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Long-Wavelength Emission from Strain Controlled InAs/GaAs Self-Assembled Quantum Dots

T. Inoue[1], K. Matsushita[1], M. Kikuno[1], T. Kita[1] O. Wada[1] H. Mori[2], T. Sakata[2] and H. Yasuda[3]

[1] Department of Electrical and Electronics Engineering, Faculty of Engineering, Kobe University,
1-1 Rokkodai, Nada, Kobe 657-8501, Japan
Phone: +81-78-803-6083 E-mail: kita@eedept.kobe-u.ac.jp
[2] Research Center for Ultrahigh Voltage Electron Microscopy, Osaka University
7-1 Mihogaoka, Ibaraki, Osaka 567-0047,Japan
[3] Department of Mechanical Engineering, Faculty of Engineering, Kobe University,
1-1 Rokkodai, Nada, Kobe 657-8501, Japan

1. Introduction

InAs-quantum dot (QD) grown on GaAs substrate is an attractive material for high performance and low-cost optical communication lasers. However, a large InAs-GaAs lattice mismatch (7%) induces an unwanted QD bandgap increase, and thereby the wavelength is shortened. The key issue of InAs/GaAs QDs is therefore extension of the emission wavelength into 1.3 µm and even 1.55 µm optical communication windows. Recently, we proposed a novel QD-growth technique using nitridation.[1] In this process, we first grow conventional InAs/GaAs QDs by the Stranski-Krastanov (SK) process. Then, we perform nitridation of the QD surface. The nitrided QDs are capped by GaAs. The atomic-layer deposition of nitrogen atoms on InAs QDs is expected to modify the strain distribution near the interface in between the QD and capping layer. In this paper, we show detailed structural properties of the nitrided QDs investigated by using high-resolution transmission-electron microscope (HRTEM), and discuss influences of the crystal structure on the optical properties.

2. Growth of Nitrided InAs/GaAs QDs

Self-assembled InAs QDs were grown on GaAs(001) substrate by solid-source molecular beam epitaxy (MBE) system. Active N species were created in radio-frequency (RF) plasma source from ultrapure N_2 gas. The N_2 gas-flow rate was 1 ccm. The RF power was set at 230 W. After growing a 510 nm buffer layer of GaAs at 530°C, 3.6 ML InAs was deposited at 460°C. The nominal deposition rate of InAs was 0.012 ML/s. After growing InAs QDs, we performed atomic-layer nitridation for three different durations of 2, 4 and 8 seconds. The sample was then capped by a 150 nm-thick GaAs layer. The substrate temperature was kept at 460°C during the growth. The structural property of QDs has been investigated in TEM. Cross-sectional TEM images have been observed by H9000-UHR.

Photoluminescence (PL) has been measured to characterize the nitrided QDs. The sample was excited by the 676.4 nm line of a Kr-ion laser. The PL signal dispersed by a 320 mm single monochromator was detected by a liquid-nitrogen cooled InGaAs-diode array.

3. TEM observation for Nitrided InAs/GaAs QDs

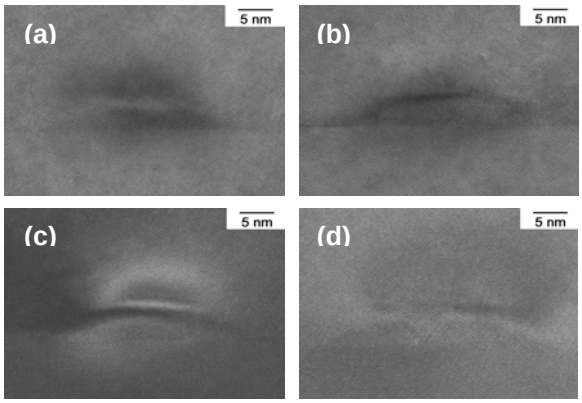

Fig. 1 Cross-sectional HRTEM images for InAs QDs nitrided in (a) 0 s, (b) 2 s, (c) 4 s, and (d) 8 s

