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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

D. Zhou, S. Anantathanasarn, P. J. van Veldhoven, F. W. M. van Otten, T. J. Eijkemans, T. de Vries, E. Smalbrugge, and R. Nötzel^{a)}

COBRA Inter-University Research Institute, Eindhoven University of Technology, 5600 MB Eindhoven, The Netherlands

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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 metal organic 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^{1–5} (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 epitaxy⁶ (MOVPE) and InAs/InP QDs grown by chemical beam epitaxy]^{7,8} 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,^{9,10} 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_x 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.^{9,10} 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 SiN_x 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 SiN_x 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 single monochromator and detected 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

^{a)} Author to whom correspondence should be addressed. Electronic mail: r.noetzel@tue.nl

FIG. 1. (Color online) (a) Scheme of the SiN_x mask and [(b) and (c)] of the growth sequence, selective-area growth of InP pyramids containing InAs QDs and regrowth of a passive InGaAsP/InP waveguide structure.

uncapped InAs QDs in the top areas formed in the same growth run. The pyramids are bound by slow-growing symmetric {101} 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.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.¹² As expected for a single QD, the PL peak position follows the Varshni law for

FIG. 2. (Color online) [(a)–(c)] Top-view SEM images of the InAs QDs formed on top of the truncated InP pyramids with reducing base width. [(d)–(f)] Micro-PL spectra taken at 5 K of the InAs QDs formed on top of the truncated InP pyramids with reducing QD number. In (f) temperature dependent micro-PL spectra of the single QD are also shown.

FIG. 3. (Color online) [(a) and (b)] Cross-sectional SEM images of the regrown passive InGaAsP/InP waveguide structure around the InP pyramids containing InAs QDs at different magnifications.