Lateral arrangements of size and number controlled 1.55-μm InAs quantum dots on InP nanopyramids

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Lateral arrangements of size and number controlled InAs quantum dots (QDs) on truncated InP (100) nanopyramids grown by selective area metalorganic vapor-phase epitaxy (MOVPE) are reported. The QDs nucleate on high-index facets on pyramids top allowing precise position and distribution control. The size and shape of QDs are related to As/P exchange determined by the growth temperature, as demonstrated for circular-based pyramids. The QD number is controlled by both the size of the high-index facets (governed by pyramids top area) and As/P exchange (governed by growth temperature). Sharp emission peaks from individual QDs are observed around 1.55 μm.

Introduction

Self-assembled semiconductor quantum dots (QDs) represent a particularly intriguing and challenging class of quantum nanostructures for novel optoelectronic device applications [1, 2]. For advanced quantum functional devices, however, precise position and number control of QDs is required. The site-controlled QDs can be realized by pre-defined nucleation on truncated nanopyramids formed by selective area epitaxy [3, 4]. Here, we report the lateral arrangements of size and number controlled InAs QDs on truncated InP (100) nanopyramids grown by selective area metalorganic vapor-phase epitaxy (MOVPE). The QDs nucleate on high-index facets on the pyramids top allowing precise position and distribution control [3]. The size of the QDs is related to As/P exchange determined by the growth temperature, as demonstrated for circular-based pyramids. The QD shape transition from round to elongate is due to the increasing adatom surface migration length at the elevated growth temperature. The QD number is controlled by both the size of the high-index facets (governed by the pyramids top area) and As/P exchange (governed by the growth temperature). The sharp emission peaks from individual QDs are observed around 1.55 μm.

Experimental procedure

A 100 nm thick SiN*x* mask layer was deposited on the semi-insulating InP (100) substrates, 2° misorientated towards (110), by plasma-enhanced chemical-vapor deposition (PECVD). The openings in the SiN*x* layer were created by electron beam lithography (EBL) and reactive ion etching (RIE). Figure 1 (a) shows the scheme of the SiNx mask patterns for various pyramid base shapes: (I) diamond, (II) square, (III) circular, and (IV) elliptical. The openings were arranged in a square lattice with center-to-center distance of 10 μm. The side lengths or diameters of the openings were varied between 500 nm and 1.5 μm. Figure 1 (b) depicts the scheme of a square-based InP nanopyramid containing InAs QDs grown by selective area MOVPE. Trimethyl-indium (TMI), trimethyl-gallium (TMG), tertiarybutyl-phosphine (TBP), and tertiarybutyl-arsine (TBA), diluted in H_2, were used as source materials. The InP nanopyramids were grown at 610 °C with a growth rate of 18.39 nm/min in unmasked areas [4]. Three

monolayers (ML) InAs were then grown on the nanopyramid tops at varied temperatures between 490 and 515 °C, with a 1.5 ML GaAs interlayer underneath to tune the QDs emission wavelength into the 1.55 μm region [3, 5, 6]. The morphology of the InP nanopyramids and InAs QDs was characterized by tapping mode atomic force microscopy (AFM) in air. For low-temperature micro-photoluminescence (micro-PL) measurements the QDs were capped by a thin InP layer.

