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# Evolution of InAs Quantum Dots during Annealing Process

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InAs quantum dots were grown by molecular beam epitaxy in the Stranski–Krastanow growth mode and annealed under  $N_2$  atmospheres at different temperatures. The evolution of quantum dots with the annealing temperature increasing were slightly different with the results reported in the literature. Atomic force microscopy investigations of quantum dots uncapped layer show a size initial increase followed by a prompt decrease as annealing temperature increases. It was found that the photoluminescence signal on quantum dots capped with GaAs layer was first slightly red-shifted and then blue-shifted with an increase in annealing temperature. The blue-shift can be attributed to In/Ga interdiffusion in annealing process. Red-shift of optical features indicates the change of the quantum dots composition, size, and strain from the barrier.

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## 1. Introduction

The growth of self-assembled InAs/GaAs quantum dot (QD) structures has been studied extensively in recent years, since these structures offer the prospect of temperature independent, ultralow-threshold lasers. The controllable QDs morphology is crucial for implementing low-dimensional semiconductor device applications [1–3]. Interdiffusion of atoms in semiconductor heterostructures has been used for improving the performance of electronic and optoelectronic devices widely, for example, tuning the emission wavelength of semiconductor device accurately [4]. Previously, the post annealing has been an important controlling and

manipulating atom composition technique. Annealing process can lead to important changes of shape, composition, structure and strain of QDs, which further influence the spectrum characteristic of QDs. Although effect of the growth conditions on the formation and properties of the QDs has been investigated widely [5–8], effect of annealing on the mobility process and mechanisms of atoms needs to be further investigated, and surface topography evolution and optical properties of QDs.

In this paper, the self-organized InAs QDs without cap layer prepared on GaAs(100) substrate is analyzed by atomic force microscopy (AFM), and effect of annealing temperature on the evolution of QDs morphology is investigated, and the QDs with cap layer were studied by photoluminescence (PL) under the different annealing conditions. Studies concerning the microstructural and the optical properties of QDs using rapid thermal annealing have been performed to improve the quality of QDs and analysis of the mechanism of QDs evolution. A complete understanding of this evolution process with short annealing period can be used to control the morphology and distribution of QDs.

## 2. Experiments

The InAs QDs are grown on the (100) semi-insulating GaAs wafers in Riber32 compact 21 solid source molecular beam epitaxy (MBE) system equipped with a valved cracker cell for arsenic and reflection high-energy electron diffraction (RHEED) for *in situ* monitoring of the growth process. Growth temperature is calibrated by infrared pyrometer. After desorbing the surface oxide at 580°C, a 100 nm GaAs buffer layer was deposited, then a single layer of QDs was grown by depositing InAs thickness 2.5 ML at 520°C growth temperature. The RHEED pattern shows a transformation from streaky to well developed diffraction spots, typical of a three-dimensional (3D) growth mode. During the growth of the subsequent layers (100 nm GaAs), the RHEED pattern is recovered with streaky pattern and shows a transition from 3D growth mode to two-dimensional (2D) growth mode.

Rapid thermal annealing (RTA) was performed in a SK3-3-10 rapid thermal processor system with a nitrogen ambient and an accurate thermometry measured. The sample was placed between two GaAs wafers without any doping. The annealing temperature is varied from 650 to 800°C with a duration 30 s.

The measurements of the distribution and topographic images of uncapped dots were taken *ex situ* by AFM (SPM Solver P47) with a silicon tip in a working condition of contact mode. PL measurements were carried out directly on this sample with GaAs capping layer. PL was excited using the 532 nm line of a Nd:YAG laser to evaluate the optical properties of the samples at room temperature.

## 3. Results and discussion

The AFM images taken from samples annealed at different temperature of 650°C, 700°C, 750°C, and 800°C are shown in Fig. 1a–d, respectively. We observed

