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Design and realization of low density InAs quantum dots on AlGaInAs lattice matched to InP(0 0 1)

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ABSTRACT

We present detailed growth studies of InAs nanostructures grown on $Al_xGa_yIn_{(1-x-y)}As$ lattice matched to an InP(0 0 1) substrate using molecular beam epitaxy. Highly elongated quantum dash like structures are typically favoured in this material system, due to very anisotropic migration lengths along the [1 −1 0] and [1 1 0] directions. In order to increase the short migration length along the [1 1 0]-direction we used ultra low growth rates down to 3×10^{-3} monolayers per second. We show that this offers the possibility to form InAs quantum dots with a low surface density, in contrast to the most commonly formed quantum dash structures. To tailor the emission wavelength of the quantum dots, three methods were studied: (i) the variation of the bandgap of the surrounding material by adjusting the aluminium to gallium ratio, (ii) the variation of the bandgap of the quantum dot material by incorporating antimony and (iii) the variation of the height of the quantum dots by closely stacking two layers of quantum dots upon each other.

1. Introduction

Self-organized quantum dots can be used for single photon generation and may therefore be key components in quantum information technology [1,2]. In particular for quantum cryptography, single photons have to be transmitted over long distances. For this purpose the photons should be emitted in the optical C-band (1535–1565 nm) to minimize losses in commonly used glass fibres. To obtain single photons using self-assembled quantum dots the light must be generated from a single dot. Thus, to enable a single dot per device a very low quantum dot surface density is needed ($<5\ \mu m^{-2}$). Low quantum dot densities offer the possibility to investigate single quantum dots via confocal luminescence spectroscopy and to couple single quantum dots to resonator modes e.g. photonic crystal defect modes to obtain a high outcoupling efficiency [3,4]. Self-assembled quantum dots on GaAs substrates have already been extensively studied, but it has proven to be extremely difficult to reach 1.55 μm, at least for samples with low quantum dot density operated at cryogenic temperatures. In contrast, InP based materials provide emission in the optical C-band. However, the fabrication of InAs quantum dots on InP or on lattice matched AlGaInAs via MBE is a challenge since self-assembled growth often leads to elongated quantum dashes with a width of 30–40 nm and length up to 500 nm [5–7]. The fabrication of InAs quantum dots on InP(0 0 1) substrates has been demonstrated using metal organic vapour phase epitaxy (MOVPE) applying for instance a "double cap" technique [8] and other technologies [9,10], but these samples exhibit a rather high dot density ($>100\ \mu m^{-2}$). Accordingly, only very small mesa structures (140 nm diameter) allow the optical isolation of single quantum dots or dashes [11]. Consequently, to realize a single photon emitting device working in the telecommunications band, quantum dots that emit around 1.55 μm are required with a low surface density ($<5\ \mu m^{-2}$). The growth of low quantum dot densities (around $10\ \mu m^{-2}$) in the InAs/InGaAsP/InP-system was recently demonstrated by MOVPE [12].

In this growth study we present a parameter range for the MBE growth of nanostructures in the $Al_xGa_yIn_{(1-x-y)}As$/InP material system wherein the formation of quantum dots with low surface density occurs. Furthermore, we show concepts to controllably adjust the emission wavelength of the dots and to realize a strong confinement for charge carriers to prevent thermal stimulation of excitons out of the quantum dot that reduce the tunnelling rate under electric field.

2. Experimental

All samples were grown in a solid-source molecular beam epitaxy (MBE) system, Varian Mod Gen II on two-inch InP(0 0 1)

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substrates. For the growth of the InAs quantum dots we used very low growth rates in contrast to the surrounding $Al_xGa_yIn_{(1-x-y)}As$. To allow very low growth rates, without growth interruption between the matrix material and the quantum dots, we used a second downward looking indium cell, calibrated using GaAs/GaInAs multi-quantum well structures analyzed by X-ray diffraction. The samples consist of a 400 nm buffer layer $Al_{0.48}In_{0.52}As$ followed by 30 nm $Al_xGa_yIn_{(1-x-y)}As$ matrix material. Afterwards two regions with quantum dots were deposited: a buried layer for investigation via photoluminescence and a surface layer, separated by a 100 nm $Al_xGa_yIn_{(1-x-y)}As$ spacer layer, for structural investigations via atomic force microscopy (AFM). To obtain a quantum dot growth independent from the aluminium content in the top most layer at the growth surface, the matrix material was grown as a digital alloy of $Al_{0.48}In_{0.52}As$ and $Ga_{0.47}In_{0.53}As$, which always ends up with a 0.6 nm layer GaInAs. The thicknesses of the $Al_{0.48}In_{0.52}As$/ and $Ga_{0.47}In_{0.53}As$ layers were 0.37 and 1 nm, respectively, for the most frequently used $Al_{0.13}Ga_{0.35}In_{0.52}As$ alloy. This aluminium free surface enables the highest possible mobility of the indium atoms.

