MBE Growth and Characterization of InAs Quantum Dots on Strained $GaAs_{1-x}Sb_x$ Buffer Layer For Application in High Efficiency Solar Cells

K.-Y. Ban,[1] G. M. Liu,[2] S. P. Bremner,[1] R. Opila,[2] C. B. Honsberg[1]
1. Department of Electrical and Computer Engineering
2. Department of Materials Sciences and Engineering
University of Delaware, Newark, DE 19716, USA

ABSTRACT

We have investigated InAs quantum dots (QDs) on strained GaAsSb barrier layer in different Sb compositions. Use of Sb incorporated barrier layer for QD growth gives better quantum dot properties such as density, lateral size and uniformity. **G**rowing $GaAs_{0.89}Sb_{0.11}$ results in a doubling of QD density and a 50% decrease in size of the QDs compared to growth on GaAs. Also, size distribution of QDs became narrower after incorporating Sb. These are described based on atomic force microscope (AFM) and its analysis data. X-ray Diffraction (XRD) shows Sb composition as a function of Sb/As flux ratio. On the basis of Reflective High Energy Electron Diffraction (RHEED) oscillation surface morphology of $GaAs_{1-x}Sb_x$ is described as well.

INTRODUCTION

Quantum dots have been of great importance for optoelectronic applications due to the nature of 3 dimensional confinement and delta-like function of density of states. The InAs / GaAs quantum dots (QDs) structure has attracted considerable interest because of the potential application for novel concept solar cells using three level transitions [1]. Self-assembled growth, so called Stranski-Krastanov (S-K) growth mode, is the most widely used method to grow quantum dots. It has been difficult to control the ordered array of QDs using S-K growth mode. Optimization of a single QD layer is necessary to improve the external quantum efficiency of the structure. It is necessary to know how to tune the QD properties for specific device requirement. Quantum dot properties depend upon many factors such as surface energy, substrate temperature, flux ratio, and growth rate. Recently, highly dense and uniform InAs QDs have been demonstrated on GaAs layers by incorporating Sb at the buffer layer surface [2]. We will report self-formation of high density uniform InAs QDs by using a strained $GaAs_{1-x}Sb_x$ (x=0, 0.07 and 0.11)/ GaAs (001) buffer layer. We have experimentally examined the effect of surface strain on the properties of self-assembled InAs QDs. To avoid excess Sb surface segregation in the buffer layer that forms non-radiative centers, a 5 monolayers thick GaAs layer was prepared on the top of GaAsSb buffer layer before growing InAs QDs. The growth process of strained GaAsSb thin films was monitored *in-situ* and controlled using RHEED. X-ray diffraction (XRD) and atomic force microscope (AFM) were performed to analyze Sb composition and surface shape of InAs QDs, respectively.

EXPERIMENTAL PROCEDURE

Quantum dot structure was grown by a solid source Gen III MBE system. *In-situ* RHEED was used to monitor growth rate and surface conditions during the whole growth process. The semi-insulating GaAs (001) substrate was heated to 585 ^oC to desorb native oxide under As_2 overpressure of $5x10^{-6}$ torr and then heated to 620 ^oC for 10 minutes for completion of de-oxidation. After de-oxidation, a 200 nm thick GaAs buffer was grown on GaAs (001) substrate at 580 ^oC. $GaAs_{1-x}Sb_x$ (5 nm) buffer layer was psedomophically grown on GaAs (001) substrate at 500 ^oC which was followed by GaAs (5MLs) capping layer. InAs (2MLs) was also grown on GaAs (5 ML) / $GaAs_{1-x}Sb_x$ (5 nm) / GaAs (200 nm). Monitoring RHEED pattern transformation from streaky to chevron shape was observed to ensure QD formation. We measured the dot size, surface density and distribution by tapping mode AFM. In addition high-resolution double-axis X-ray diffraction (XRD) was also performed to check composition of the grown layers.

RESULTS

The growth details of strained $GaAs_{1-x}Sb_x$ layers on GaAs substrate were studied by RHEED beam intensity oscillation as a function of substrate temperature and Sb/As flux ratio, to reveal some interesting features which may be important in understanding the growth mechanisms in lattice mismatch system of $GaAs_{1-x}Sb_x$ on GaAs. Figure 1 shows a typical RHEED beam intensity oscillation of $GaAs_{1-x}Sb_x$ grown on GaAs as a function of the substrate temperature at Sb/As flux ratio of 0.023 and 0.036 for comparison.

