Ordered 1-D and 2-D InAs/InP quantum dot arrays at telecom wavelength

N Sritirawisarn¹, F W M van Otten¹ and R Nötzel¹

¹ COBRA Research Institute on Communication Technology, Eindhoven University of Technology, 5600MB Eindhoven, The Netherlands

n.sritirawisarn@tue.nl

Abstract. Lateral one-dimensional (1-D) and two-dimensional (2-D) InAs/InP quantum dot (QD) arrangements are created by the concept of self-organized anisotropic strain engineering of InAs/InGaAsP superlattice (SL) templates on InP (100) and (311)B substrates by chemical-beam epitaxy (CBE). The SL templates comprise several-periods of an InAs QD layer plus a thin cap layer, post-growth annealing, and a separation layer. QDs order on top of the templates due to local strain recognition. Distinct preferential In adatom surface migration during annealing and substrate miscut lead to linear QD arrays along [001] for InP (100) substrates and a periodic square lattice aligned ±45˚ off [-233] for InP (311)B substrates. Optimization of the growth parameters balances In desorption and leads to well-separated and highly uniform QD arrays. Importantly, strong photoluminescence (PL) of defect-free InAs QD arrays is observed with the wavelength tuned into the 1.55-μm telecom region at room temperature through the insertion of GaAs interlayer beneath the QDs. Finally, the concept of self-organized anisotropic strain engineering for QD ordering is extended for formation of more complex architectures by combining it with step-engineering on shallow- and deep-patterned substrates. On the sidewall areas, the steps generated by the artificial patterns play the major role in determination of the In adatom surface migration during annealing, altering the QD arrays direction away from [001] on stripe-patterned InP (100) substrates. On the contrary, the sidewalls on patterned InP (311)B are faceted, not affecting the orientation of the 2-D InAs QD arrays.

1. Introduction

Lateral ordering of semiconductor quantum dots (QDs) is of prime importance for the exploitation of novel functionalities, e.g., coherent quantum state manipulation, quantum information processing, and quantum computing, which rely on the operation at the single and multiple electron and photon level with controlled quantum mechanical and electromagnetic interactions for future quantum functional devices. High quality QDs grown in the Stranski-Krastanow (S-K) growth mode are usually randomly distributed over the wafer surface. Therefore, efforts to position the QDs have gained prime attraction. In most of the case, artificially patterned substrates are prepared to control the QDs nucleation sites, however, often degrading the structural and optical qualities of the QDs due to lithographic imperfections and etching defects. We have previously introduced a concept for the lateral ordering of InAs QDs based on self-organized anisotropic strain engineering of InGaAs/GaAs superlattice (SL) templates in molecular-beam epitaxy (MBE) to produce well-ordered QD arrays with excellent optical properties [1,2]. To be compatible with telecom applications, the general concept has been transferred
to the InAs/InP material system where the important 1.55-μm wavelength region at room temperature (RT) is covered [3,4].

InAs/InGaAsP SL template formation comprises InAs QD formation, thin InGaAsP capping, annealing, InGaAsP overgrowth, and stacking. This produces wire-like InAs nanostructures for InP (100) substrates and periodic shallow mound-like InAs nanoclusters for InP (311)B substrates due to anisotropic surface migration during annealing, together with lateral and vertical strain correlations and strain gradient driven In adatom migration during stacking. The lateral strain field modulations on the SL template surfaces govern InAs QD ordering due to local strain recognition. Excellent PL emission from the QD arrays is observed up to room temperature (RT) with the PL tuned into the 1.55-μm-wavelength region through the insertion of ultrathin GaAs interlayer beneath the InAs QD arrays. Finally, the self-organization concept is extended for formation of more complex architectures of lateral QD arrays by combining it with step engineering on artificially patterned shallow- and deep-etched substrates.

