Brief communication

Growth of InGaAs-capped InAs quantum dots characterized by Atomic Force Microscope and Scanning Electron Microscope

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Abstract

Atomic force microscopy (AFM) is typically used to measure the quantum dot shape and density formed by lattice mismatched epitaxial growth such as InAs on GaAs. However, AFM images are distorted when two dots are situated in juxtaposition with a distance less than the AFM tip width. Scanning electron Microscope (SEM) is much better in distinguishing the dot density but not the dot height. Through these measurements of the growth of $\text{In}_x\text{Ga}_{1-x}\text{As}$ cap layer on InAs quantum dots, it was observed that the InGaAs layer neither covered the InAs quantum dots and wetting layer uniformly nor 100% phase separates into InAs and GaAs grown on InAs quantum dots and wetting layer, respectively.

Self-assembled InAs quantum dots (QDs) on GaAs substrate prepared by molecular beam epitaxy (MBE) have attracted much attention in recent years (Chang et al., 1993; Chang et al., 1996; Schmidt et al., 1998; Alessi et al., 1999; Chu et al., 1999). Due to its long capture and relaxation times (Schmidt et al., 1997), the QD structure is suitable for the optoelectronic applications of the infrared photodetector (Tang et al., 2001; Lin et al., 2001) and lasers (Xie et al., 1996; Chang et al., 2003). But there is adversity that the vertical dimension of InAs/GaAs QDs cannot be grown higher than a certain limit, i.e., ~ 5 monolayer (ML) InAs, without degrading the dot quality. The photoluminescence (PL) peak position is then limited to around $1.1\ \mu\text{m}$ and far away from $1.3\ \mu\text{m}$. One of the methods to extend it to longer wavelength, i.e., $1.3\ \mu\text{m}$, is to grow a InGaAs cap layer on InAs/GaAs QDs before depositing GaAs barrier layer (Ustinov et al., 1999). One possible mechanism to explain the phenomenon is attributed to the phase separation growth of InGaAs on

InAs QDs (Maximov et al. 2000; Chen et al., 2002). That is, InGaAs is separated into InAs and GaAs; InAs is grown on top of the InAs QDs, whereas GaAs is grown in the valley between InAs QDs. For most studies of the phase separation, the thickness of the $\text{In}_x\text{Ga}_{1-x}\text{As}$ layer was several nanometers and then covered by a thick GaAs spacer. Also, the Indium composition is low. To clarify the detailed growth mechanism of InGaAs on InAs QDs, a growth of thin and high-Indium-composition $\text{In}_x\text{Ga}_{1-x}\text{As}$ layer is needed and then characterized by scanning electron microscopy (SEM) and atomic force microscopy (AFM).

The InAs/GaAs samples were grown by solid-source molecular beam epitaxy (MBE) on semi-insulating GaAs (100) substrates using a VG Semicon V80 MBE. Four samples (R1869, R1870, R1871, and R1872) were grown. First, for sample R1869 (R1871), a $0.5\ \mu\text{m}$ GaAs buffer layer was grown at 580°C on semi-insulating GaAs substrate, followed by the deposition of 3 (5) ML InAs QDs at 510°C under Arsenic shutter-closed

Figure 1. SEM images of (a) 3 ML InAs QDs, (b) 3 ML InAs QDs capped by 6 ML $\text{In}_{0.33}\text{Ga}_{0.67}\text{As}$, (c) 5 ML InAs QDs and (d) 5 ML InAs QDs capped by 4 ML $\text{In}_{0.5}\text{Ga}_{0.5}\text{As}$.

condition. After the growth of InAs QD, 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 layer was deposited. The purpose of the upper InAs QDs layer was for density measurements by AFM or SEM. The lower InAs QDs were for photoluminescence (PL) measurements. The structure of sample R1870 (R1872) is similar to that of sample R1869 (R1871) described above, but an additional 6 ML $\text{In}_{0.33}\text{Ga}_{0.67}\text{As}$ (4 ML $\text{In}_{0.5}\text{Ga}_{0.5}\text{As}$) cap layer was deposited after the growth of 3 (5) ML InAs QD and 5 sec migration for both upper and lower InAs QD layers. The SEM images were measured by a LEO 1530 field-emission SEM with a 5 kV supply to the electron beam, and the AFM images were obtained from a NT-MDT Solver P47 AFM operated in the atmosphere with tapping mode.

Figures 1 and 2 show the SEM and AFM images of samples R1869, R1870, R1871, and R1872 which correspond to 3 ML InAs QDs, 3 ML InAs QDs capped by 6 ML $\text{In}_{0.33}\text{Ga}_{0.67}\text{As}$, 5 ML InAs QDs, and 5 ML InAs QDs capped by 4 ML $\text{In}_{0.5}\text{Ga}_{0.5}\text{As}$, respectively. The densities of these four samples measured by SEM are 6.7×10^{10} , 1×10^{11} , 1.3×10^{10} , and $1.3 \times 10^{10} \text{ cm}^{-2}$, respec-

tively. From the AFM images, the densities of these four samples are 4×10^{10} , 4×10^{10} , 1×10^{10} , and $1 \times 10^{10} \text{ cm}^{-2}$, respectively. The dot heights are among 6–8, 3–6, 5–25, and 5–20 nm, respectively. The average lateral diameters are 40–60, 30–60, 40–150, and 30–150 nm, respectively.