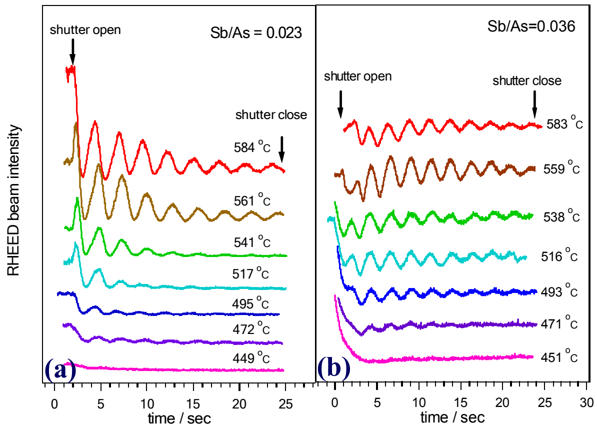


Fig.1 RHEED oscillation of GaAs1-xSbx grown on GaAs substrate as a function of the substrate temperature at Sb/As flux ratio of (a)0.023 and (b)0.036

The growth of $GaAs_{1-x}Sb_x$ on GaAs shows damped oscillation over the temperature range from 475 °C to 580 °C, which is strongly dependent on the substrate temperature and Sb/As flux ratio. The waveform of the RHEED oscillation reflects the growth kinetics and mechanism, such as growing islands, and changes in step and terrace width distributions, which are closely related to lattice mismatch induced strain at the growth front [3]. If comparing Figures 1a and 1b it is revealed that the higher Sb/As flux, the more strain on $GaAs_{1-x}Sb_x$ which causes surface roughness. It is evident that damping down and asymmetry of RHEED **are severer** at higher Sb/As flux ratio. Consequently, this roughness can introduce preferential sites for QD formation.

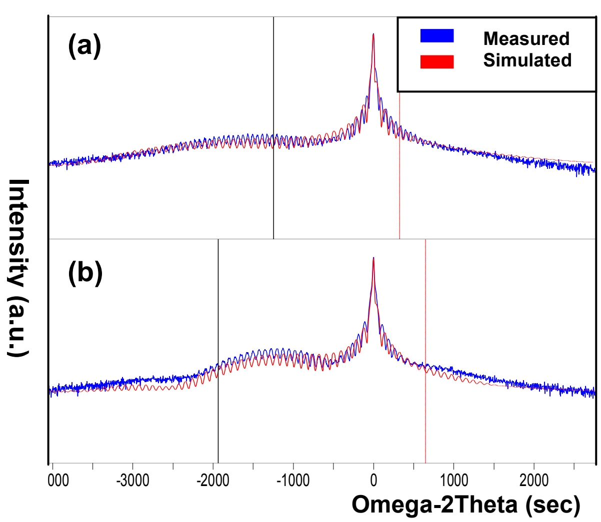
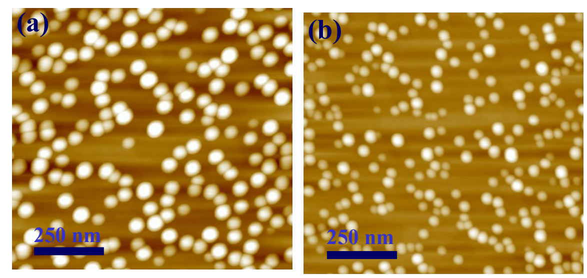


Figure 2 X-ray diffractions for Sb/As flux ratio of (a) 0.023 and (b) 0.036

Double axis X-ray diffraction is performed to check Sb composition in barrier layer. We also simulated a plotting with fitting model from X'Pert Epitaxy program. There are two peaks in these XRD spectra. One sharp and strong peak is from GaAs substrate while $GaAs_{1-x}Sb_x$ corresponds to shallow and broad one on left side. As a result simulation results indicate that Sb/As flux ratio of 0.023 and 0.036 correspond to 7 % and 11 % of Sb, respectively (Fig. 2).



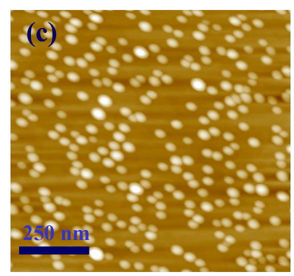


Fig. 3. AFM images of InAs QDs on the GaAs (5 ML) / $GaAs_{1-x}Sb_x$ (5nm) buffer layers with various Sb compositions at (a) 0%, (b) 7% and (c) 11% respectively

It has been reported that the elastic strain field of the substrate largely affects nucleation and diffusion of adatoms [4] which means that the strain field plays a key role in determining the final morphology of lattice mismatched systems. In the case of the GaAs (5 ML) / $GaAs_{1-x}Sb_x$ (5 nm) / GaAs (200 nm) buffer layer, the top 5 ML GaAs layer also includes many Sb atoms since the surface exchange reaction occurs between Sb and As atoms and also diffusion of the Sb atoms occurs during MBE growth [5]. With increase of Sb composition in $GaAs_{1-x}Sb_x$ interlayer, surface morphology from Sb incorporation in barrier layer provides preferential site for QDs. Fig. 3 shows AFM images of the InAs QDs grown on the GaAs (5 ML) / $GaAs_{1-x}Sb_x$ (5nm) buffer layers with various Sb compositions (0, 7, and 11%). It is obviously seen that not only does dot size decrease but uniformity and dot density also get improved by increase of Sb composition.

