Strain compensation effect on stacked InAs self-assembled quantum dots embedded in GaNAs layers

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ABSTRACT

We have studied the effect of strain compensation in multiple stacking of InAs self-assembled quantum dots on GaAs (001) substrates grown by atomic hydrogen assisted RF-molecular beam epitaxy. The GaN_xAs_{1-x} material was used as a strain compensating spacer layer. We confirmed by high resolution x-ray diffraction measurements that a 40 nm $GaN_{0.005}As_{0.995}$ strain compensating layer provides compressive strain to compensate for tensile strain induced by 2.0 ML InAs quantum dots. Consequently, we achieved a multiple stack of InAs QDs up to 30 layers without formation of coalesced QDs, and the density of QDs exceeded $3\times10^{12}cm^{-2}$.

INTRODUCTION

Recently, studies on the self-assembled quantum dots (QDs) have attracted a strong attention because QDs have the potential to improve the properties of optoelectronic devices such as QD lasers [1], semiconductor optical amplifiers [2], and next generation photovoltaic device [3]. In order to achieve these improvements, the fabrication technique to obtain sufficient densities in active region is required. It is well known that stacking is a powerful way of increasing the density. However, too many layers of stacking lead to degradation of quality because of accumulation of internal strain with an increase number of QDs layers.

In InAs QDs/GaAs systems, to overcome these problems, several novel techniques such as In-flush methods [4] and columnar QD structures [5] have been reported. On the other, the strain compensation technique has been proposed by using InGaP [6] or GaNAs [7] as strain compensating spacer layers (SCL). However, this approach has been carried out to stack only less than 10 QD layers and a further increase of QD stacking is required to realize a more useful QD superlattice structure. In this letter, we propose a novel fabrication procedure in order to multiply the number of InAs QDs on GaAs (001) substrates without degradation of size uniformity, by strain compensation scheme using GaNAs as an embedding layer.

EXPERIMENTAL DETAILS

For fabrication of multiple stacked self-assembled InAs QDs on GaAs (001) substrates, we employed atomic hydrogen-assisted molecular beam epitaxy (H-MBE) [7,8] with a radio frequency (RF) nitrogen plasma source. After native oxide desorption at 500°C by irradiating atomic hydrogen, a 250 nm-thick GaAs buffer layer was grown at a growth rate of 1μm/h at 580°C. Then, 2.0 monolayers (MLs) of InAs QD layer and 40 nm-thick GaN_xAs_{1-x} SCL were consecutively grown in stack from 10 up to 30 multiple cycles at 480°C. The growth rate of QD and spacer layers were 0.1 and 1.2 μm/h, respectively. In a separate experiment, we determined that for the first QD layer, the average QD size was 23.8 nm in diameter, 3.1 nm in height, 13.4 % in diameter dispersion, and 1.0×10^{11} /cm^2 in area density, respectively. The RF power was fixed at 175 W in order to obtain 0.5 % N composition in GaNAs spacer layers. The arsenic (As_4), hydrogen, and nitrogen back pressure was set to 1.2×10^{-6} Torr, 5.0×10^{-6} Torr, and 1.4×10^{-4} Torr, respectively.

Figure 1 shows the schematic concept of strain compensation technique in the growth of stacked QD structure. In In(Ga)As QDs/GaAs system, the tensile strain with respect to GaAs substrate generated by growth of QD layer can not be completely compensated after the growth of GaAs spacer layer, since the lattice constant of spacer layer is the same as substrate. This residual strain affects the formation of QDs in the next stacked layer [9,10]. On the other, in In(Ga)As QDs/GaNAs system, the lattice constant of GaNAs can be controlled to be smaller than GaAs. Therefore, we can satisfy the strain compensation by capping InAs QDs with a GaNAs layer of suitable lattice constant.

The growth process and surface morphology were studied in situ by reflection high-energy electron diffraction (RHEED), and ex situ by atomic force microscope (AFM) and scanning transmission electron microscope (STEM). The strained state of superlattice structure in each sample was determined by high resolution x-ray diffraction (HR-XRD).

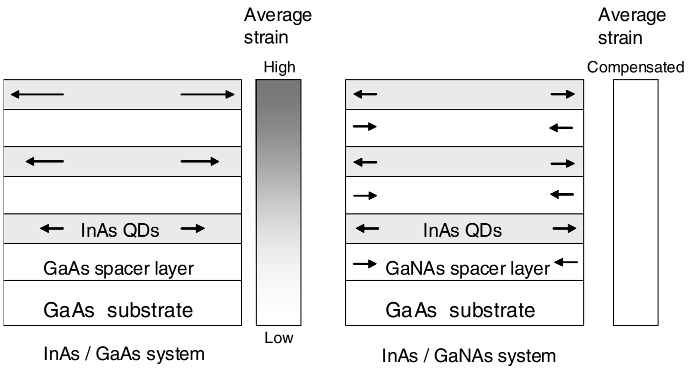


Figure 1. Schematic concept of strain compensation technique in stacking of self- assembled QDs.

