InAs quantum dots grown on InAlGaAs lattice matched to InP

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The self−assembled formation of three−dimensional islands is considered to be one of the most promising ways to make quantum dots (QDs). Quantum dot lasers have been extensively studied due to the low threshold current, low chirp, and temperature insensitive operation. Typical devices, realized with InAs QDs on GaAs substrate, operate at wavelengths as long as 1.2 μm with longer wavelengths achievable by the use of InGaAs capped InAs dots. There is great interest in being able to extend this wavelength to 1.55 μm, and beyond, for use in fiber optic telecommunication systems. Growth of InAs on InP allows for these wavelengths to be readily reached.

For laser applications, it is desirable to achieve samples with a high density of QDs in a narrow size distribution, and it would be advantageous to have a large refractive index change between the active region and the surrounding InP. For this purpose, we have grown InAs QDs on InAlGaAs, lattice matched to InP, in low−pressure (50 mBar) metal organic vapor phase epitaxy (MOVPE). We studied the effect of varying the Al content in the quaternary compound from 0 to 30% on dot formation. Atomic force microscopy (AFM) measurements on freestanding QDs revealed that dots on material with higher Al content are smaller, and that the local densities on step−bunches formed on the vicinal (001) surfaces increase.

The samples were grown in MOVPE with phosphine (PH_3), arsine (AsH_3), trimethyl−indium (TMI), trimethyl−gallium (TMG), and trimethyl−aluminium (TMA) as precursors, and hydrogen as carrier gas. The process was controlled by a flow and pressure balanced ventilation/run system. The total gas flow in the reactor cell was about 6000 cm^3 /min. We used S doped (n+) InP (001) "epi−ready" wafers with a 2^o misorientation towards the nearest <011> direction for our experiments. A 150 nm thick InP buffer layer was grown, initially at an elevated growth temperature of 630^o C, after which the reactor was cooled down to 600^o C. Then a 500 nm thick $In_x\ Al_y\ Ga_{1-x-y}\ As$ layer was grown with a V/III ratio of 30. The growth rates for InP and $In_x\ Al_y\ Ga_{1-x-y}\ As$ were 1.4 ML/s and 2.8 ML/s, respectively. The temperature was ramped down to 500^o C during a 5 min period without growth, to keep the well−defined terrace structure before dot deposition. 2.5 ML InAs dot material was deposited on the surface at a growth rate of 0.5 ML/s and then the surface was annealed for 12 s under an arsine flow. At this point, the samples were either cooled down under arsine containing atmosphere, or capped with 50 nm InP during which the temperature was ramped up to 600^o C. For capping the samples, the arsine was switched off and replaced by phosphine. Then TMI was reintroduced into the reactor, after a delay time of 1 s in order to reduce carry over effects. Photoluminescence (PL) of capped dot structures was measured by Fourier transform infrared spectroscopy with the samples either immersed in liquid nitrogen, or in air at room temperature. As excitation source we used an Ar−ion laser with an excitation power of 50 mW. An InSb detector was used for detection. For non−capped samples, the lattice matching of the quaternary layer was checked by a combination of PL and X−ray diffraction measurements. The Al content in the $In_x\ Al_y\ Ga_{1-x-y}\ As$ layers, lattice matched to InP, was varied between 0−30%. Surfaces were then studied with tapping−mode atomic force microscopy (AFM). The height distributions of the islands were evaluated by measuring the height of 324 islands from respective AFM image, and from these data histograms were made. We take the height values as representative for the size of the islands. The dot densities were evaluated by counting the islands on 2 x 2 μm^2 images.

We start by looking at the effect on dot formation when Al is introduced into the layer onto which dot material is deposited. Figure 1 and 2 shows 1 x 1 μm^2 AFM images of InAs QDs on $In_x\ Al_y\ Ga_{1-x-y}\ As$, with 0 and 15 % Al content, respectively. On our samples, with increasing Al content, the local density of dots at the step bunch becomes higher, and the dot sizes become smaller. This can be observed on the graph of figure 3.