Fig. 4 (a) and (b) are analysis data based on AFM images. They show QD density as a function of Sb composition and histograms of dot lateral size (island) with a Gaussian curve, respectively. In Fig. 4(a), it is shown that QD density almost linearly increases as incorporating more Sb. In addition there are sample A and B in Fig. 4(b) corresponding to 0 and 11% of Sb, respectively. Peak position for average lateral size for sample A is around 60nm diameter. However, if incorporating 11% Sb there is peak shift of 30nm to smaller size. Also, full width at half maximum (FWHM), QD homogeneity, of sample B is 11.5nm while that of sample A is much broader (28.5nm). As shown above, it is obviously revealed that Sb incorporation plays an important role to reduce lateral size and improve uniformity simultaneously.

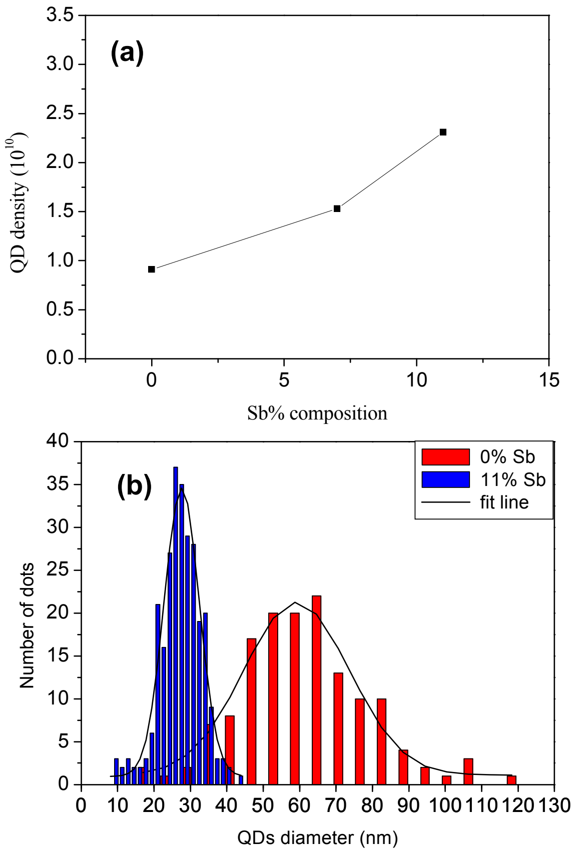


Fig. 5. (a) InAs QD density as a function of Sb composition (0, 7 and 11%) (b) Histograms of dot lateral size (island) with a Gaussian curve for sample A (0% Sb) and sample B (11% Sb),

CONCLUSIONS

RHEED oscillation study revealed that higher Sb composition has rough surface which may provide preferential sites for QDs. Sb composition at Sb/As flux ratio of 0.023 and 0.036 was checked by XRD. We did see the fact that higher dot density and smaller dot size with narrower size distribution were observed as increasing Sb composition up to 11% by AFM images. This result suggests strain field by Sb incorporation plays a critical role in the control of InAs QDs formation and ordering.

REFERENCES

[1] A. Marti, N. Lopez, E. Antolin, E. Canovas, A. Luque, C.R. Stanley, C.D. Farmer, and P. Diaz, *Appl. Phys. Lett.,* 90 233510 (2007)
[2] K. Yamaguchi, and T. Kanto, *J. Cryst. Growth*, 275, e2269̃ (2005)
[3] B.F. Lewis, T.C. Lee, F.J. Grunthaner, A. Madhukar, R. Fernandez, and J. Maserjian, *J. Vac. Sci. Technol. B*, 2 419̃424, (1984)
[4] F. Patella, F. Arciprete, E. Placidi, S. Nufris, M. Fanfoni, A. Sgarlata, D. Schiumarini, and A. Balzarotti, *Appl. Phys. Lett.,* 81 2270̃2272 (2002)
[5] T. Nakai, and K. Yamaguchi, *Jpn. J. Appl. Phys.*, Part 1 44 3803 (2005)