UNVEILING THE DIFFERENCES BETWEEN SUBMONOLAYER AND STRANSKI-KRASTANOV QUANTUM DOTS

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Abstract

The submonolayer deposition technique is a method that has recently gained notoriety to grow InAs quantum dots (QDs) due to its capacity to overcome most disadvantages of the traditional Stranski-Krastanov growth mode. Submonolayer quantum dots (SML-QDs) can be grown with a high density (that can reach $10^{12}\ cm^{-2}$) and provide a flexible control of their height without the presence of a wetting layer. These new nanostructures are smaller, their growth is planar and more complex, and usual characterization techniques like scanning electron microscopy (SEM) and atomic-force microscopy (AFM) are only able to provide very limited information. As a consequence, their structural properties are difficult to analyze and are still under debate [1]. For instance, their size, shape, density and composition are not yet well known, but need to be determined and optimized, as they strongly influence the optical and electrical properties of devices. In the present work, we used low-temperature photoluminescence (PL) and rapid thermal annealing (RTA) to shed some light on these features. PL measurements at low temperature as a function of the incident optical power allowed us to check the presence (or not) of multiple energy levels in Stranski-Krastanov quantum dots (SK-QDs) and SML-QDs, which are mainly related to their size and composition. Since the InAs/GaAs system is grown under strain (due to the lattice mismatch between InAs and GaAs), RTA usually provides an out diffusion of the In atoms from the In-rich regions in order to reduce the local strain, a phenomenon whose strength can also be estimated using PL.

Introduction

SK-QDs and SML-QDs are two very different types of quantum dots. SK-QDs can be obtained easily by depositing a thin layer of InAs material on top of a GaAs substrate. Above a thickness of 1.7 monolayers (MLs), the strained InAs layer will relax and form an ensemble of small 3D InAs islands having a base and height around 20 nm and 7 nm, respectively, and surrounded by a 1 ML-thick wetting layer. On the other hand, SML-QDs are obtained by cyclic deposition of a fraction of InAs monolayer (generally 0.3-0.5 ML) followed by a few monolayers of GaAs. Due to the strain field present in the InAs/GaAs system, one expects the small 2D islands nucleated in consecutive InAs layers to stack vertically and form individual structures behaving as quantum dots. SML-QDs are usually 5 nm wide, and their height depends on the number of repetitions of the basic cycle.

Samples

We grew one sample of each type of QDs in order to compare their properties. Sample #1 contains SK-QDs obtained from 2.2 MLs of InAs deposited at 515 °C and covered with 15 nm of GaAs at 515 °C and 85 nm at 570 °C. Sample #2 contains SML-QDs grown at 490 °C repeating 6 times a basic cycle consisting of 0.5 ML of InAs followed by 2.5 MLs of GaAs. The GaAs cap layer consists of 15 nm grown at 490 °C and 85 nm at 570 °C. *Ex-situ* RTA was performed at 900 °C during 30 s with a rising ramp of 80 °C/s.

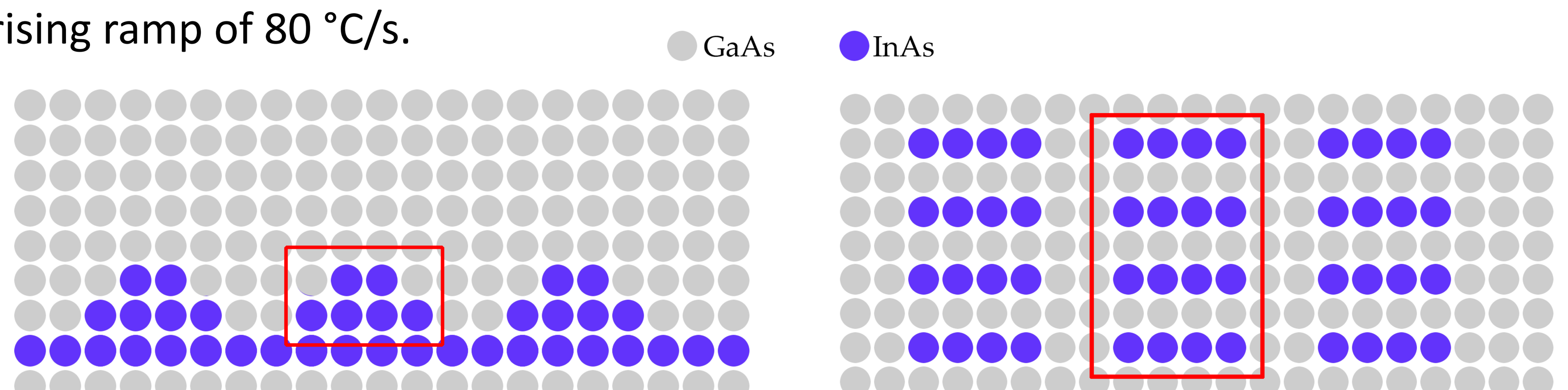

Fig 1: (left) Illustration of SK-QDs (red rectangle). (right) Illustration of SML-QDs (red rectangle).