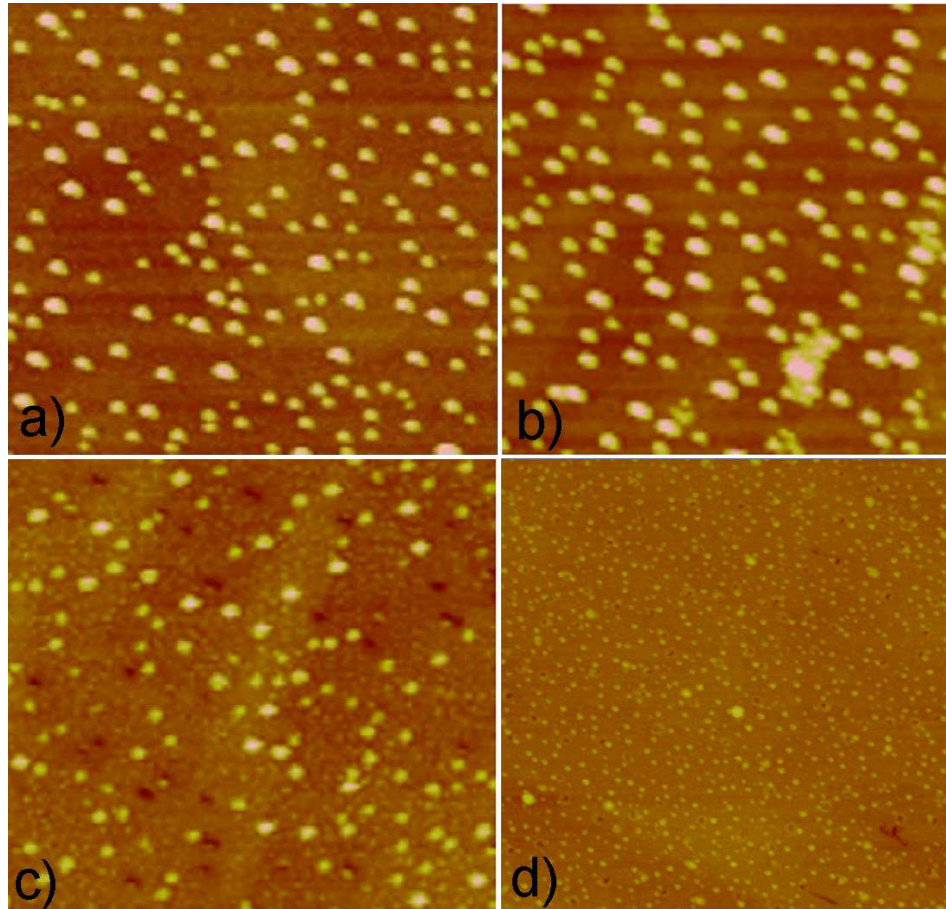


Fig. 1. AFM images ( $1 \mu\text{m} \times 1 \mu\text{m}$ ) of InAs QDs annealed at different temperatures of  $650^\circ\text{C}$  (a),  $700^\circ\text{C}$  (b),  $750^\circ\text{C}$  (c),  $800^\circ\text{C}$  (d), respectively.

that the height of QDs is bimodal distribution in Fig. 1a and b. The height and lateral distribution of QDs in Fig. 1a is mainly concentrated on near 3.2 nm and 5.0 nm, the height and lateral distribution in Fig. 1b on near 3.9 nm and 5.2 nm. By comparing Fig. 1a with 1b, we can see that by increasing the annealing temperature, the density of the small dots decreased, while the density of the large dots increases. The height, lateral size, and the density of QDs decrease rapidly, when the annealing temperature was further increased from  $700^\circ\text{C}$  to  $800^\circ\text{C}$ . According to self-limiting effects of quantum dot, an optimization value at a certain annealing condition exists in strain-induced self-organized growth of QDs [9, 10]. At the low annealing temperature ( $T = 650^\circ\text{C}$ ), the strain energy between QDs edge and wetting layer will increase with the growth of QDs, which will prevent atoms crossing strain energy barrier to arrive as the quantum dots [11]. The uniform size distribution had not been found for the short annealing period

due to the atom short diffusion length. When the annealing temperature rises beyond 700°C, the interdiffusion of In and Ga atoms at the interface between QDs and GaAs matrix can be enhanced, which can result in the strain energy inside the dots significantly reduced. As shown in Fig. 1c, smaller size QDs with lower dot densities are obtained with increasing annealing temperature. It is obvious that the role of atoms migration becomes primary from the wetting layer to QDs surface at lower annealing temperature with the short annealing period ( $t = 30$  s), while the interdiffusion and desorption can be primary at higher annealing temperature. At the same time, the defects can appear in the QDs with large size due to the QDs abnormal regrowing from the fast mass transfer between different size QDs or between QDs and barrier (Fig. 1b).

Figure 2 shows the room temperature PL spectra measured for the samples annealed at different temperature. The low energy peak can be ascribed to the InAs wetting layer. The PL spectrum for the annealed samples shows a dominating peak at near 1210 nm, which is related to interband transitions of InAs QDs. The broadness of PL peaks might origin from the QDs with the various different

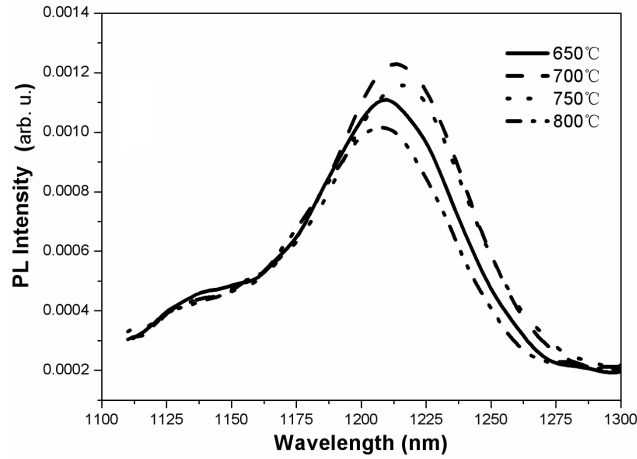


Fig. 2. The PL spectra of the samples with the annealing temperature increase.

sizes. A slight red-shift and blue-shift can be found in the PL peaks at the different annealing process. When the sample was annealed at low temperature, the influence of the annealing process can be weak due to the short diffusion length, which would decrease the effect of composition in QDs on PL peak energy level. It can be confirmed that some of In atom in QDs will diffuse into GaAs cap layer resulting in the strain between QDs and cap layer decreased, which can be the main cause of the red-shift of the QDs sample PL peak [12]. The peak energy and intensity of PL were changed very little during the annealing process. This also can be ascribed to the diffusion of atom between different size QDs or between QDs and barrier inhibited by the strain from the GaAs cap layer. The results

cannot simply be ascribed to one of the above mechanisms. The post annealing evolution process of QDs with cap layer is more complicated than that of QDs without cap layer.

#### 4. Conclusion

The shape of InAs QDs annealed under nitrogen ambient is investigated at various annealing temperatures. Effect of annealing temperature on the evolution of QDs morphology is investigated by combining the atomic force microscopy and PL spectra. The average size of QDs without cap layer increases first and then decreases with annealing temperature increasing from 650°C to 800°C. A luminescence peak shift of the QDs with GaAs cap layer toward higher energies can result from interdiffusion between barrier and QDs, whose evolution process may be influenced by various mechanisms, including the interdiffusion, and the strain between the GaAs cap layer and InAs QDs and so on.

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