Phase Separation Growth of InGaAs Cap Layer on InAs/GaAs Quantum Dots

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Abstract — **The mechanisms responsible for the shift of the photoluminescence spectrum to longer wavelength by depositing an InGaAs cap layer on InAs/GaAs quantum dots are studied in detail. It is demonstrated that the phase separation growth of InAs and GaAs rather than the stress in the InAs quantum dots is the main reason for the wavelength shifts. Also, AFM image of single InAs quantum dot is observed. The reason for the differences between AFM and SEM images is discussed.**

I. INTRODUCTION

Self-assembly InAs quantum dots (QDs) grown on GaAs substrate using Stranski-Krastanov (SK) growth mode by molecular beam epitaxy (MBE) have attracted wide attention and been applied to optoelectronic devices, i.e, 1.3 _m wavelength laser diode [1-5], quantum dot infrared photodetector (QDIP) [6-10]. But there is adversity that the vertical dimension of InAs/GaAs QDs can't be grown higher than a certain limit, i.e., ~4 ML InAs, without degrading the dot quality. The photoluminescence (PL) peak position is then limited to around 1.1~1.2 _m and far away from 1.3 _m. One of the methods to push it to longer wavelength is to grow a InGaAs cap layer on InAs/GaAs QDs before depositing GaAs barrier layer [11-12].

Two possible mechanisms to explain the phenomenon were proposed in the past: (1) InGaAs cap layer serves as a strain-reducing layer [13], (2) phase separation growth of InGaAs occurs on InAs QDs [14]. In this paper, evidences are presented that favor the latter explaination.

II. GROWTH CONDITIONS AND EXPERIMENTAL SETUP

The InAs/GaAs samples were grown by solid-source molecular beam epitaxy (MBE) on semi-insulated (SI) GaAs (100) substrates using a VG Semicon V80 MBE machine. To examine the phenomenon of phase separation, four samples (R1869, R1870, R1871, and R1872) were grown. First, for sample R1869 (R1871), a 0.5 _m GaAs buffer layer was grown at 585 _, followed by the deposition of 3 (5) monolayer (ML) InAs QDs at 510 _ under Arsnic shutter-closed condition. After the growth of InAs QDs, all shutters were closed for 5 sec to allow atoms to migrate on the surface. Then, 50 nm GaAs spacer was grown. Finally, the second 3 (5) ML InAs QD was deposited. The purpose of the upper InAs QDs layer was grown for atomic force microscopy (AFM) or scanning electron microscopy (SEM) measurements, and the lower InAs QDs were for PL measurements. The structure of Sample R1870 (R1872) is similar to that of sample R1869 (R1871) described above, but an additional 6 ML $In_{0.33}Ga_{0.67}As$ (4 ML $In_{0.5}Ga_{0.5}As$) cap layer is deposited after the growth of 3 (5) ML InAs QD and 5 sec migration for both upper and lower InAs QD layers.

For AFM measurements of single InAs QD, the sample was placed in the vacuum chamber on the optical table to prevent the influences of air and vibrations. For the 1_m X 1_m AFM images, the samples were measured with another machine in air.

For PL measurements, the samples were mounted in a closed-cycle He cryostat which provides lowest temperature of 11 K. PL was excited by an Ar^+ laser with a 514.5 nm wavelength and an excitation density of ~100 W cm^{-2}. Finally, PL through a monochromator was detected by a InGaAs detector whose detection range is below 1.7 _m.

III. RESULTS AND DISCUSSION

Fig. 1 shows the images of single InAs QD. The height of the InAs QD is about 6~7 nm, and the lateral size is around 40 nm. It can be seen that the QD is not symmetric both in the orientation of $[01\bar{1}]$ and $[011]$. There are facets with different orientations on the QD, which tells that the QD cannot be regarded as a symmetric dome. Along the direction of $[01\bar{1}]$, the numbers of the facets are more than that of $[011]$. During the theoretical calculations with more accuracy, the quantum confinement of different facets must be considered.

