Wavelength controlled multilayer-stacked linear InAs quantum dot arrays on InGaAsP/InP(100) by self-organized anisotropic strain engineering: a self-ordered quantum dot crystal

Citation for published version (APA):

DOI:
10.1063/1.2993178

Document status and date:
Published: 01/01/2008

Document Version:
Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:
• A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
• The final author version and the galley proof are versions of the publication after peer review.
• The final published version features the final layout of the paper including the volume, issue and page numbers.

Link to publication

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

• Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
• You may not further distribute the material or use it for any profit-making activity or commercial gain
• You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the “Taverne” license above, please follow below link for the End User Agreement:
www.tue.nl/taverne

Take down policy
If you believe that this document breaches copyright please contact us at:
openaccess@tue.nl
providing details and we will investigate your claim.

Download date: 16. Sep. 2023
Wavelength controlled multilayer-stacked linear InAs quantum dot arrays on InGaAsP/InP (100) by self-organized anisotropic strain engineering: A self-ordered quantum dot crystal

N. Sritirawisarn, a) F. W. M. van Otten, T. J. Eijkemans, and R. Nötzel

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

(Received 7 May 2008; accepted 11 September 2008; published online 30 September 2008)

Multilayer-stacked linear InAs quantum dot (QD) arrays are created on InAs/InGaAsP superlattice templates formed by self-organized anisotropic strain engineering on InP (100) substrates in chemical beam epitaxy. Stacking of the QD arrays with identical emission wavelength in the 1.55 \( \mu \text{m} \) region at room temperature is achieved through the insertion of ultrathin GaAs interlayers beneath the QDs with increasing interlayer thickness in successive layers. The increment in the GaAs interlayer thickness compensates the QD size/wavelength increase during strain correlated stacking. This is the demonstration of a three-dimensionally self-ordered QD crystal with fully controlled structural and optical properties. © 2008 American Institute of Physics.

[DOI: 10.1063/1.2993178]

Future quantum functional devices with well-designed control of the quantum mechanical and electromagnetic interactions of single and multiple electrons and photons require the lateral ordering of semiconductor quantum dots (QDs), 1 ultimately together with vertical ordering toward three-dimensional QD crystals. Lateral ordering of QDs formed in the Stranski–Kastronov growth mode, otherwise producing randomly arranged QDs, has been achieved by artificial substrate patterning 2–4 and combined with vertical strain correlated stacking. 5,6 Artificial patterning techniques, however, often introduce defects and irregularities in the QDs given by the spatial resolution of the lithography and etching steps which degrade the electronic and optical qualities. Recently we have introduced a concept for the lateral ordering of InGaAs QDs in linear arrays on planar GaAs (100) substrates by molecular beam epitaxy 7,8 and planar InP (100) substrates by chemical beam epitaxy (CBE), 9 on which we concentrate here. Based on anisotropic adatom surface migration and lateral and vertical strain correlations, wirelike InAs nanostructures are created during growth of an InAs/InGaAsP superlattice (SL), which acts as a template for the formation of linear InAs QD arrays due to local strain field recognition. This self-organization process has been proven to produce ordered QD arrays with excellent optical properties up to room temperature (RT) and whose emission wavelength was tuned into the technologically important 1.55 \( \mu \text{m} \) telecommunication wavelength region through the insertion of ultrathin GaAs interlayers beneath the QDs. 9

In this letter, we demonstrate the formation of multilayer-stacked linear InAs QD arrays on the InAs/InGaAsP SL template on InP (100) demonstrating a fully self-ordered three-dimensional QD crystal. Identical emission wavelength of the stacked QD arrays is achieved by increasing the thickness of the GaAs interlayer in successive layers. The increment in the GaAs interlayer thickness compensates the QD size/wavelength increase encountered in strain correlated stacking for relatively thin separation layers. 10–12 The stacked QD arrays exhibit strong photoluminescence (PL) emission in the 1.55 \( \mu \text{m} \) wavelength region up to RT.

