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Submicron active-passive integration with position and number controlled InAs/InP (100) quantum dots (1.55 μm wavelength region) by selective-area growth


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The authors report lateral positioning and number control of InAs quantum dots (QDs) on truncated InP (100) pyramids by selective-area metalorganic vapor-phase epitaxy. With reducing QD number, sharp emission peaks are observed from individual and single QDs with wavelength tuned into the 1.55 μm telecom region by insertion of ultrathin GaAs interlayers beneath the QDs. Regrowth of a passive waveguide structure around the pyramids establishes submicrometer-scale active-passive integration for efficient microcavity QD nanolasers and single photon sources. © 2007 American Institute of Physics. [DOI: 10.1063/1.2790378]

Semiconductor quantum dot (QD) nanolasers and single photon sources, compatible with fiber-based telecommunication systems require position and number controlled QDs with emission wavelength in the 1.55 μm region, embedded in a low absorption passive waveguide structure for microcavity fabrication. Selective-area growth (SAG) of truncated pyramids has been shown to provide nanotemplates for the selective deposition of a few down to single QDs [InAs/GaAs QDs grown by metal organic vapor-phase epitaxy] and InAs/InP QDs grown by chemical beam epitaxy depending on the pyramid base width and the shrinking size of the pyramid top area during growth. We demonstrate (i) the SAG of truncated InP (100) pyramids by MOVPE, the preferred growth method for InP based photonic devices, (ii) the selective positioning and number control of InAs QDs, down to a single QD, on top of the truncated pyramids, (iii) their sharp photoluminescence (PL) emission well above liquid nitrogen temperature tuned into the 1.55 μm telecom wavelength region through the insertion of ultrathin GaAs interlayers beneath the QDs, and (iv) the selective regrowth of a passive InGaAsP/InP waveguide structure, free of absorbing QDs and wetting layer around the pyramids, establishing submicrometer-scale active-passive integration for the realization of efficient microcavity QD nanolasers and single photon sources and their implementation in photonic integrated circuits.

A 100 nm SiN mask layer was deposited on the InP (100) substrates, 2° misorientated towards (110) by plasma-enhanced chemical-vapor deposition. Square-shaped openings in the mask, aligned along [010] and [001] with side lengths between 1.5 and 2 μm and center-to-center distance of 10 μm, were processed by conventional photolithography and reactive ion etching. Selective growth was performed by low-pressure MOVPE using trimethyl indium, trimethyl gallium, tertiarybutyl arsine (TBA), and tertiarybutyl phosphine (TBP) as precursors. For truncated InP pyramid formation, the growth temperature was 650 °C, the TBP flux rate was 50 SCCM (SCCM denotes cubic centimeter per minute at STP), and the total reactor pressure was 50 mbars. These optimized growth parameters considerably differ from our standard growth conditions on unmasked substrates: 585 °C growth temperature, 125 SCCM TBP flux rate, and 100 mbars total reactor pressure to enhance the In adatom surface migration for well defined pyramid formation. Growth of the GaAs interlayer and InAs QDs was performed at the substrate temperature of 500 °C and TBA flow rate of 6 SCCM for GaAs growth and 0.5 SCCM for InAs QD growth. The thickness of the GaAs interlayer on unmasked substrates was 0.05 monolayers (ML) and the amount of InAs for QD formation was 0.1 ML. Taking into account a growth rate enhancement factor of about 30 due to lateral gas phase and surface diffusion, this results in a GaAs interlayer thickness on the pyramid top area of around 1.5 ML and an amount of InAs of 3 ML. The GaAs interlayer suppresses As/P exchange to reduce the QD height and, thus, the emission wavelength from above 1.65 μm into the 1.55 μm region. After QD formation and growth of a 10 nm InP cap layer at 500 °C, the pyramids were completed at 650 °C to a total thickness of 15 nm on unmasked substrates, the SiNx mask was removed, and a 10 nm InP/500 nm InGaAsP/500 nm InP waveguide structure was regrown at 610 °C around the pyramids. The scheme of the SiNx mask layout and growth sequence is presented in Figs. 1(a)–1(c). The band gap of the quaternary lattice-matched InGaAsP waveguide core layer was at 1.25 μm (Q1.25). The InP and InAs growth rates on unmasked substrates were 0.75 and 0.21 ML/s for GaAs. The surface morphology of the InP pyramids and uncapped InAs QDs on top and the cross section of the regrown structures were examined by scanning electron microscopy (SEM). The optical properties of the capped QDs were studied by micro-PL with a spatial resolution of 5 μm with the samples mounted in a He-flow cryostat. The PL was excited by the 632.8 nm line of a He–Ne laser with excitation power of 10 μW through an optical microscope objective, which also served to collect the PL. The PL was dispersed by a cooled InGaAs linear array detector.

