Self-Assembled InAs QDs Grown on AlGaAs Surfaces

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Introduction

Quantum dots (QDs) have been under intense investigation during the last years due to their appealing electronic and optical properties. As they offer the ultimate limit in carrier confinement, they gave rise to novel opto-electronic device applications such as QD lasers. To implement the QDs into such devices it is vital to have control over the QD density and size which are in turn determined by the growth parameters. Furthermore, it is desirable to have control over the lateral position of the QDs on the substrate. To achieve this placement, the growth of QDs on substrates pre-patterned with nano-scale structures can be exploited to laterally align the QDs [1], [2]. In this work, we demonstrate the growth of self-assembled InAs QDs on patterned and unpatterned surfaces. The growth of QDs on $Al_xGa_{1-x}As$ surfaces with different Al concentrations was studied in detail.

QDs on $Al_xGa_{1-x}As$ Surfaces

QD Growth

The QDs were grown using a solid-source molecular beam epitaxy (MBE) system. For the surface QD samples the $Al_xGa_{1-x}As$ was grown at 590 °C while subsequent InAs QDs were grown 490 – 520 °C. The sample surface, QD size, shape, volume, and density were analyzed by atomic force microscopy (AFM) with a Digital Instruments 3100 operated in tapping mode. How critical the QD density depends on the growth surface and temperature can be seen in Fig. 1.

All data points are for 0.556 nm (1.83 ML) of InAs at a growth rate of 0.01 µm/h. As can be seen, on GaAs surfaces, temperatures 500 °C – 520 °C produce a QD density variation up to two orders of magnitude. For substrate temperatures above 520 °C the In amount incorporated into the epilayer is reduced significantly. Furthermore, a rise in the Al concentration at the same growth temperature will also increase the dot density dramatically, while reducing the dot size. This is due to the reduced In surface diffusion compared to a GaAs surface. How the amount of InAs incorporated into the QDs depends on the growth temperature is shown in Fig. 2. 0.556 nm (1.83 ML) of InAs were deposited for the growth of self-assembled surface QDs as the substrate temperature was varied from 490 °C to 520 °C. Because of the reduced surface mobility there is an increase in QD volume for surfaces with a higher Al concentration. At growth temperatures of 510 °C and above there is a sharp decline of the dot volume as less InAs can be incorporated into the epilayer at high temperatures. Also at highest Al concentrations there appears to be a sharp decline in QD volume.

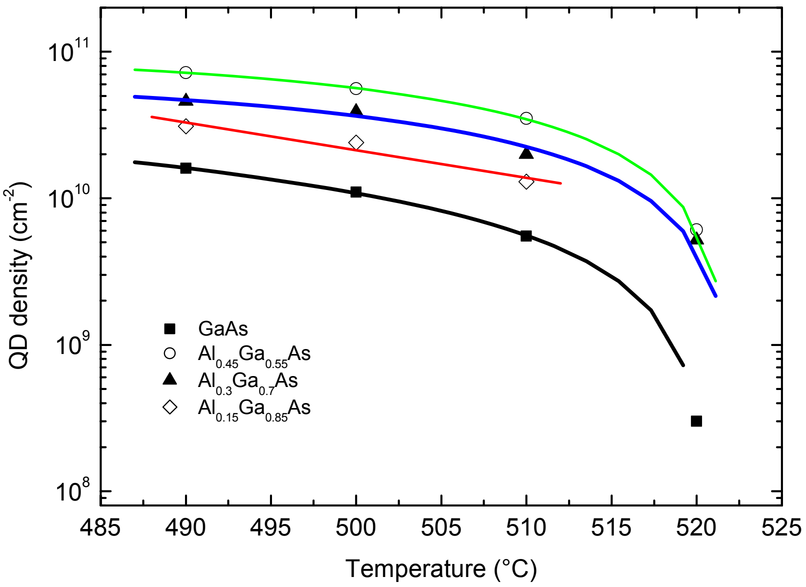

Fig. 1: QD density dependence on growth temperature and Al concentration. The fits are guides to the eye.