DISCUSSION

First, we measured symmetric scans around (004) reflection in ω-2θ geometry by HR-XRD in order to investigate the strain compensation effect of GaN_xAs_{1-x} SCLs. The XRD spectra around (004) reflection in ω-2θ geometry for 30 layers of stacked InAs QDs samples with (a) GaAs spacer layer, and (b) $GaN_{0.005}As_{0.995}$ SCLs are shown in Figure 1. Several satellite peaks originating from superlattice structure can be observed and these spectra are characterized by the zeroth order peak located at 32.9544 ° for sample (a), and 33.03725 ° for sample (b), respectively. The zeroth order peak for sample (a) is located at a lower angle than GaAs peak. This indicates that the tensile strain generated from QD layer is still remaining. Most importantly, we note that zeroth order peak for sample (b) shows a near perfect match with GaAs peak. In this case, the averaged lattice constant of 2.0 ML-InAs QDs/40 nm-$GaN_{0.005}As$ is almost matched to GaAs, i.e. the tensile strain accumulated around each QDs layer has been successfully cancelled out by an introducing compressive strain generated by 40nm-thick $GaN_{0.005}As_{0.995}$ SCLs.

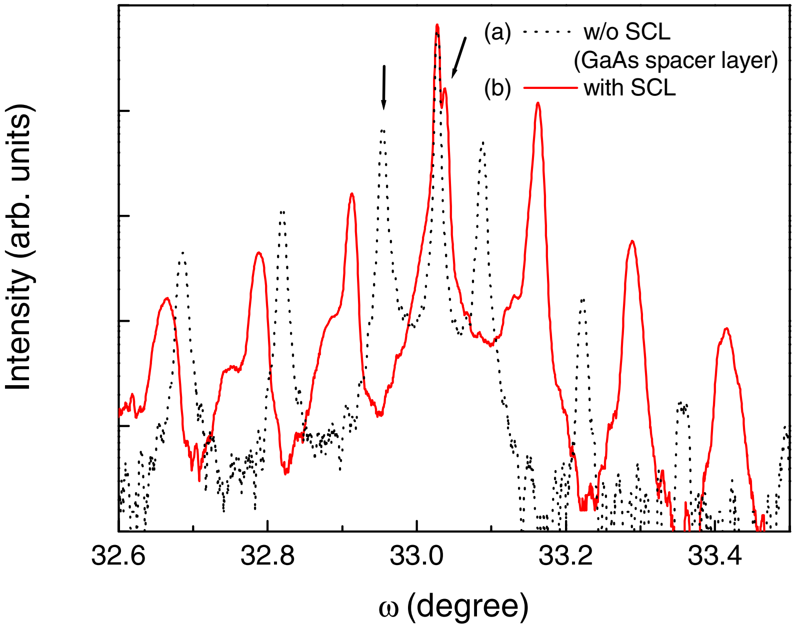
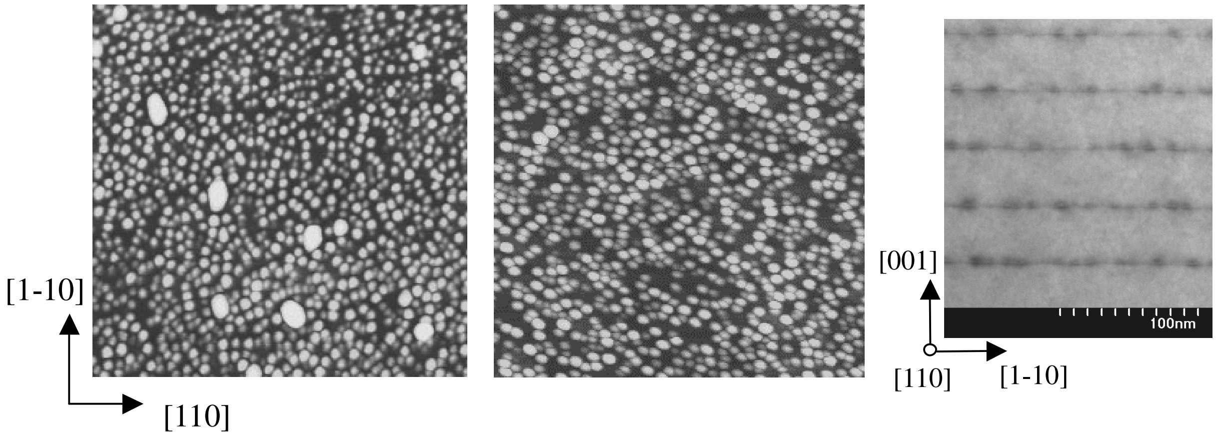


Figure 2. Symmetric (004) x-ray diffraction patterns for 30 stacked InAs QDs structure (a) without and (b) with $GaN_{0.005}As_{0.995}$ SCL, respectively.



