Distribution control of 1.55 μm InAs quantum dots down to small numbers on truncated InP pyramids grown by selective area metal organic vapor phase epitaxy

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Distribution control of InAs quantum dots (QDs) on truncated InP pyramids by selective area growth is reported. The top surface of the pyramids is composed of a (100) facet and high-index facets aside. The arrangement of the facets is governed by the shape of the pyramid base and top surface area. The QDs preferentially nucleate on the high-index facets determining position and distribution. The QD number is reduced with shrinking top surface size. Positioning of four, three, two, and single QDs is realized depending on the top surface’s shape and size. Emission from single QDs is observed at 1.55 μm. © 2009 American Institute of Physics. [DOI: 10.1063/1.3116146]

Self-organized semiconductor quantum dots (QDs) have brought enhanced performance to lasers and optical amplifiers due to their discrete energy states, which is of particular importance for operation in the 1.55 μm telecommunication wavelength region.1,2 These devices rely on QDs grown in the Stranski–Krasanow mode which are distributed randomly on the substrate surface. For advanced quantum functional devices such as nanolasers and single photon sources, however, precise position and number control of a few down to a single QD are required. This can be realized by pre-defined QD nucleation on truncated pyramids formed by selective area growth in dielectric mask openings3–7 and has been demonstrated for the InAs/GaAs material system by metal organic vapor phase epitaxy (MOVPE)8,9 and molecular beam epitaxy and for the InAs/InP material system by chemical beam epitaxy5 and MOVPE.3 Moreover, for efficient nanolasers and single photon sources employing high-index facets and the pyramid top surfaces are composed of a single optical mode with certain size and shape.10,11

Here, we report the control of position and distribution of InAs QDs on truncated InP pyramids grown by selective area MOVPE. The shape of the pyramid base determines the facets and their relative sizes on the pyramid top surface, resulting in position and distribution control of the QDs. The QD number, for a specific shape of the pyramid top surface, is controlled by the area down to a single QD emitting at 1.55 μm.

A 100 nm thick SiN x mask was deposited on the InP (100) substrates by plasma-enhanced chemical–vapor deposition, followed by defining the mask openings by electron beam lithography and reactive ion etching. Selective area MOVPE was performed using trimethyl indium, trimethyl gallium, tertiary butyl phosphine, and tertiary butyl arsine as precursors. The InP pyramids were grown at 610 °C with a growth rate of 18.39 nm/min to a thickness of 75 nm in unmasked areas. For QD formation, the growth temperature was reduced to 515 °C and 3 ML InAs on the pyramid top surfaces were deposited. Beneath the QDs, 1.5 ML GaAs were inserted at 515 °C to tune the QD emission wavelength into the 1.55 μm range.10 The morphology of the InP pyramids and QDs was investigated by atomic force microscopy (AFM) in air. For micro-photoluminescence (micro-PL) of InP capped QDs, the 632.8 nm line of a He–Ne laser with 10 μW power was used as the excitation source.5

Figures 1(a)–1(c) show the AFM images of the truncated InP pyramids with square, circular, and triangular mask openings, i.e., pyramid base, together with schematic drawings. The pyramid side walls are bound by {110} and {111} facets and the pyramid top surfaces are composed of a (100) facet and high-index {103} and {115} facets around, determined from AFM line scans.13 The shape of the top surfaces and the (relative) size of the facets are determined by the shape of the pyramid base and the area of the top surfaces, as summarized in Fig. 1(d) showing the ratio of the sum of the areas of the {103} and {115} facets divided by the total top surface area as a function of the top surface area for various shapes. For all base shapes, the relative size of the {103} and {115} facets increases with the area of the top surface, and below an area of 0.2–0.3 μm², the facets do not form. For a certain top surface area, the relative size of the {103} and {115} facets is, for instance, larger for elliptical-based pyramids (long axis along [011]), indicated by the blue line in Fig. 1(d), than for square-based pyramids (side along [001]), indicated by the red line in Fig. 1(d), suggesting the presence of extended {115} facets (suppressed for the square-based pyramids) to increase the ratio.

The size and shape of the pyramid top surfaces govern the distribution and number of the InAs QDs grown on top, shown in Fig. 2. The distribution of the QDs is [Figs. 2(a) and 2(b)] square for square base, [Fig. 2(c)] triangular for triangular base, [Figs. 2(d) and 2(e)] circular for circular base, and [Figs. 2(f) and 2(g)] elliptical for elliptical base with the QDs aligned close to the edge of the top surfaces. This is due to the preferential nucleation of the QDs on the high-index facets. Similar to InAs QDs on GaAs pyramids,8 it is believed that the high-index facets allow optimal strain relaxation.

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When changing the shape of the pyramid base from circular to elliptical, the relative size of the \( \{103\} \) and \( \{115\} \) facets is reduced with the aspect ratio, as shown in Figs. 2(f) and 2(g), where the aspect ratio is increased from 1.4 to 2. This changes the QD distribution from elliptical-ring-like to an oval ring.

For reduced pyramid top area/base size, the shape of the QD distribution is maintained with reduced extension, as shown in Figs. 2(d) and 2(e) for circular base. For all pyramid base shapes, the QD number is reduced with reduced pyramid top area, which is summarized in Fig. 2(h). This is consistent with the reduced size of the \( \{103\} \) and \( \{115\} \) facets on which the QDs nucleate. The difference in QD number for the various shapes is directly related to the relative size of the \( \{103\} \) and \( \{115\} \) facets. The QD number is highest for elliptical-based pyramids with larger relative size [blue line in Fig. 2(h)] and lowest for square-based pyramids with lower relative size [red line in Fig. 2(h)].

With the decrease in the top surface area, only the (100) facets form, as discussed above, with rounded corners, and the QDs uniformly nucleate there on. Close to pinch off, four, three, two, and single QDs are positioned around/at the center for optimized growth conditions (reduced growth temperature of 500 °C enhancing the reproducibility, 30% reduced InAs amount due to higher growth rate enhancement close to pinch off), with the QD number being related to the shape of the pyramid base. Four for elliptical base, three for triangular base, two for hexagonal base, and a single QD for circular base (with more than 60% reproducibility mainly limited by the lithography accuracy), as shown in Figs. 3(a)–3(d). Hence, it is the combination of top (100) facet shape and size that determines the number of QDs.

High optical quality of the QDs is revealed by the micro-PL spectrum of a single QD on a circular-based pyramid at 5 K, as shown in Fig. 3(e). The broad emission around 1200–1300 nm is attributed to the InAs wetting layer on the pyramid side facets. The single sharp peak at 1542 nm with resolution-limited linewidth of 2 nm stems from the single position controlled InAs QD.
In conclusion, position and distribution control of 1.55 μm InAs QDs on truncated InP pyramids grown by selective area MOVPE was achieved. The top surface of the truncated InP pyramids was composed of a (100) facet and {103} and {115} facets aside. The arrangement of the facets and their relative sizes were determined by the shape of the mask openings and the top surface area. The arrangement of the {103} and {115} facets allowed the precise position and distribution control of the QDs. The realization of four, three, two, and single QDs revealed the effectiveness of the shape and size of the pyramid top surface for QD number control.

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