The samples were grown by CBE on semi-insulating InP (100) substrates with 2° miscut toward (110). Pressure controlled trimethylindium, triethylgallium, AsH 3, and PH 3 gases were used as precursors. The AsH 3 and PH 3 gases were thermally decomposed in a high temperature injector at 900 °C. After growth of a 200 nm InP buffer layer and 100 nm lattice-matched InGaAsP with band gap of 1.25 \( \mu \text{m} \) (Q1.25), the SL template was grown consisting of 2.1 monolayers (ML) InAs, 10 s growth interruption under As flux, 0.3 nm Q1.25 cap layer, 2 min annealing, and 15.3 nm Q1.25 separation layer, and repeated for seven periods. On top of the SL template a 2.6 ML InAs QD layer was grown with 0.6 ML GaAs interlayer inserted beneath. The multilayer-stacked 2.6 ML InAs QD arrays were separated by 16 nm Q1.25. The increment in the GaAs interlayer thickness in successive 2.6 ML InAs QD layers was 0.12 or 0 ML for comparison. The growth temperature was 505 °C for all layers and the annealing temperature was 520 °C. The growth rate of InAs was 0.24 ML/s. The surface morphology of the uncapped samples was characterized by tapping mode atomic force microscopy (AFM) in air. For the PL studies, the samples were capped by 100 nm Q1.25 and 50 nm InP, and excited by a neodymium doped yttrium aluminum garnet laser (532 nm) with excitation power density of 256 mW/cm². The PL was dispersed by a single monochromator and recorded by a cooled InSb detector.

Figures 1(a)–1(c) show the AFM images of the uncapped single-layer QD arrays (described in detail in Ref. 9), the uncapped twofold-stacked, and the uncapped threelfold-stacked QD arrays with increment in the GaAs interlayer thickness. For comparison, the AFM image of the uncapped threelfold-stacked QD arrays without increment in the GaAs interlayer thickness is shown in Fig. 1(d). The QD arrays are...
aligned along the elastically soft [001] direction to minimize the strain energy,\textsuperscript{13,14} which is selected by the miscut of the substrate with steps in the same direction.\textsuperscript{9} InAs amount and growth rate, cap layer thickness, annealing temperature, and number of SL template periods are optimized for self-organized ordering due to anisotropic adatom surface migration during annealing and lateral and vertical strain correlations during stacking. Strain correlated stacking of the QD arrays separated by 16 nm Q1.25 manifests itself by the maintenance of linear ordering. With increment in the GaAs interlayer thickness, the height of the top twofold-stacked and threefold-stacked 2.6 ML InAs QD arrays with 0.12 ML increment in the GaAs interlayer thickness in successive layers.

The PL measurements taken at RT of the capped multilayer-stacked QD arrays shown in Fig. 3 corroborate the structural properties. The PL peak wavelength of the threefold-stacked QD arrays (1553 nm) is almost identical compared to that of the single-layer QD arrays (1551 nm). The PL efficiency of the threefold-stacked QD arrays increases by 44% compared to that of single-layer QD arrays indicating good crystal quality of the multilayer-stacked structure. Without increment in the GaAs interlayer thickness, the PL peak wavelength redshifts to 1582 nm due to the gradual increase in the QD size upon stacking (see inset in Fig. 3).

In summary, the formation of multilayer-stacked linear InAs QD arrays on InAs/InGaAsP SL templates formed by self-organized anisotropic strain engineering on InP (100) substrates in CBE has been achieved. Identical emission wavelength of the stacked QD arrays in the 1.55 $\mu$m telecommunication region at RT has been accomplished through the insertion of ultrathin GaAs interlayers beneath the QDs.
with increasing thickness in successive layers, demonstrating a three-dimensionally self-ordered QD crystal.

This work was partially supported by NanoNed (STW).