2. Experimental details

The samples were grown by CBE using pressure controlled trimethylindium (TMI), triethylgallium (TEG), AsH$_3$, and PH$_3$ as precursors. The AsH$_3$ and PH$_3$ gases were thermally decomposed in a high temperature injector at 900 °C. The planar and artificially patterned InP (100) substrates with miscut 2° toward (110) and singular InP (311)B substrates were mounted on Mo block. The mesa patterns were prepared by optical lithography and wet chemical etching in the 3 H$_2$SO$_4$ : 1 H$_2$O$_2$ : 1 H$_2$O solution. In this study, for InP (100) substrates, we concentrate on periodic mesa stripes with width and separation of 4 μm oriented along [010] and [001], and etched mesa depth of 50 and 200 nm. For InP (311)B substrates, periodic mesa stripes with width and separation of 2 μm oriented along [0-11], and etched mesa depth of 15 and 200 nm are presented. After etching, the samples were cleaned by oxygen plasma stripping followed by oxide removal in diluted 10 H$_3$PO$_4$ : 1 H$_2$O and rinsing in deionized water for three times before loading into the CBE growth chamber.

For InP (100) substrates, the growth started with 50 nm thick InP and 100 nm thick lattice-matched InGaAsP with RT bandgap at 1.27 μm (Q1.27), followed by a seven-periods InAs/InGaAsP SL template. Each of SL periods comprised 2.1 monolayers (ML) InAs, 10 s growth interruption under As flux, thin capping by 0.3 nm Q1.27, annealing for 2 min, and growth of a 15.3 nm Q1.27 spacer. On top of the SL template, 2.6-3.2 ML InAs were deposited for QD formation with width and separation of 4 μm oriented along [010] and [001], and etched mesa depth of 50 and 200 nm. For InP (311)B substrates, periodic mesa stripes with width and separation of 2 μm oriented along [0-11], and etched mesa depth of 15 and 200 nm are presented. After etching, the samples were cleaned by oxygen plasma stripping followed by oxide removal in diluted 10 H$_3$PO$_4$ : 1 H$_2$O and rinsing in deionized water for three times before loading into the CBE growth chamber.

For InP (100) substrates, the growth commenced with 200 nm thick InP and 100 nm thick lattice-matched InGaAsP with RT bandgap at 1.18 μm (Q1.18). The nine-periods InAs/InGaAsP SL templates were grown on top of the buffer layers with each period consisting of 2.1 ML InAs, 10 s growth interruption under As flux, thin capping by 0.3 nm Q1.18, annealing for 2 min, and growth of a 5.5-nm Q1.18 spacer. On top of the SL template, a 3.2 ML InAs QD layer was deposited for QD formation with a 0-0.8 ML GaAs interlayer inserted beneath the QD layer. For the PL studies, the samples were capped by 100 nm Q1.27 and 50 nm InP. The growth temperature was kept constant at 505 °C and the annealing temperature was at 520 °C. The growth rate of InAs was 0.23 ML/s, calibrated by high-resolution X-ray diffraction (HXRD).

For InP (311)B substrates, the growth commenced with 200 nm thick InP and 100 nm thick lattice-matched InGaAsP with RT bandgap at 1.18 μm (Q1.18). The nine-periods InAs/InGaAsP SL templates were grown on top of the buffer layers with each period consisting of 2.1 ML InAs, 10 s growth interruption under As flux, thin capping by 0.3-nm Q1.18, annealing for 2 min, and growth of a 5.5-nm Q1.18 spacer. On top of the SL template, a 3.2 ML InAs QD layer was grown with a 0-2.0 ML GaAs interlayer beneath the QD layer. The growth temperature was 505 °C throughout the entire structure and the annealing temperature was 514 °C. The growth rate of InAs was 0.18 ML/s, calibrated by HXRD.

These optimized growth parameters were chosen for well-separated and highly uniform QD arrays on both substrates. The surface morphology of uncapped samples was characterized by tapping mode atomic-force microscopy (AFM) in air. For the PL studies at RT and 4.8 K, a neodymium-doped yttrium aluminum garnet (Nd:YAG) laser (532 nm) with power density of 256 mW/cm$^2$ was used as excitation source and the PL signal was collected by a cooled InGaAs linear array detector and an InSb single channel detector.
3. Results and discussion

3.1. 1-D InAs QD arrays
The AFM image of the linear 1-D 2.6 ML InAs QD arrays on the optimized InAs/InGaAsP SL template on planar InP (100) is shown in the inset (a) of Figure 1. The QD arrays are aligned along the elastically soft [001] direction of the cubic crystal to minimize the total strain energy, selected by the substrate miscut generating steps in the same direction. Inset (b) shows the AFM image of the 2.6 ML InAs QD arrays with 0.8 ML GaAs interlayer inserted beneath the QD layer. The GaAs interlayer suppresses As/P exchange during InAs deposition which reduces the QD height from 7-11 to 4-5 nm and, consequently, the emission wavelength from far above 1.65 µm at RT into the 1.55-µm region, as shown in the PL spectra in Figure 1.

