# Thermal annealing of InAs quantum dots on patterned GaAs substrates

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**Abstract.** We investigated the effect of *in-situ* thermal annealing on InAs quantum dots (QDs) grown site-selectively on pre-patterned GaAs substrates. We compare as grown and annealed samples. A morphological transition is observed where originally two QDs merge into one larger dot.

**Keywords:** Quantum dots, site-selective growth, annealing, molecular beam epitaxy
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## INTRODUCTION

Quantum information devices are moving closer to realization since single semiconductor quantum dots (QDs) can be manufactured on demand. Essentially, it is necessary to fabricate QDs with controllable properties at predefined locations. In the past decade, substrate prepatterning has become a reliable technique in order to achieve good control of QD nucleation sites. [1, 2] Nevertheless, the lower quality of site-controlled QDs compared to randomly nucleating QDs remains an obstacle. The patterning process introduces defects at the regrowth interface below the QDs. [3]

Besides growing QDs in stacks, a different approach to improve QD distribution and optical properties utilizes an in-situ post-growth treatment. QDs undergo morphological changes during annealing. At lower temperatures they tend to ripen whereas they dissolve at higher temperatures. [4, 5] Under certain annealing conditions, QD sizes remain constant while the QD density as well as the In concentration can be controlled by annealing time. [6, 7]

## EXPERIMENTAL

All samples were grown by molecular beam epitaxy (MBE) with (0 0 1) GaAs wafers serving as substrates. The surface patterning was performed by electron beam lithography on top of a 90 nm GaAs epitaxial layer. 50-70 nm wide and 30 nm deep holes were wet chemically etched into the surface. This was followed by resist stripping and careful cleaning of the samples in a series of solvent baths. The surface oxide was removed by Ga-assisted deoxidation at around 480 °C by successively depositing a total amount of 8 ML of Ga. A 16 nm GaAs buffer layer (BL) was then grown at 500 °C followed by 1.7 ML or 1.9 ML of InAs. Thereafter *in-situ* annealing was performed for 2:30 min. The samples were characterized by atomic force microscopy (AFM), whereas a 80 nm GaAs capping layer was introduced to allow for micro-photoluminescence (μ-PL) measurements.

## RESULTS AND DISCUSSION

Figure 1 shows AFM images of a set of samples with as grown (*left*) and annealed QDs (*right*). We observe in both cases QDs nucleating at locations pre-defined by the holes. The as grown sample shows predominant nucleation of double dots on each site. This feature might be caused by a change in hole shape during BL growth. In comparison, the annealed sample shows considerable single dot occupation per site. That is because the annealing step causes the material to redistribute by facilitating the migration of adatoms. As a result, we observe a change in morphology from double dots to single dots due to annealing. Since two dots merge into a single one, the annealed dots are larger in size and volume, which is seen from the representative linescan. The average annealed QD diameter is 82.6±9.5 nm, whereas for as grown QDs it is 49.1±4.4 nm. The volume of the single dots is larger than the combined volume of the double dots. That is related to a reduction of interstitial QDs, which are present due to the high amount of InAs provided. The material of interstitial dots is collected in the single dots.

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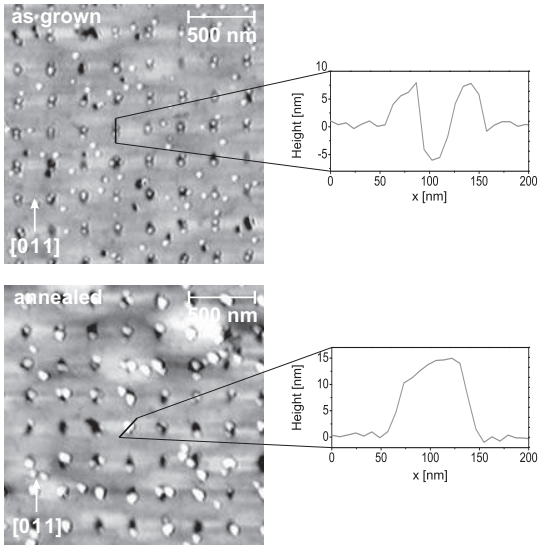


**FIGURE 1.** AFM images of as grown (*top*) and annealed (*bottom*) QDs (1.7 ML InAs) grown on pre-patterned samples. A morphological transition from double dots to single dots is observed, which is confirmed by representative linescans.

These facts can be put in numbers by analyzing the corresponding QD densities. For the as grown sample, the QD densities are roughly $n^{\text{on-site}}_{\text{as grown}} \approx 4.8 \times 10^9\,/\text{cm}^2$ and $n^{\text{off-site}}_{\text{as grown}} \approx 1.6 \times 10^9\,/\text{cm}^2$ in the pre-patterned (on-site) and unpatterned (off-site, not shown) areas, respectively. For the annealed sample the densities are about $n^{\text{on-site}}_{\text{annealed}} \approx 2.6 \times 10^9\,/\text{cm}^2$ and $n^{\text{off-site}}_{\text{annealed}} \approx 0.9 \times 10^9\,/\text{cm}^2$ (not shown). The density of QDs in the patterned area is reduced by a factor of about 2. That is because the double dots merge into single ones and additionally, the density of interstitial dots is halved when comparing the off-pattern densities of annealed and as grown QDs.

The optical quality of the annealed QDs was analyzed by μ-PL measurements and compared to annealed QDs grown on an unpatterned substrate, as shown in Fig. 2. Individual QD peaks are visible. The luminescence intensity of the QDs grown on the pre-patterned substrate is reduced but the linewidth is comparable to that of QDs grown on the unpatterned substrate.

## CONCLUSION

In conclusion we have investigated the effect of thermal *in-situ* annealing on InAs QDs grown on pre-patterned substrates. We have found that site-selective QDs undergo a morphological transition due to annealing with double dots merging into single dots. As a consequence, the QD density is reduced. First μ-PL measurements

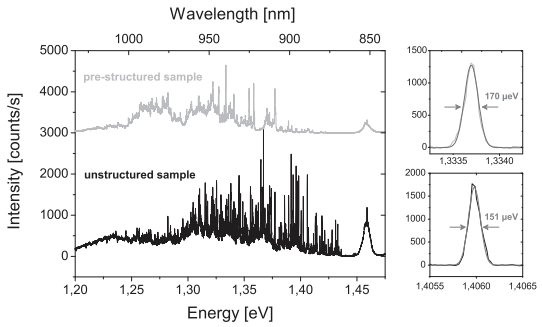


**FIGURE 2.** Large energy range μ-PL measurements of annealed QDs (1.9 ML InAs) on pre-patterned (*top*) and unpatterned (*bottom*) sample with representative QD peaks, respecitvely. The linewidths are comparable, but the intensity of QDs grown on the pre-patterned sample exhibit lower luminescence intensity.

show luminescence of annealed QDs in the pre-patterned area with excitonic linewidths down to 170 μeV.

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