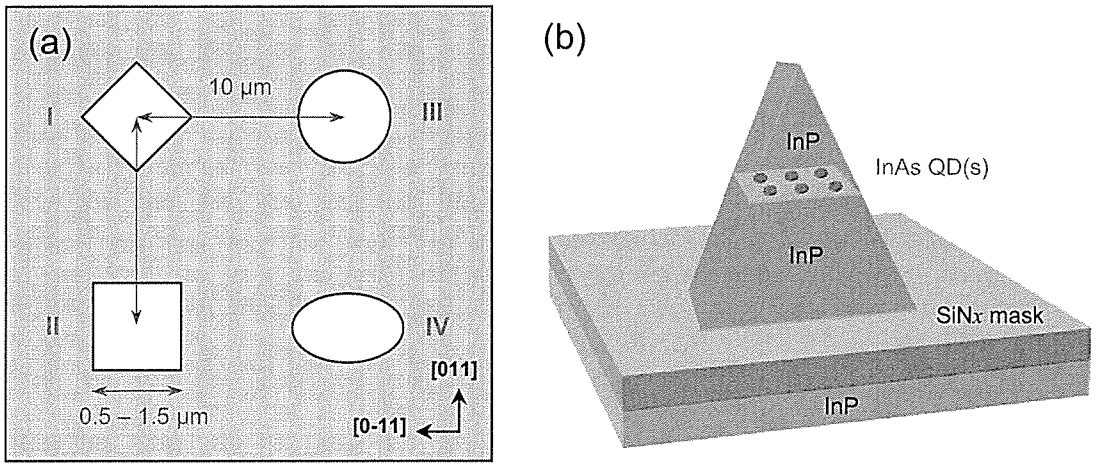

Figure 1. (a) Scheme of the SiN*x* mask patterns for various pyramid base shapes: (I) diamond, (II) square, (III) circular, and (IV) elliptical. (b) Scheme of a square-based InP nanopyramid containing InAs QDs.

Results and discussion

Figure 2 shows AFM images (2 × 2 μm^2) of the truncated InP nanopyramids with InAs QDs grown on top for (a) diamond, (b) square, (c) circular base, and (d) elliptical bases. The shape and size of the high-index facets, i.e., {103} and {115} facets, on top of the pyramids govern the QD distribution and number. The QDs are aligned at the edges of the pyramid tops with the same shapes as the pyramid bases. This is due to the preferential nucleation of the QDs on the {103} and {115} facets resulting in the lateral distribution control of the QDs [3]. The differences in QD number for the various shapes are directly related to the relative sizes of the {103} and {115} facets. The QD number, for instance, is the lowest for diamond-based pyramids due to the suppressed formation of {115} facets [4] to reduce the QD number. It is the largest for elliptical-based pyramids due to the enlarged sizes of the {103} and {115} facets.

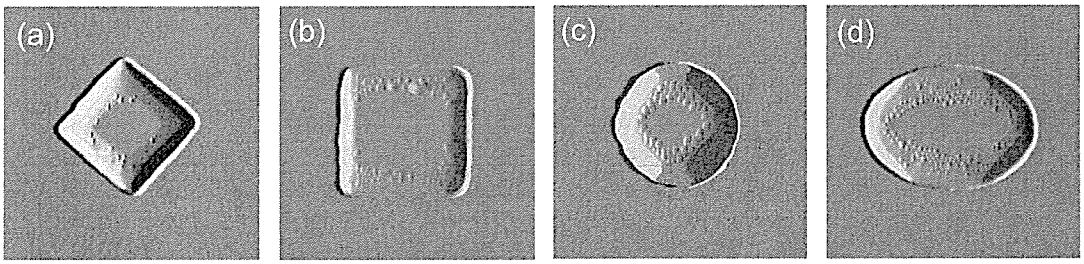

Figure 2. AFM images (2 × 2 μm^2) of the truncated InP nanopyramids with InAs QDs grown on top for (a) diamond, (b) square, (c) circular, and (d) elliptical bases.

Figure 3 (a, b) shows the AFM images (2 × 2 μm^2) of 3 ML InAs QDs grown at (a) 515 °C and (b) 490 °C on top of circular-based InP nanopyramids with the same top areas / base sizes. The average diameter and height of the InAs QDs grown at 490, 500, and 515 °C are depicted in Fig. 3 (c). The QDs grown at 515 °C exhibit a larger average diameter and height of 78 and 13 nm than the QDs grown at 490 °C with diameter and height of 55 and 7 nm. The larger dimension of the QDs grown at higher temperature is primarily attributed to the enhanced thermally activated As/P exchange [6], even in the presence of the GaAs interlayer which partly suppresses excess InAs formation [3, 5]. Moreover, the QD number is increased at higher growth temperatures, shown in the inset in Fig. 3 (c). The interesting QD elongation at higher growth temperature of 515 °C [Fig. 3 (a)] is attributed to the increasing adatom surface migration length which is generally larger along the [01-1] direction and the increasing QD size leading to a shape transition from round to elongate [7]. High optical quality of few InAs QDs on top of circular-based InP nanopyramids is demonstrated by micro-PL at 5 K, shown in Fig. 4. The sharp emission peaks from individual QDs are observed around 1.55 μm.