![Figure 1. PL spectra of capped 2.6 ML InAs QD arrays with 0.8 ML GaAs interlayer taken at 4.8 K (solid line) and room temperature (dashed line). Inset: AFM image of uncapped 2.6 ML linear InAs QD arrays on the optimized SL template on InP (100) substrate (a) without GaAs interlayer and (b) with 0.8 ML GaAs interlayer beneath the InAs QD layer.]

Figure 2 shows the InAs QD arrays grown on the optimized SL template on the shallow- and deep-patterned InP (100) substrates with mesa stripes along (a), (c) [010] and (b), (d) [001]. For the Vicinal sidewall planes towards (00-1) of the shallow [010]-oriented stripes with relatively large inclination [Figure 2 (a)], the linear QD arrays are rotated away from the natural [001] direction due to the sidewall step edges along [010] modifying the direction of adatom surface migration during annealing. On the opposite sidewall planes towards (001), the arrays orientation is rotated by 90˚ along [010], which is the other elastically soft direction, selected by the high density of steps along the [010] sidewall. On top of the mesa stripes, no change of the QD arrays orientation is observed due to the relatively small step density, maintaining the natural arrays direction along [001]. On the vicinal sidewall planes of [001]-oriented stripes, shown in Figure 2 (b), the sidewall step edges are in the same direction as those due to the substrate miscut having no influence on the orientation of the QD arrays. For the deep-patterned substrates the steep side facets (inclination more than 10 degrees) are QD free due to the slow-growing behavior. On the less steep vicinal sidewall planes similar trends of QD arrays formation as on the shallow-patterned substrates are observed.

3.2. 2-D InAs QD arrays
The AFM image of the 2-D InAs QD arrays on the optimized InAs/InGaAsP SL template on planar singular InP (311)B is shown in the inset (a) of Figure 3 without a GaAs interlayer and in the inset (b)
with a 2.0 ML GaAs interlayer beneath the QDs. The QDs are aligned in a 2-D network along ±45° off [-233]. As the result of the GaAs interlayer, the QD height is reduced from 18-22 nm to 5-7 nm and the wavelength is shifted from far above 1.9 μm to the 1.55-μm region at RT, shown in the PL spectra in Figure 3.

Figure 4 shows the AFM images of the InAs QD arrays grown on the optimized SL template on the (a) shallow-patterned and (b) deep-patterned InP (311)B substrates with [0-11]- mesa stripes. For both shallow and deep patterns only QD free mesa side facets are developed. The 2-D QD arrays are not affected in accordance with the flat mesa top and bottom.

4. Conclusion

We have demonstrated the formation of ordered InAs QD arrays by self-organized anisotropic strain engineering of InAs/InGaAsP SL templates in CBE on planar and patterned InP (100) and (311)B substrates. The QD arrays emission wavelength at RT is tuned into the important 1.55-μm telecom wavelength region through the insertion of ultrathin GaAs interlayers. On shallow- and deep stripe-patterned InP (100) substrates, depending on the stripe geometry, the linear 1-D InAs QD arrays are rotated away from their natural [001] direction, selected by the substrate miscut, due to the presence of vicinal sidewall steps modifying the adatom surface migration during SL template formation. On shallow- and deep-patterned InP (311)B substrates only QD free sidewall facets are observed with flat top and bottom areas not affecting the formation of the natural 2-D InAs QD arrays. Hence, self-organized anisotropic strain engineering has shown the potential for the creation of laterally ordered QD arrays with excellent structural and optical properties compatible with telecom application. By combination with step engineering on artificially patterned substrates, complex QD arrays and networks have been realized for next generation quantum functional devices.

References

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