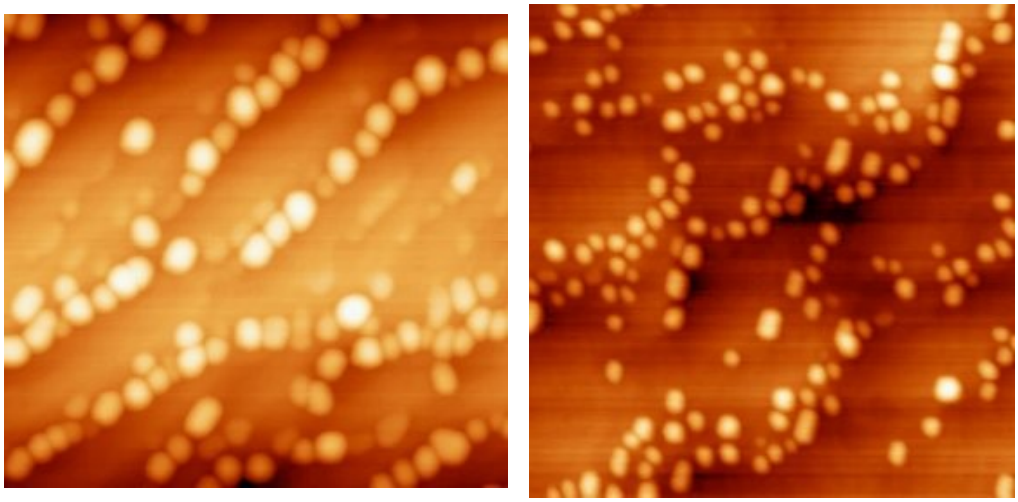
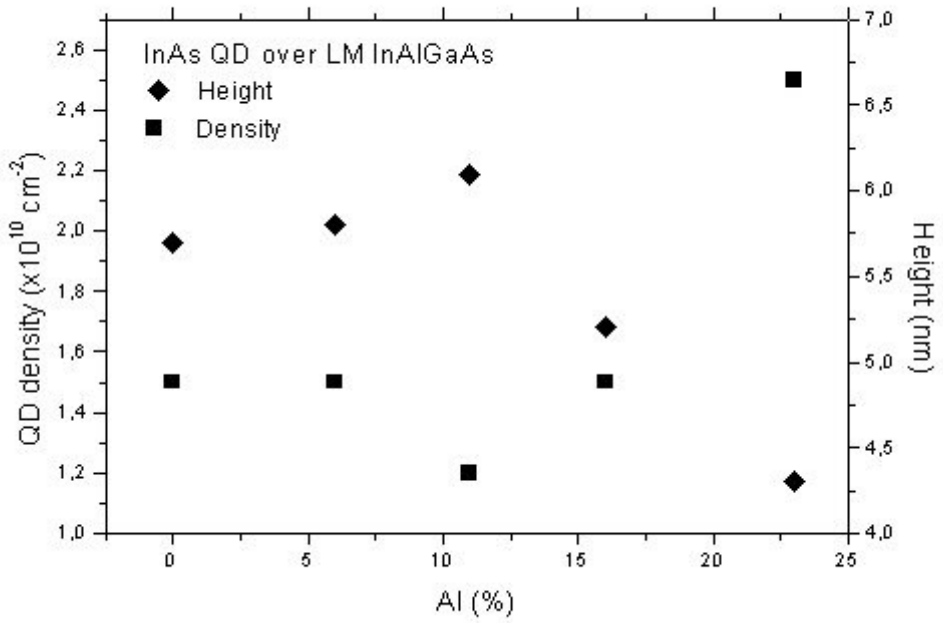
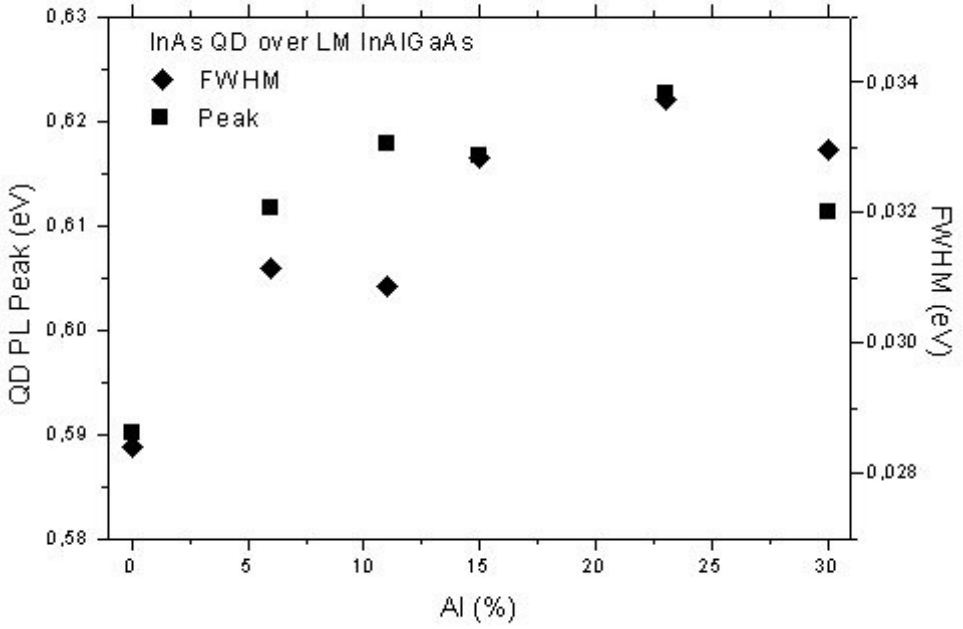


Figure 4 depicts the change of the QD PL peak and the full width of half maximum (FWHM) of the PL spectra with the Al concentration change. With increasing Al content, the emission energy of the dots increases for two reasons: First, a higher density of dots (using the same amount of dot material) leads to a smaller dot size, due to materials distribution over the nuclei, and thereby to an increased quantum confinement of the dot. Second, the larger the Al content in the barrier material, the larger its bandgap. Both effects influence the electronic level structure of the dots. Thus, the emission wavelength of the dots can, in principle, be tuned by adjusting the Al content in the barrier material. We find that these dots emit at very long wavelengths (2.1 µm) and that the emission wavelengths are blue−shifted with an increase of Al in the surface onto which the dots nucleate.





Analyzing the height histograms of the AFM images it is possible to measure the size homogeneity of the dots. The results indicate that the dots become more homogeneous with the insertion of Al into the layer immediately beneath the InAs. It is interesting to note that the PL measurements show the opposite trend, something that could be explained by the observed shift in dot size. A narrow apparent dot size only (as observed by AFM), will not correctly reflect the distribution of the electronic states within the dots since a change in dot size for a smaller dot has relatively larger impact on the change in quantization energy.

Growth temperature, deposition rate, and V/III ratio are adjustable parameters that offer additional possibilities of tuning the electronic states of the dots, and consequently the energy of light emission in devices based on InAs/ $In_x Al_y Ga_{1-x-y} As$ quantum dot structures.