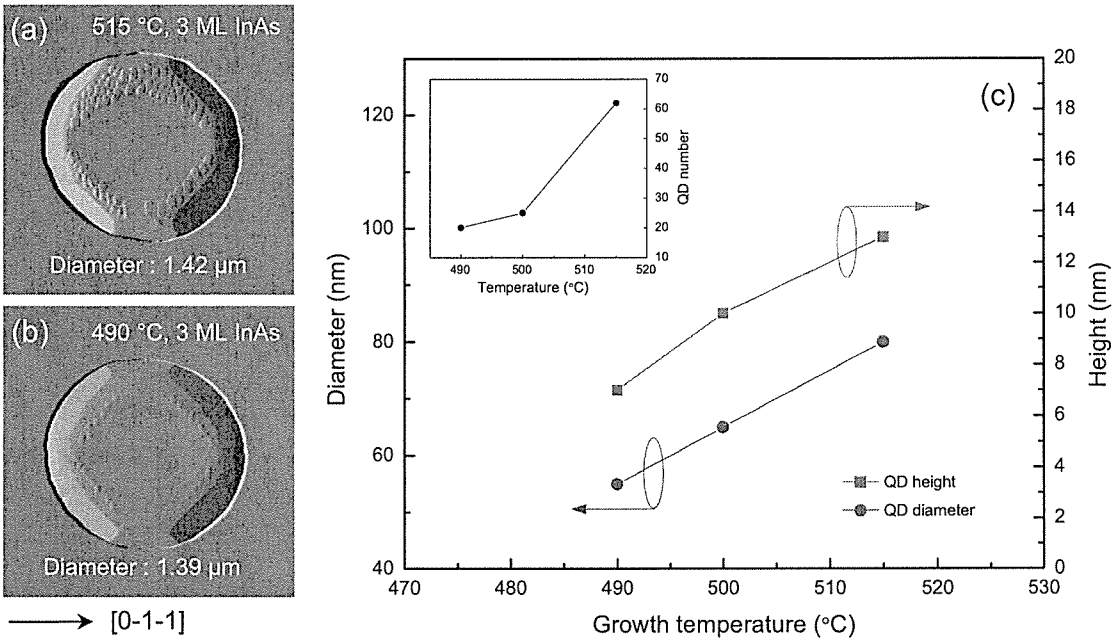

Figure 3. AFM images (2 × 2 μm^2) of 3 ML InAs QDs grown at (a) 515 °C and (b) 490 °C on top of the circular-based InP pyramids with the same top areas / base sizes. (c) Average diameter, height, and number (inset) of the InAs QDs as a function of the growth temperature.

Conclusion

Size and number control of site-positioned InAs QDs on truncated InP (100) nanopyramids grown by selective area metalorganic vapor-phase epitaxy has been achieved. The QDs nucleate on the high-index facets allowing precise position and distribution control. The size and shape of the QDs are related to As/P exchange determined by the growth temperature. The shape transition of QDs from round to elongate is attributed to the increasing adatom surface migration length at the elevated growth temperature. The QD number is controlled by both the size of the high-index facets (governed by the pyramids top area) and As/P exchange (governed by the growth temperature). Sharp emission peaks from individual QDs are observed around 1.55 μm.

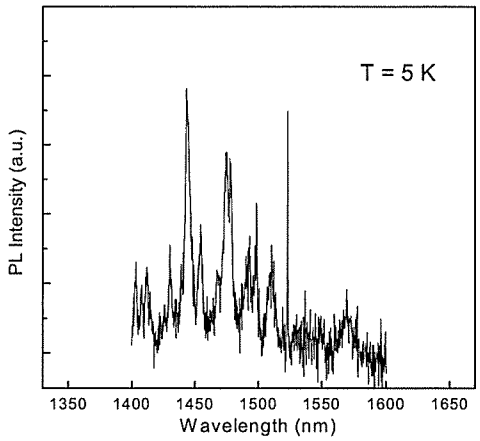

Figure 4. Micro-PL spectrum taken at 5 K of the InAs QDs on a circular-based InP nanopyramid.

Acknowledgements

The authors gratefully acknowledge the support of the Smart Mix Programme of the Netherlands Ministry of Economic Affairs and the Netherlands Ministry of Education, Culture and Science.

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