Figures 2(a)–2(c) show the top-view SEM images of the InP pyramids with base widths between 2 and 1.5 μm and...
uncapped InAs QDs in the top areas formed in the same growth run. The pyramids are bound by slow-growing symmetric \{100\} side facets and smaller \{111\} facets evolving from the mask corners. With reduction of the base width, the size of the (100) pyramid top areas decreases to submicrometer dimensions with side lengths of several 10 nm due to preferential In adatom migration from the side facets to the mesa top and the number of InAs QDs decreases from >100, to a few, and down to a single QD. The micro-PL spectra taken at 5 K of the capped InAs QDs in the pyramid top areas with reducing size are shown in Figs. 2\(d\)–2\(f\). With reducing QD number, the smooth, inhomogeneously broadened PL spectra split into sharp lines due to emission from individual QDs and, for the smallest top area, emission from a single QD is observed. The emission wavelength of the QDs, in the 1.55-μm region, is relatively stable with decrease of the pyramid top area, i.e., larger growth rate enhancement due to compensation of the simultaneously increasing GaAs interlayer thickness, leading to PL blueshift, and InAs amount, leading to PL redshift.\(^\text{11}\) Most importantly, the emission from the single InAs QD in Fig. 2\(f\) is observable well above liquid nitrogen temperature (77 K), which is even higher compared to our InAs QDs grown on unmasked substrates and isolated by mesa etching.\(^\text{12}\) As expected for a single QD, the PL peak position follows the Varshni law for...
the temperature dependent band gap of InAs.

To integrate such submicrometer-scale QD active regions in photonic devices, regrowth of a passive InGaAsP/InP waveguide structure around the InP pyramids is performed after removal of the SiN<sub>x</sub> mask. Taking advantage of the slow-growing nature of the pyramid side facets, the waveguide structure planarizes and uniformly covers the areas between the pyramids, as shown in the cross-sectional SEM images taken after stain etching in Figs. 3(a) and 3(b) for different magnifications. Some composition modulation is present in the InGaAsP layers close to the InP pyramids, which can hardly be avoided. The smooth height increase of the waveguide structure above the pyramids is less than 100 nm. In addition to being grown easier compared to quaternary material, the InP pyramids increase the collection efficiency of light emitted from the QDs into the waveguide due to refraction at the InP/InGaAsP interface and are expected to improve the quality factor of microcavities processed around the pyramids due to reflection at the InP/InGaAsP interface.

In conclusion, we have investigated positioning and number control of InAs QDs formed on selectively grown truncated InP (100) pyramids by MOVPE. The InAs QDs are located in the top areas of the pyramids and their number was controlled by the dimensions of the top areas down to a single QD depending on the pyramid base width and the shrinking pyramid top area during growth. With reducing QD number, sharp emission from individual and single QDs was observed well above liquid nitrogen temperature which was tuned into the 1.55 µm wavelength region through the insertion of ultrathin GaAs interlayers underneath the QDs. Regrowth of a passive InGaAsP/InP waveguide structure around the active InP pyramids was accomplished. Hence, submicrometer-scale active-passive integration for efficient microcavity QD nanolasers and single photon sources operating in the 1.55 µm telecom wavelength region and their implementation in photonic integrated circuits is established.