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We report on the shape and polarization control of site-controlled multiple and single InAs quantum dots (QDs) on InP pyramids grown by selective-area metal-organic vapor phase epitaxy. With increasing growth temperature the QDs elongate causing strong linear polarization of the photoluminescence. With reduced pyramid base/pyramid top area/QD number, the degree of polarization decreases, attributed to the symmetric pyramid top, reaching zero for single QDs grown at lower temperature. This control of linear polarization is important for entangled photon sources operating in the 1.55 μm wavelength region.

Semiconductor quantum dots (QDs) provide the basis for novel devices in photonics and quantum information.1–3 The envisioned devices such as cavity enhanced single and entangled photon sources4,5 require precise site control of the QDs. This has been achieved by growth on truncated pyramids,6–8 in V-grooves,4,9 and nanoholes10,11 for InAs/GaAs and InAs/InP QDs with emission in the important telecom wavelength region.12,13 In general, control of the QD shape and consequently linear polarization of the emission is crucial for entangled photon sources. They require symmetric QDs with zero degree of polarization (DOP) and, hence, vanishing fine structure splitting (FSS). This makes InAs/InP QDs particularly promising exhibiting an about ten times smaller FSS for a certain shape than InAs/GaAs QDs.14 Various approaches to control the polarization of QDs have been demonstrated employing (111) oriented substrates,9 thermal annealing,15 and in-plane magnetic fields.16

Here, we report a different approach to control the shape and polarization of site-controlled 1.55 μm region multiple and single InAs QDs by growth on InP (100) pyramids formed by selective-area metal-organic vapor phase epitaxy (MOVPE). The size of the QDs increases with increasing growth temperature and the QDs elongate causing strong linear polarization of the photoluminescence (PL). Importantly, the DOP decreases with reduced pyramid base, i.e., pyramid top area, i.e., QD number induced by the symmetric pyramid top, reaching zero for single QDs grown at lower temperature.

The samples were grown by MOVPE on InP (100) substrates misoriented 2° toward (110). Trimethyl-indium, trimethyl-gallium, tertiarybutyl-phosphine, and tertiarybutyl-arsine were used as source materials. The substrates were masked by 100 nm SiNx with circular openings of 0.7–1.5 μm diameter and 10 μm pitch. Truncated InP pyramids were selectively grown at 610 °C. On the pyramid top, three monolayers InAs QDs were grown at 490 and 515 °C which were capped by 70 nm InP. The uncapped InAs QDs were characterized by atomic force microscopy (AFM) in air. Micro-PL spectroscopy of the capped QDs was performed by exciting the samples, mounted in a He-flow cryostat, with a continuous-wave He–Ne laser operating at 635 nm. Excitation and detection of the PL were through a microscope objective with a spatial resolution of ~2 μm. The PL was dispersed by a 0.25 m single monochromator and detected by an InGaAs photodiode array. For the polarization analysis, a linear polarizer followed by a quarter-wave plate was inserted in front of the monochromator. The polarization-dependent PL from 34 multiple QD and 26 single QD samples was measured for statistical analysis.

Figures 1(a)–1(f) show the AFM images of the multiple and single InAs QDs on top of the InP pyramids grown at [(a)–(c)] 490 °C and [(d)–(f)] 515 °C. In general, for the larger pyramid top areas (pyramid bases), the QDs nucleate on the high-index {103} and {115} facets surrounding a (100) center facet.7,13 For shrinking pyramid top area the QD number decreases, attributed to the symmetric pyramid top, reaching zero for single QDs grown at lower temperature. This control of linear polarization is important for entangled photon sources operating in the 1.55 μm wavelength region.

FIG. 1. (Color online) AFM images (2×2 μm²) of the multiple and single InAs QDs grown at [(a)–(c)] 490 °C and [(d)–(f)] 515 °C on the InP pyramids with base diameters varying between 1.5 and 0.7 μm.

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largest base area. and number and size increase. The pronounced QD elongation along $\bar{011}$ and the increased QD size leading to a shape transition from symmetric diamond-shaped to a top facet. For higher growth temperature the QDs strongly elongate along $\bar{011}$ and number and size increase.