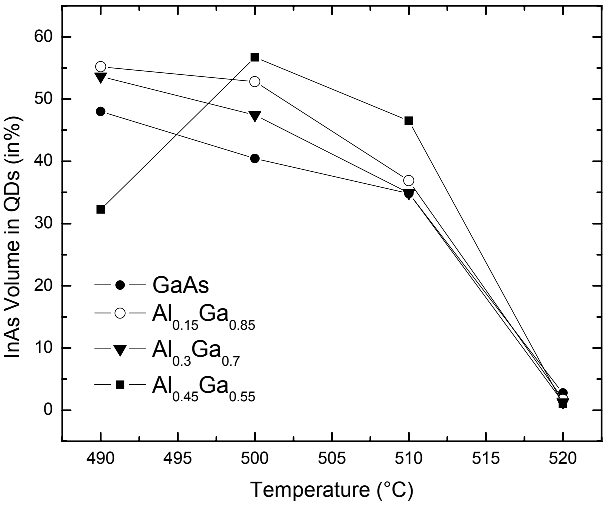

Fig. 2: InAs volume in QDs for different substrate temperatures and surfaces for 0.556 nm of InAs.

Photoluminescence Measurements

To probe the optical properties of the QDs, the buried dots were characterized by photo luminescence (PL) measurements. For the PL measurements a diode pumped solid state laser operating at a wavelength of 532 nm is used. The emission of radiation from the photo-excited carriers via interband optical transitions is measured with a cooled photomultiplier tube and a lock-in amplifier. The measurements were performed at room temperature. The samples consist of 30 layers of self-assembled QDs grown at a surface temperature of 490 °C. Figure 3 shows the measured luminescence for dots grown on surfaces with varying Al concentrations. As the Al concentration increases, the center of the emission peak is shifted to higher energies. This blue-shift can be attributed mainly to the decrease in QD size and the increase in barrier height surrounding the dots. This allows tuning the wavelength of the QD emission within a certain range. Also the luminescence peaks become noticeably broader as the Al content of the growth surface increases. Because surfaces with a high Al concentration show a reduced In diffusion compared to a GaAs surface, the size distribution of the QDs is also broader. This appears in the PL signal as an increased full width at half maximum (FWHM) of the emission peak. The exact values for the FWHM are displayed next to the luminescence peaks in Figure 3.

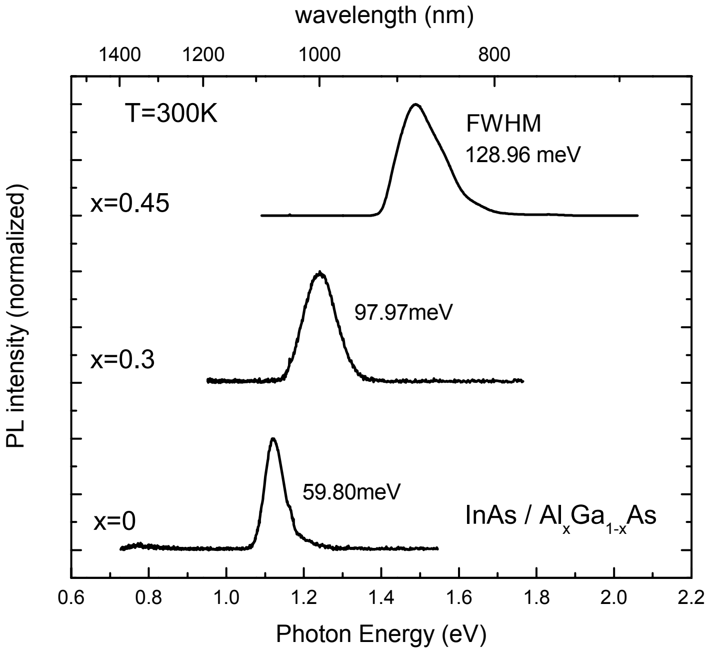

Fig. 3: PL intensity of QDs grown on surfaces with varying Al contents.