The SEM and AFM images exhibited different dot densities on the same sample. In Figures 1(a), 1(b), 2(a) and 2(b), it was clearly observed that the lateral size was enlarged but the dot densities were smaller in the AFM measurements compared to the SEM images. The dot densities measured by SEM are 67.5–150% higher. But in Figures 1(c), 1(d), 2(c), and 2(d), the distribution of the dot size was roughly the same for both SEM and AFM measurements. The dot densities measured by SEM are 30% higher. This phenomenon can be explained by the fact that the AFM tip has certain size as shown in Figure 3, it will not touch the wetting layer region when two QDs are closely spaced. This results in a larger measured dot size and a smaller dot density. The larger the dot density is, the shorter the distance between QDs is, the more errors the AFM measurement results. In average, the AFM tip miscalculates 2.5 QDs into one QD under high dot density of $1 \times 10^{11} \text{ cm}^{-2}$. At lower dot density of $1.3 \times 10^{10} \text{ cm}^{-2}$, only 1.3 QDs will be counted as one

Figure 2. AFM image of (a) 3 ML InAs QDs, (b) 3 ML InAs QDs capped by 6 ML $\text{In}_{0.33}\text{Ga}_{0.67}\text{As}$, (c) 5 ML InAs QDs and (d) 5 ML InAs QDs capped by 4 ML $\text{In}_{0.5}\text{Ga}_{0.5}\text{As}$.

QD by AFM. The degree of miscalculation depends on the size of AFM tips, their radius is about 10–15 nm. The densities of InAs quantum dots on GaAs grown by MBE are around the order of $10^{10} - 10^{11} \text{ cm}^{-2}$. In other words, the average center-to-center distance between QDs is about 30–100 nm. Consider the extreme case, i.e., dot density of 10^{11} cm^{-2} , the average distance between the boundaries of 20 nm QDs may be less than the tip size. The AFM tip is hard to touch the wetting layer and the measured dot height might be incorrect. But the real QDs distribution is random, the tip still has the chance to touch upon some wetting layer region. In such a situation, the counting of dot height needs to be very careful to prevent miscalculations. When depositing more InAs on GaAs, the lateral size of InAs QDs become larger, the dot density becomes smaller, so the enlargement effect by AFM becomes less. Since the material wavelength of high-energy electron (5 KeV) used in the SEM is only 0.25 nm, it gives much accurate results. But AFM has an advantage that it can tell the height of QD which cannot be derived from SEM measurements, even with a tilting technique.

Comparing 3 ML InAs QDs (Figure 1(a)) with 3 ML InAs QDs covered by 6 ML $\text{In}_{0.33}\text{Ga}_{0.67}\text{As}$ (Figure 1(b)), the dot density increases almost by 50%. Such a huge increase was not due to the non-uniformity of QD samples because we measured several areas in our samples and this increase was for sure. This phenomenon was also observed by other researchers (Yeh et al., 2001, Chang et al., 2003). If the InGaAs caplayer covers QDs and wetting layer region uniformly, some smaller QDs might be totally covered and disappear, thus the dot density would decrease or stay the same. This 50% increase 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 the original InAs QDs that will lead to an increase of vertical size of InAs QDs more than its lateral dimension. This also explains why the dot height and lateral dimensions of 3 ML InAs QDs covered by 6 ML $\text{In}_{0.33}\text{Ga}_{0.67}\text{As}$ are smaller than those of 3 ML InAs QDs. Moreover, the phase separation of InGaAs into InAs and GaAs is NOT 100%. The 100% phase separation will result in the same dot

Figure 3. Schematic diagram of the AFM tip scanning on the two closely spaced QDs.

density after being capped by a 6-ML-thick $\text{In}_{0.33}\text{Ga}_{0.67}\text{As}$. Thus, it comes to a conclusion that some phase-separated Indium atoms migrate in the wetting layer region and finally form new QDs. Not all the Indium atoms are phase-separated and move to the original InAs QDs. This observation of the increase of dot density is also agreed with the increase of PL intensity which is not shown here. The dot densities of 5 ML InAs QD (Figures 1(c) and 2(c)) and 5 ML InAs covered by 4 ML $\text{In}_{0.5}\text{Ga}_{0.5}\text{As}$ (Figures 1(d) and 2(d)) are the same as measured by both SEM and AFM. This is because the dot sizes of 5 ML InAs QDs are too large, many of them contact each other, the effect of phase separation is diminished.

To summarize, the AFM and SEM images of surface uncapped and InGaAs-capped InAs QDs

are studied and compared. The SEM measurements give us the real lateral dimension and dot density due to its shorter material wavelength of electron beam. But its adversity is that SEM cannot measure the dot height which can only be done by AFM. Another discovery from the images is that the increase of dot density after capping the InGaAs layer. Our explanation is the Indium and Gallium atoms do not 100% phase separate. Some Indium atoms landing on the wetting layer region form new QDs.

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