2.1. Low growth rates

First of all we analyzed the influences of different indium-fluxes, the growth temperature and the total InAs coverage on the formation of the InAs nanostructures. Fig. 1 shows atomic force microscopy (AFM) graphs taken from the middle of the wafer of samples grown under identical conditions besides the growth rate that was increased from 0.003 monolayers per second (ML/s) to 0.03 ML/s. These four samples were grown with a total InAs coverage of 2.1 monolayers (ML) on $Al_{0.13}Ga_{0.35}In_{0.52}As$ matrix material. The temperature used for the growth of the samples shown in Figs. 1 (a)–(c) was 495 °C (measured by pyrometer). As the figure shows, a transition from quantum dashes (Fig. 1(a)) with height of 2–3 nm, a width of 30 nm and a length up to 400 nm to chain like arranged quantum dots with a height of 4–5 nm and a diameter of 30 nm (Fig. 1(b)) can be observed while lowering the growth rate from 0.03 to 0.006 ML/s. A further reduction of the growth rate to 0.003 ML/s leads to the formation of single quantum dots with a height of 3–4 nm and a diameter of 25–30 nm (Fig. 1(c)). Very low growth rates provide long migration times for the arriving indium atoms and therefore make high migration lengths possible. The migration length can also be enhanced by raising the growth temperature. The sample in Fig. 1(d) was grown with 0.006 ML/s, which is the same rate used for the sample shown in Fig. 1(b) but at a higher temperature (505 °C pyrometer). The quantum dots grown under these conditions have a diameter of 30 nm and a height of 3–5 nm. They are not as homogeneous as the quantum dots grown with 0.003 ML/s at 495 °C but therefore also higher quantum dots (around 5 nm) appear. Aiming for a strong carrier confinement we used these conditions for further studies, to fabricate high quantum dots with lower quantisation energy. Using the parameters corresponding to Fig. 1(c) and (d), we realized low density quantum dots ($\sim 4\ \mu m^{-2}$) within an InAs coverage of 2.1–2.6 monolayers. Corresponding to growth parameters that allow long migration lengths or migration times, respectively, for the arriving indium atoms, we observe a transition from quantum dash like structures via chain like structures to single quantum dots in a low surface density. It is important to point out that we observed formation of quantum dots only when using very low growth rates from 0.003 to 0.006 ML/s as shown in Fig. 1(b) and (c). Due to an exponential dependence of the indium desorption rate on the growth temperature, a high mobility of the indium atoms operating at higher temperatures is not practical.

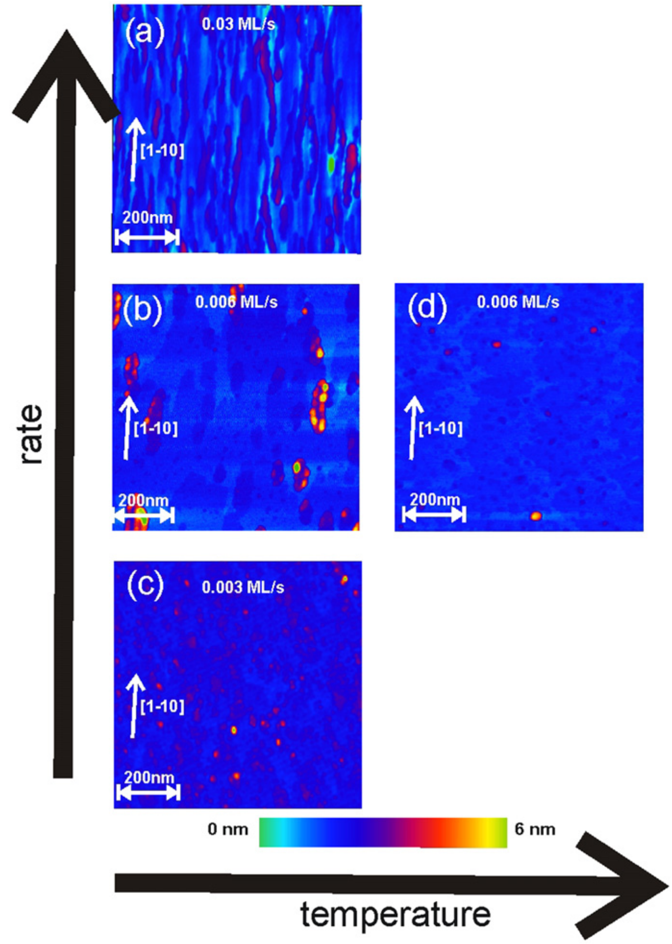

Fig. 1. AFM-micrographs (1 μm^2) show a transition from dash- to dot-like structures lowering the growth rate from (a) 0.03 ML/s and 495 °C, (b) 0.006 ML/s and 495 °C to (c) 0.003 ML/s and 495 °C. Sample (d) shows similar density and geometry like sample (c), it is grown with 0.006 ML/s and 505 °C pyrometer temperature. All samples have an InAs coverage of 2.1 ML.

In the following, we discuss the optical properties of the buried layer of quantum dots grown under similar conditions to the samples shown in Fig. 1. Photoluminescence measurements were taken from single quantum dots using a confocal micro-photoluminescence setup. A helium–neon-laser operating at 623.8 nm was used for optical excitation. This laser was focused on the sample using an M-Plan NIR objective with a numerical aperture of 0.55. All measurements were performed at 10 K with the samples mounted in a helium flow cryostat. The photoluminescence light was detected using a Triax-550 spectrometer combined with an InGaAs-photodiode array. Due to the low quantum dot density no patterning of the sample is required to perform optical experiments on single quantum dots. Typical micro-photoluminescence spectra are shown in Fig. 2. The figure shows several samples with low density quantum dots. To achieve emission in the optical C-band, the wavelength tuning was performed by adjusting the bandgap of the surrounding $Al_xGa_yIn_{(1-x-y)}As$ matrix material using different contents of aluminium and gallium. Three samples were fabricated with aluminium contents of 48%, 13% and 4%. Lowering the bandgap of the matrix material leads to lower quantisation energy in the quantum dot and therefore to a longer wavelength of the emission.

Due to the digital alloy growth mode, the total aluminium in the barrier material has only a minor influence on the formation of the nanostructures. As can be seen in Fig. 2(a) an emission