Results & Discussion

As can be seen in Fig. 2 (left), after RTA, SK-QDs show a strong change in their PL spectrum that is blueshifted, more intense and narrower than that of the as-grown sample. These effects are due to the original high In content of the nanostructures and, consequently, to the large out diffusion of In atoms during RTA, which leads to an increase of their size and a reduction of their average In content [2]. The blueshift is mainly due to the lower In content after RTA, whose influence overcomes that of the larger size. The increase of PL intensity comes from the passivation of part of the defects introduced during the growth of this highly strained system, whereas the narrowing of the spectrum originates from the fact that quantum effects are weaker in larger structures. In figure 2 (right), one can observe that, as the optical power increases, more peaks become visible. The tallest one, around 1075 nm, refers to the ground state and is the only one present at very low optical power (25 nW). The two other ones, around 1024 nm and

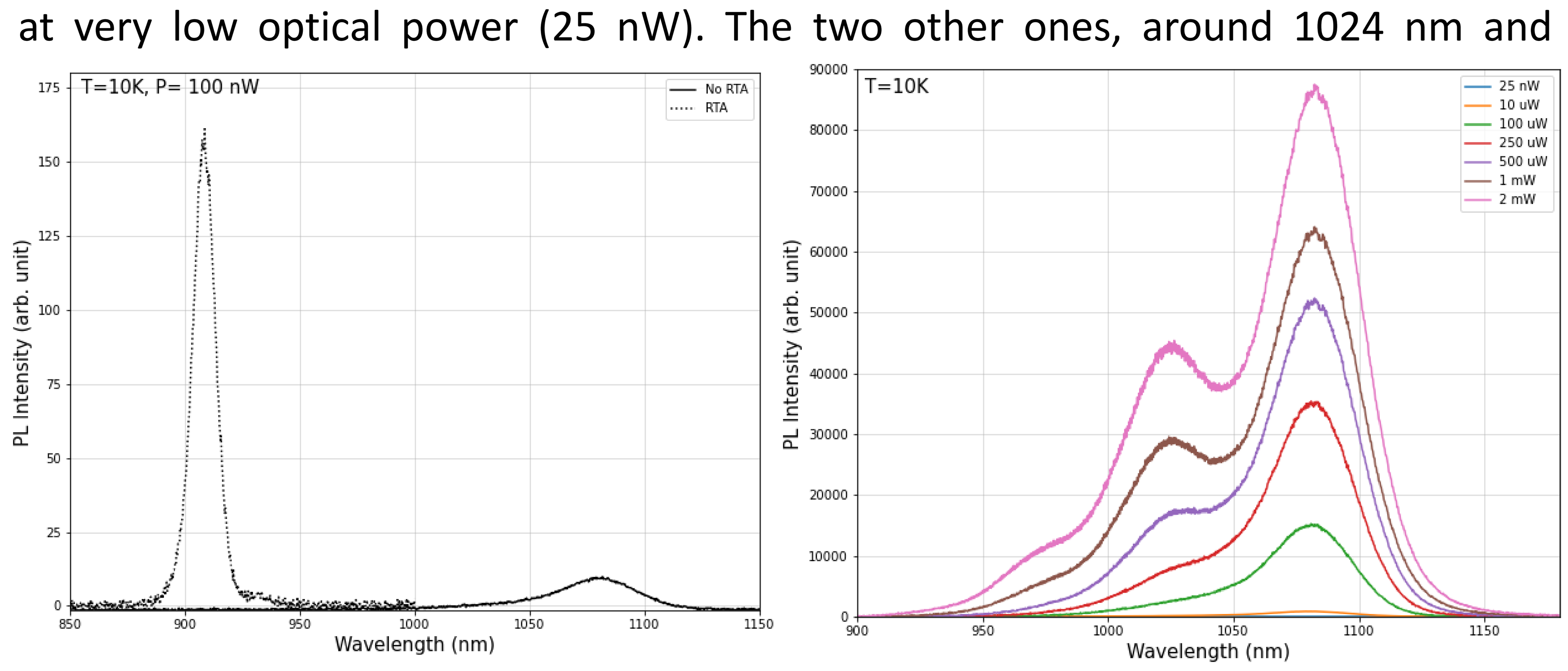

Fig 2: (left) PL spectra of sample #1 (SK-QDs) at 10 K and 100 nW before (dotted line) and after (solid line) RTA. (right) PL spectra at 10 K of sample #1 before RTA as a function the incident optical power ranging from 25 nW to 2 mW.

Results & Discussion

976 nm, are due to excited states that only appear at higher power. The presence of these 3 energy levels is a direct consequence of the large size and high In content of such SK-QDs.