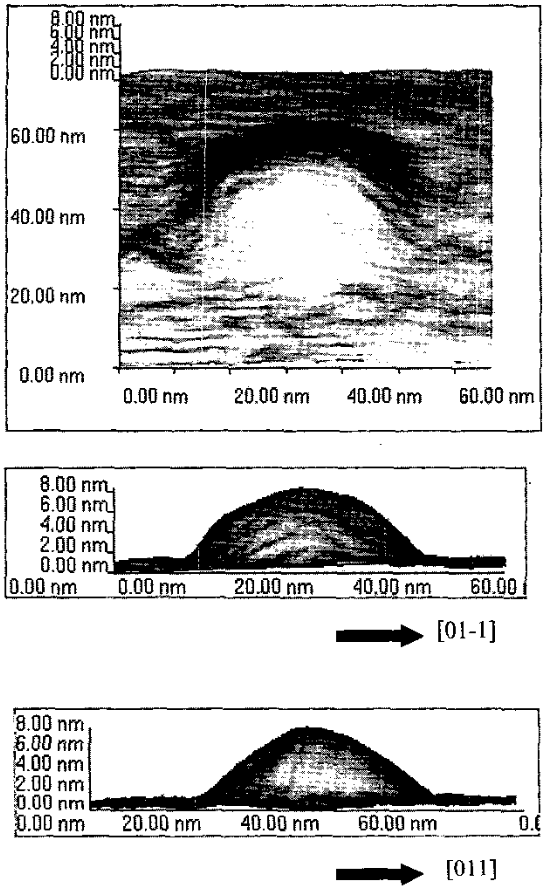
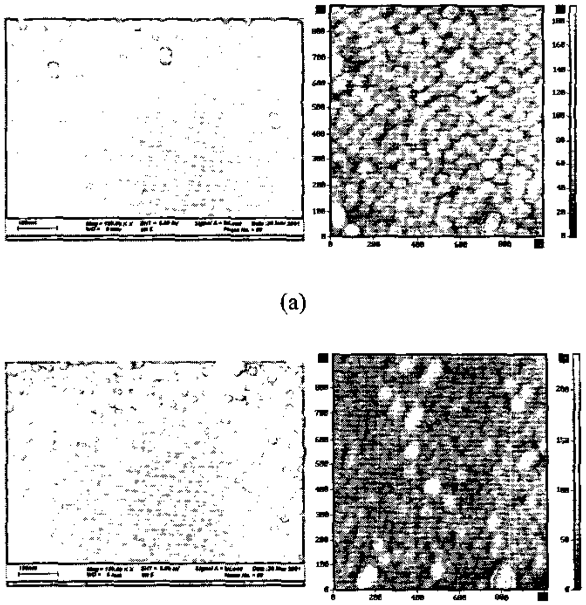


Fig. 1. AFM images of single InAs QD with different orientations measured in the vaccum chamber.

Fig. 2 shows the AFM (right) and SEM (left) images of sample (a) R1869, (b) R1870, (c) R1871, and (d) R1872 which correspond to 3 ML InAs QDs, 3 ML InAs QDs capped by 6 ML $\mathrm{In_{0.33}Ga_{0.67}As}$, 5 ML InAs QDs, and 5 ML InAs QDs capped by 4 ML $\mathrm{In_{0.5}Ga_{0.5}As}$, respectively. The densities of these four samples measured by SEM are 6.7 _10^{10}, 1 _10^{11}, 1.3 _10^{10}, and 1.3 _10^{10} cm^{-2}, respectively. From the AFM images, the densities of these four samples are 4 _10^{10}, 4 _10^{10}, 1 _10^{10}, and 1 _10^{10} cm^{-2}, respectively. The average heights (lateral sizes) are 6~8 (40~60), 3~6 (30~60), 5~25 (40~150), and 5~20 (30~150) nm, respectively.

The SEM and AFM images show different results about the same sample. In the Fig. 2(a) and (b), it is clearly observed that the lateral size is enlarged in the AFM measurements compared to the SEM images. The densities are 70% to 250% higher for SEM results. But, in the Fig. 2(c) and (d), the distribution of the dot size is roughly the same for both SEM and AFM measurements. The densities of dots are 30% higher for SEM results. This phenomenon can be explained as that the AFM tip will not touch the wetting layer region when two QDs are closely spaced. Thus, the tip is on the higher position through few QDs that results in the larger measured dot size and fewer measured dot density. The larger the density is, the shorter the distance between QDs is. And the more errors the AFM results are. Since the material wavelength of high-energy electron (5 keV) used in the SEM is only 0.25 nm, the correct data should be obtained from the measurements of SEM.

Compare 3 ML InAs QDs with 3 ML InAs QDs covered by 6 ML $\mathrm{In_{0.33}Ga_{0.67}As}$, the dot density increases almost by 50%. Also, the densities of sample R1871 and R1872 are the same. If the InGaAs caplayer covers QDs and wetting layer region uniformly, some smaller QDs might be totally covered, thus the dot density will decrease. This implies that the InGaAs tends to phase separate into GaAs and InAs. GaAs covers the wetting layer region because the lattice constant of wetting layer is close to GaAs. InAs covers not only the original InAs QDs that will lead to an increase of vertical size of InAs QDs more than lateral dimension and also on the wetting layer between dots.



(a)

(b)