 80 K from a single fast-growing sidewall of a wide mesa stripe and from an unpatterned, planar area, shown in the inset. No distinct change of the PL spectrum compared to that in the planar areas is observed at the opposite slow-growing sidewall. The relative increase with temperature of

FIG. 2. (Color online) Temperature dependent PL spectra of the sidewall QDs and quantum dashes in the mesa-patterned area. The excitation power density is 10 W/cm^2 . Micro-PL spectra at 80 K from the single fast-growing sidewall of a wide mesa stripe and from an unpatterned, planar area are shown in the inset.

the emission of the sidewall QDs compared to that of the quantum dashes in the adjacent planar areas indicates thermally activated carrier transfer from the shallower quantum dashes with higher band gap energy to the larger sidewall QDs with lower band gap energy. This leads to strong and well-separated PL peaks around 80 K before the overall intensity drops due to thermal activation of carriers into the InGaAsP barriers.

Figure 3 shows the normalized excitation power density dependent PL spectra from the mesa-patterned areas taken between 1 and 100 W/cm^2 at the temperature of 80 K. A clear high-energy shift of the PL spectrum of the sidewall QDs and quantum dashes in the planar areas is observed with increase of the excitation power density. The high-energy shift of the PL peak of the sidewall QDs is as large as 25 meV, while that of the PL peak of the quantum dashes in the planar areas of 5 meV is much smaller. The weak peaks in the PL spectrum of the quantum dashes around 0.9 eV are due to water absorption. The PL spectra of the samples with larger InAs amount for QD formation behave very similar as a function of excitation power density and also temperature with the only difference being an overall shift to lower energies. The high-energy shift of the PL spectra of the sidewall QDs and quantum dashes with excitation power density in-

FIG. 3. (Color online) Excitation power density dependent PL spectra at 80 K of the sidewall QDs and quantum dashes in the mesa-patterned area. The lower panels show the PL peaks at magnified scale.

cludes the PL peaks and the low- and high-energy sides, while the linewidths rather reveal a slight decrease in the excitation power density range under investigation. Hence, for these highly strained sidewall QDs and quantum dashes, the high-energy shift of the PL spectra as a function of excitation power density is attributed to piezoelectric effects present in strained nanostructures on non-(100)-oriented substrates.^{16,17}

Upon screening of the internal piezoelectric field by photo-generated carriers, the optical band gap shifts to higher energies resulting in a blueshift of the whole PL spectrum. The linewidth of the PL spectrum remains unchanged or even reduces due to a shift of the wave function moduli away from the interfaces, reducing the influence of structural imperfections and size fluctuations. This is in contrast to the PL spectra of the weakly strained InGaAs QWRs,¹⁸ exhibiting a high-energy shift and broadening with increase of the excitation power density due to state filling. In the case of state filling, the low-energy side of the PL spectrum remains unchanged or even shifts to lower energies due to Coulomb interactions, and the PL spectrum broadens or develops excited state emission at the high-energy side. For the same lattice mismatch, i.e., strain, the energy reduction of the optical band gap due to the vertical and lateral internal piezoelectric field is larger for the larger sidewall QDs compared to that for the shallower quantum dashes as the total change in potential energy across the QDs is directly proportional to the size.¹⁹ Hence, the high-energy shift of the PL spectrum with excitation power density due to screening of the internal piezoelectric field is much larger for the sidewall QDs than for the quantum dashes in the planar areas.

FIG. 4. (Color online) Linear polarization dependent PL spectra at 80 K (a) of the quantum dashes in an unpatterned, planar area and (b) of the sidewall QDs and quantum dashes in the mesa-patterned area. The excitation power density is 10 W/cm². (c) Polar diagram of the degree of linear polarization at 80 K at the PL peak position of the sidewall QDs and quantum dashes in the mesa-patterned area.

In Fig. 4 the linear polarization dependent PL spectra taken at 80 K from (a) an unpatterned, planar area and (b) the mesa-patterned area are depicted. The excitation power density is 10 W/cm². The PL from the quantum dashes is polarized along $[-233]$ in accordance with lateral quantum confinement in the presence of the asymmetric, elongated

shape. The degree of linear polarization at the PL peak position $(I_{[-233]} - I_{[01-1]}) / (I_{[-233]} + I_{[01-1]})$ is 0.17 both, in the planar area and in the patterned area, indicating that the pattern does not affect the polarization properties of the emission from the quantum dashes. Strikingly, the degree of linear polarization of the PL from the sidewall QDs is always reduced in the different samples with varying In amount and even reversed for the sidewall QDs shown in Fig. 4. The degree of linear polarization at the PL peak position along $[01-1]$ is -0.16 . The polar diagram of the degree of linear polarization at the PL peak position of the sidewall QDs and quantum dashes is shown in Fig. 4(c). As for the QWRs, also revealing linear polarization of the PL along $[01-1]$ due to quantum confinement,¹⁸ electromagnetic (grating) effects²⁰ from the etched mesas are excluded due to the shallow height and the fact that they would affect the polarization of the emission from the sidewall QDs and quantum dashes similarly. Therefore, the linear polarization of the PL from the sidewall QDs along $[01-1]$ is attributed to quantum confinement in the more symmetric QDs and nonuniform triaxial strain distribution in the growth plane perpendicular to the sidewall²¹ in those sidewall QDs formed on shallow-patterned InP (311)A substrates.

IV. CONCLUSION

Growth and optical properties of highly strained InAs quantum dots (QDs) embedded in InGaAsP at the fast-growing $[01-1]$ mesa sidewall on shallow-patterned InP (311)A substrates by chemical beam epitaxy have been reported. Temperature dependent photoluminescence (PL) revealed efficient carrier transfer from the adjacent dashlike QDs in the planar areas to the larger sidewall QDs, resulting in well-separated emission around 80 K. The large high-energy shift of the PL from the sidewall QDs as a function of excitation power density was attributed to internal piezoelectric effects. The linear polarization of the PL from the sidewall QDs is reversed compared to that of the quantum dashes in the planar areas due to the more symmetric shape and

nonuniform strain distribution in the growth plane in the sidewall QDs. The distinct carrier transfer, enhanced optical nonlinearity due to internal piezoelectric effects, and polarization behavior make these sidewall QDs on shallow-patterned InP (311)A substrates interesting candidates for further basic physics studies and applications.

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