Growth on Patterned Substrates

As mentioned previously an ensemble of self-assembled QDs usually shows a broad size distribution. Therefore, the emission from the dots shows a broad spectral broadening. Also, the lateral position of the dots on the substrate can not be controlled. There have already been different approaches to seed the dots on predefined positions on the surface. The most promising approach is the growth of QDs on patterned substrates. In our work we prepared substrates patterned with focused ion beam (FIB) sputtering and laser holography.

Pattern Preparation

For the seeding of QDs, the substrates were patterned using laser holography. With this technique large areas can be exposed in a short time compared to other methods like e-beam lithography. However, in laser holography the resolution that can be achieved is limited by the wavelength of the laser. In our setup we used a He-Cd laser with a wavelength of 325 nm. With this setup patterns with a period as small as 180 nm could be realized. Using subsequent wet chemical or dry etching, the pattern is then transferred into the substrate.

With e-beam lithography, patterns as small as 40 nm in diameter were created. Figure 4 shows a patterned substrate with a period of 100 nm. For the dry etching an Ar sputter process has been employed with an RIE Plasmalab 100. The etch depth is 20 nm.

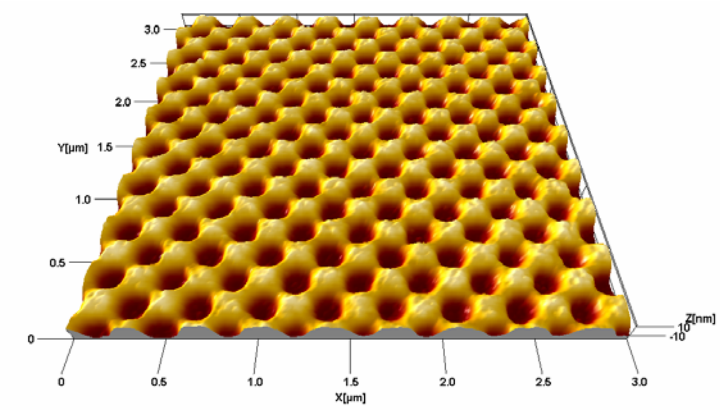

Fig. 4: AFM scan of a patterned GaAs substrate, where the pattern was created using e-beam lithography and Ar sputtering.

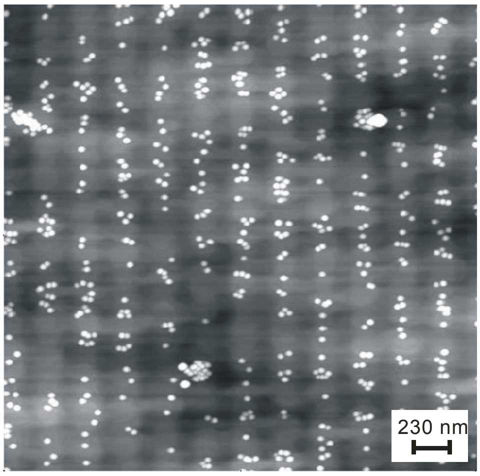

Fig. 5: AFM scan of a patterned substrate with a period of 230 nm overgrown with 20 nm $In_{0.2}Ga_{0.8}As$, 10 nm GaAs and 0.495 nm InAs. Due to preferential nucleation spots created by the template and the InGaAs layer, the dots align according to the pattern.