Figure 3 (left) shows that, in the case of SML-QDs, there is almost no change of intensity, width and emission wavelength after RTA, the latter being naturally much lower than for SK-QDs because of the smaller size and lower In content of SML-QDs. In addition, the thin GaAs interlayer and In segregation contribute to lower the In content of the 2D islands and to increase the In content of the surrounding matrix [3,4], contributing to reduce even more the strain in the SML-QDs. Since RTA has almost no effect on such structures, their PL spectra look similar before and after. They have the same intensity because SML-QDs generate less defects due to their planar growth. Figure 3 (right) shows that the PL spectra of SML-QDs have only a single peak around 879 nm, whatever the optical power. This is due to their small size [4] and low In content that allow only a single confined state.

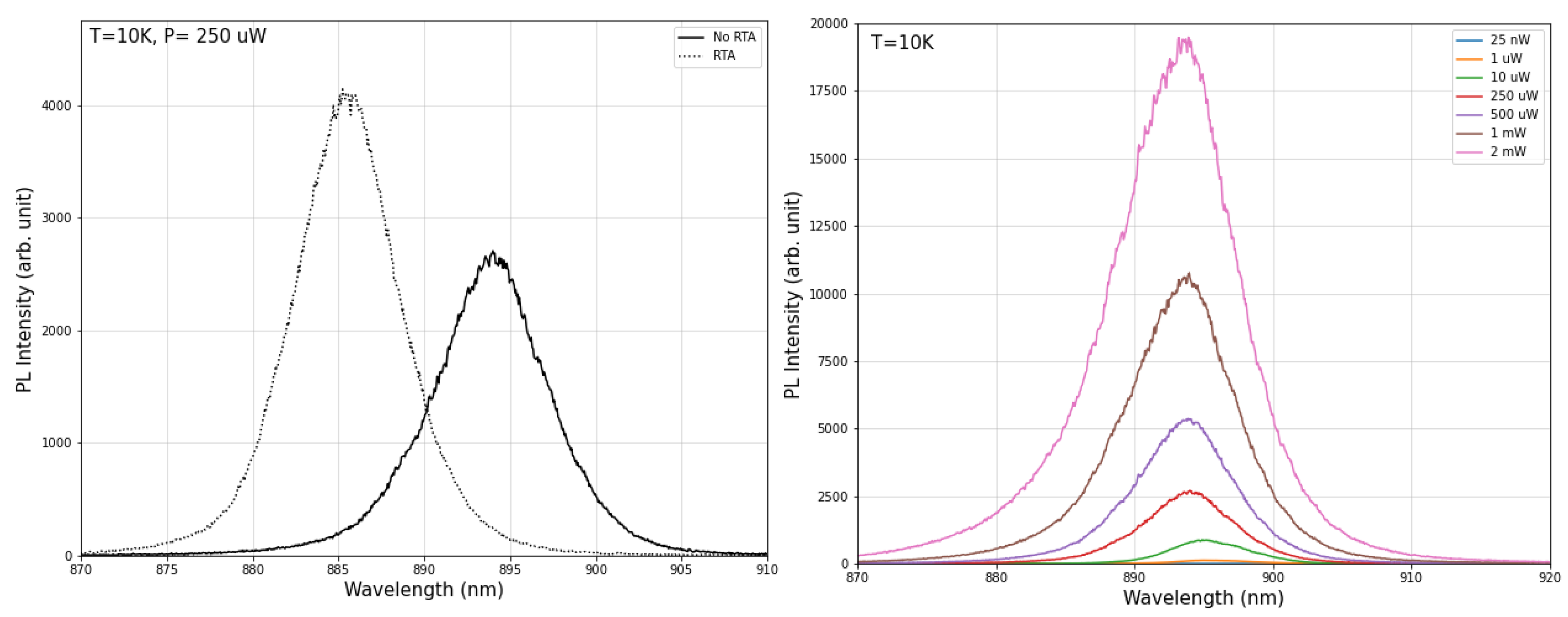

Fig 3: (left) PL spectra at 10K of sample #2 (SML-QDs) before (dotted line) and after RTA (solid line). (right) PL spectra of sample #2 at 10K before RTA for several optical powers.

Conclusions

The PL results showed a single confined state in SML-QDs and at least three in SK-QDs, suggesting that SML-QDs are smaller and In-poorer than SK-QDs, as expected from their structure, growth mode and from the larger influence of In segregation. After performing RTA, the PL spectra of SK-QDs were more intense, blueshifted and narrower than before, confirming that the density of structural defects was reduced, and that many In atoms diffused out of the original SK-QDs. For SML-QDs though, the effect of RTA was marginal, suggesting that they have less structural defects and contain less In atoms. The consequence is a much lower internal strain that might be at the origin of the lack of vertical stacking of the small 2D InAs islands recently observed [4].

References & Acknowledgements

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