The average QD width along $\bar{011}$ [Fig. 2(a)] increases from 50 nm for the QDs grown at 490 °C to 75 nm for the QDs grown at 515 °C with a broader distribution while the average width along [011] [Fig. 2(b)] of 50 nm remains almost unchanged. The increase in the QD number and size for higher growth temperature is attributed to the enhanced As/P exchange during QD growth, leading to more incorporation of InAs, which also accounts for the broader size distribution. The pronounced QD elongation along $\bar{011}$ at higher growth temperature is attributed to the increased adatom surface migration length which is generally larger along $\bar{011}$ and the increased QD size leading to a shape transition from round to elongated.

Micro-PL spectra taken at 5 K of the capped multiple and single QDs grown at 490 °C are shown in Fig. 3. The PL spectrum of the multiple QDs on the pyramid with the largest base is centered at 1465 nm with a full width at half maximum (FWHM) of 34 nm while the PL line of the single QD is at 1471.4 nm with the FWHM of 0.6 nm limited by the spectrometer resolution. For the higher growth temperature of 515 °C, the PL spectrum of the multiple QDs is centered at 1495 nm with a broader FWHM of 59 nm while the PL line of the single QD is at 1483 nm. This PL redshift and broader FWHM are in agreement with the larger size and less uniform size distribution of the QDs grown at higher temperature. The excitation power dependent integrated PL intensity of a typical single QD grown at 490 °C, plotted in the inset of Fig. 3, increases linearly with a slope of 1.08 indicating high optical quality of the single QD.

The shape anisotropy of the QDs results in distinct linear polarization of the PL. Figures 4(a) and 4(b) show the polar plot of the PL peak intensity ($I$) of the multiple (on the pyramids with the largest base) and single InAs QDs grown at 490 and 515 °C. 0° designates the PL polarized along $[011]$ and 90° the PL polarized along $[011]$. The angular dependence of the PL intensity is fitted by $I=I_{[011]}\sin^2\theta + I_{[011]}\cos^2\theta$, where $\theta$ is the polarization angle. Most important, the DOP=$\langle I_{[011]}-I_{[011]}\rangle/(I_{[011]}+I_{[011]})\times100\%$ at the PL peak position reduces with reduced pyramid base, i.e., reduced pyramid top area and QD number, plotted in Fig. 4(c). The DOP for the multiple QDs on the pyramid with the largest base area of 1.58 $\mu$m$^2$ [Fig. 1(d)] is 38%. This is comparable with polarization measurements of InAs QD ensembles on GaAs truncated pyramids. The DOP decreases monotonically down to 17% for the single QD on the pyramid with the smallest base area of 0.48 $\mu$m$^2$ [Fig. 1(f)]. This is attributed to an increasing influence of the shape of the shrinking pyramid top area, approaching the symmetric (100) top facet with diamondlike boundary, on the QD shape rendering it more symmetric. For the QDs grown at 490 °C, which are generally more symmetric, the slight DOP for the multiple QDs is completely eliminated for the single QD.

It is difficult to quantitatively relate the DOP to the FSS which is the figure of merit for realizing entangled photon sources and within the spectral resolution the FSS cannot be resolved directly. In general, for InAs/InP QDs the FSS mainly depends on the QD shape. The FSS from the intrinsic Dresselhaus term due to the bulk inversion asymmetry is a minor factor because of the small lattice mismatch (3%) and the strong confinement of holes. Moreover it has been reported that the FSS is directly related to the DOP. Hence, zero DOP implies the sought for zero FSS for our single symmetric InAs QDs grown at reduced temperature on the InP pyramids close to pinch-off.

In conclusion, we have studied the shape and polarization control of site-controlled 1.55 $\mu$m region multiple and single InAs QDs on InP (100) pyramids grown by selective-area MOVPE. The QD size increases with elevated growth temperature and the QDs strongly elongate causing pronounced polarization of the PL. Most important the DOP reduces with reduced pyramid base/pyramid top area/QD number due to increasing influence of the symmetric pyramid top on the QD shape, reaching zero for single QDs.
grown at lower temperature. This is important for the realization of single and entangled photon sources operating in the 1.55 µm telecom wavelength region.

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