Overgrowth

Before inserting the samples into the molecular beam epitaxy (MBE) growth chamber, they were carefully cleaned using solvents. Afterwards, they were exposed to an oxygen plasma to remove any residual resist. Finally, an HCl etch was performed to remove the oxide on top. The cleaning process was completed with a rinse under DI water to grow a fresh layer of oxide. Inside the MBE the oxide was thermally removed under an As_4 overpressure. *In situ* reflection high energy electron diffraction (RHEED) was used to monitor the substrate surface. Directly on the pattern 20 nm of $In_{0.2}Ga_{0.8}As$ was grown followed by a 10 nm GaAs buffer layer. The QDs were grown at 510°C with an InAs deposition of 0.495 nm (1.63 ML). Figure 5 shows a typical result with a QD density of 6.8×10^{9} cm^{-2} and an average dot height of 3.9 nm. After overgrowth the original depth of the pattern is reduced as the holes are covered with the strained $In_{0.2}Ga_{0.8}As$ layer and the GaAs buffer layer. The pattern together with the layer of InGaAs forms preferential nucleation spots for the QDs and therefore the dots align according to the pattern. Compared to dot densities that can be achieved on unpatterned substrates under the same growth conditions, the patterned substrates also show higher dot densities. It is also visible that the size of the template is not small enough to achieve an alignment of one QD per hole. Therefore, other methods like e-beam lithography have to be employed to realize smaller pattern sizes to achieve the ultimate goal of aligning one QD per hole.

FIB Patterning

Maskless patterning of GaAs substrates with ion beams focused to nanometer diameters for subsequent MBE overgrowth has been investigated. Using a focused ion beam offers the advantage that the patterns can be written directly onto the substrate and no lithographic processing is needed. The focused ion beam experiments were performed with a Micrion twin lens FIB system (model 2500) equipped with a Ga liquid metal ion source. The system was operated at an acceleration voltage of 50 kV with a selectable 50 µm beam-limiting aperture corresponding to a beam current of 45 pA. The diameter of the ion beam is 52 nm. The exposure of the holes to the ion beam was varied to achieve different diameters and sputter depths. Patterns with a pitch as small as 200 nm and a depth of the sputtered holes of 30 nm are demonstrated. Shown in Fig. 6 is the cross-section of the FIB sputtered holes. On the bottom of the holes small peaks are visible. As has been shown previously, FIB micro-patterning results in selective sputtering of arsenic, causing Ga-rich precipitations on the surface. For single dot milling these, in principle, mobile precipitations are fixed in the center of the crater. Regarding overgrowth, these precipitations can prevent the growth of crystalline In(Ga)As on the bottom of the holes. Post-exposure annealing followed by wet chemical etching to remove Ga contamination due to ion beam exposure has already shown promising results on silicon substrates and will be further investigated.

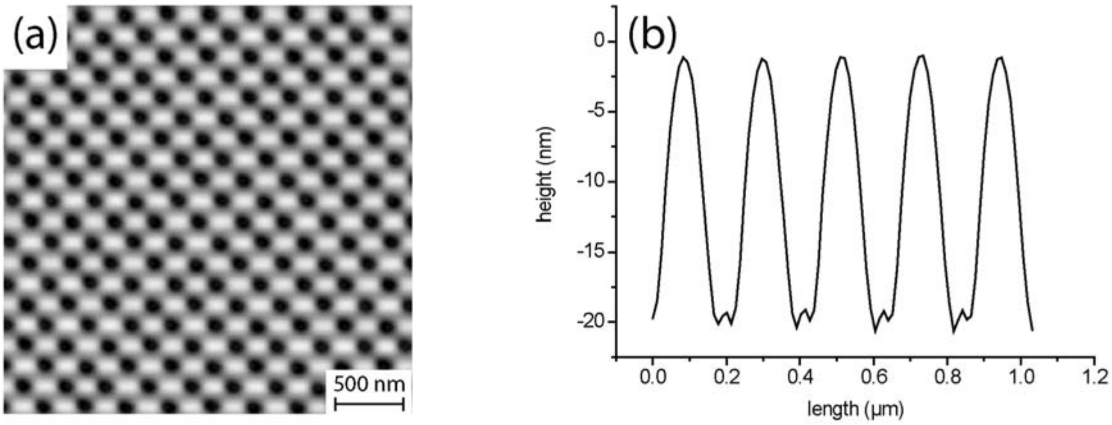

Fig. 6: AFM image (a) and cross-section (b) of a patterned substrate created by FIB sputtering, with a period of 200 nm.

References

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[2] M. Schramboeck, W. Schrenk, T. Roch, A.M. Andrews, M. Austerer, G. Strasser, *Microelectron. Eng.***83,** 1573 (2006)