(a) (b) (c)

Figure 3. (a) and (b) show AFM images of 30 layer stacked InAs QDs samples covered with GaAs and $GaN_{0.005}As_{0.995}$ SCLs, respectively. Scan size is 500 nm × 500 nm. (c) shows the cross sectional STEM image of 20 layer stacked InAs QDs grown by strain compensation technique.

The AFM images of the top QD layer of 30 stacked sample with (a) GaAs spacer layers, and (b) $GaN_{0.005}As$ SCLs are shown in Figure 3. The sample with no strain compensation in Fig. 3 (a) shows many coalesced islands, while sample with GaNAs SCL results in a significantly reduced size fluctuation and better homogeneity as shown in Fig. 3 (b). We calculate a total QD density of as high as ~3.0×10^{12} cm^{-2} after 30 layer stacking from Fig. 3 (b). Figure 3 (c) shows the cross sectional STEM image of 20 layers of InAs QDs embedded in $GaN_{0.005}As$ SCLs. This image shows an overall good crystalline quality without any dislocation and defects. Several features can be also noted; (1) only a few groups of QDs are vertically aligned, and (2) QD size in an upper layer is almost the same as that in the lower layers.

An improved size uniformity of stacked QDs is also evident from the dependence of average QD lateral size, height, and size fluctuation in the lateral size on stack number embedded in GaAs spacer layers and $GaN_{0.005}As_{0.995}$ SCLs as shown in Figure 4. In the case of sample with GaAs spacer layers, as the stack number increases, dot size significantly increases and size dispersion becomes degraded due to accumulation of internal strain caused by a build up lattice mismatch. On the other, QD size in sample with $GaN_{0.005}As_{0.995}$ SCLs is nearly constant even after 30-layer stacking process. These results suggest that GaNAs SCLs reduce the net strain and also acts to suppress the increase of QD size in the stacking process.

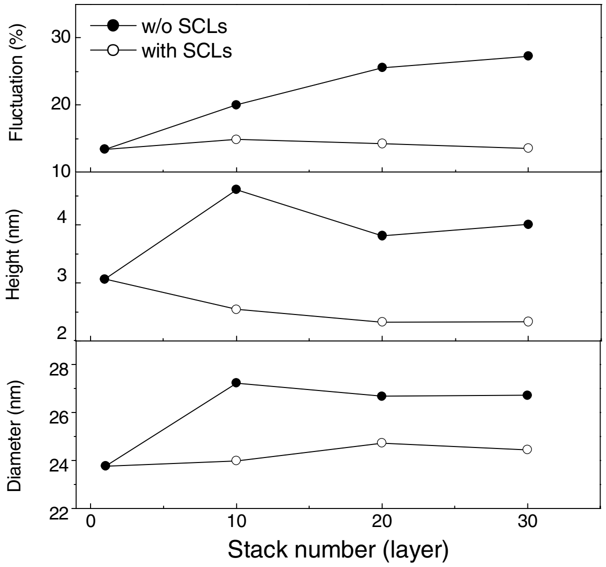


Figure 4. Dependence of average QD lateral size, height, and size fluctuation of stacked InAs QDs samples on stack number for w/o (closed circle) and with (open circle) $GaN_{0.005}As_{0.995}$ SCLs, respectively.

CONCLUSION

We have characterized the effect of strain compensation in multiple stacked InAs QDs structures grown by atomic H assisted RF-MBE. Samples were fabricated with 40 nm-thick $GaN_{0.005}As_{0.995}$ for SCLs and 10 ~ 30 layers of InAs QDs were stacked on GaAs(001) substrates. From XRD measurements, $GaN_{0.005}As_{0.995}$ SCLs provide compressive strain to compensate for tensile strain induced by 2.0 ML InAs QDs. The reduced overall strain leads not only to suppress the generation of coalesced islands due to a build up of lattice mismatch, but also no degradation in size uniformity is observed. These results suggest that use of GaNAs SCL is powerful in realizing high quality optoelectronic device such as long communication wavelength lasers and 1eV junction in ultra high efficiency tandem solar cells.

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