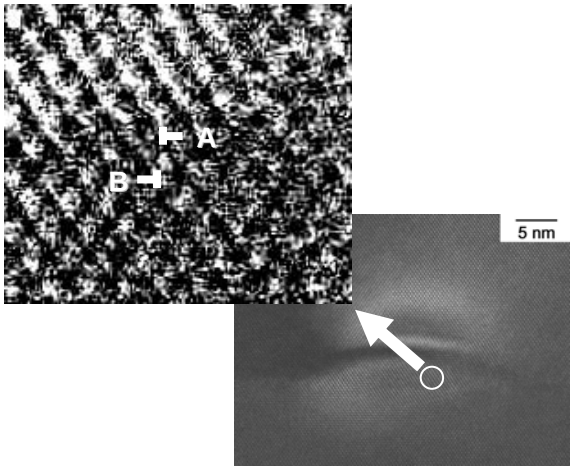

Fig. 2 Magnification image of Fig.2 (c) (4 s-Nitrided InAs QD) Black parallel lines indicate (001) planes

Figure 1 shows (110) cross-sectional HRTEM images of typical InAs QDs nitrided for (a) 0 s, (b) 2 s, (c) 4 s, and (d) 8 s. Conventional InAs QDs show flattened shape and alloy mixing because of strain induced In segregation during GaAs capping layer grownth. Consequently, the interface in between QD and capping layer is unclear. On the

other hand, in nitrided QDs, the interface is sharp. Furthermore, strain field in nitrided QDs is clear in comparison with conventional one. These sharp interface and strain field in nitrided QDs indicate a steep variation of the material composition. This demonstrates that the reduced interface strain by nitridation controls In segregation and results in the larger QDs with high-In concentration.

As shown in Fig 1 (d), dislocations on {111} planes are clearly observed in many of the 8-s nitrided QDs. These dislocations lead to a significant reduction of the PL intensity. Figure 2 shows the magnification image of Fig 1 (c). We found edge dislocations in the 4-s nitrided QDs, which are indicated by A and B. However, the dislocations are on the (001) planes, which is a different from that of the 8-s nitrided QDs. That is considered as a precursor to the {111} slip planes. The dislocations observed in the nitrided QDs are generated by the large lattice mismatch between the QD with high-In concentration and the GaAs capping layer.

4. Long-Wavelength Emission from Nitrided InAs/GaAs QDs

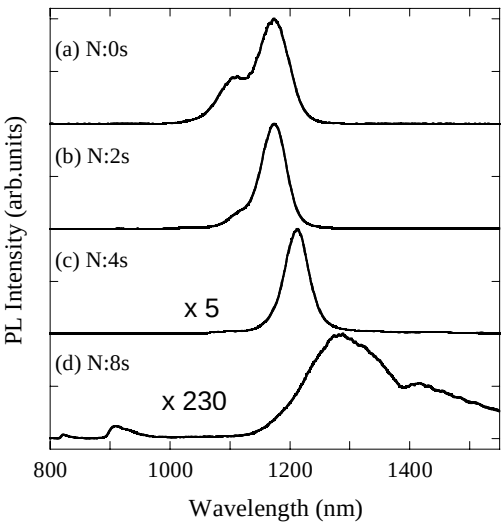

Fig. 3 PL spectra at 13K of nitrided InAs QDs for (a) 0 s, (b) 2 s, (c) 4 s, and (d) 8 s

Figure 3 shows 13K-PL spectra of InAs QDs nitrided for (a) 0 s, (b) 2 s, (c) 4 s, and (d) 8 s. With increasing the nitridation time, the PL-peak wavelength is extended. In particular, the 4-s nitrided QDs show bright room-temperature PL at 1.3 μm. However, the 8-s nitridation gives rise to a quite different PL feature. The spectrum linewidth is considerably broad, which covers wavelengths over 1.55 μm even at 13K. However, the PL intensity is reduced significantly. Such behavior can be explained by dislocation formation mentioned in Sec. 3.

Figure 4 shows the detailed temperature dependence of nitrided QDs. At room temperature, the emission wavelength from the nitrided QDs is close to 1.3 μm. We have fitted experimentally obtained emission data by well-known Varshni empirical equation. The fitted parameters are listed in the inset. The estimated α and β parameters of InAs QDs are larger than those of bulk values. This result indicates additional band gap energy increase due to the thermal expansion mismatch in between InAs and GaAs. Both parameter values, α and β, are much smaller for nitrided QDs in comparison with InAs QDs. We found that the parameters of nitrided QDs are close to those of bulk InAs. These optical characteristics indicate that the thermal expansion mismatch is reduced by nitridation.

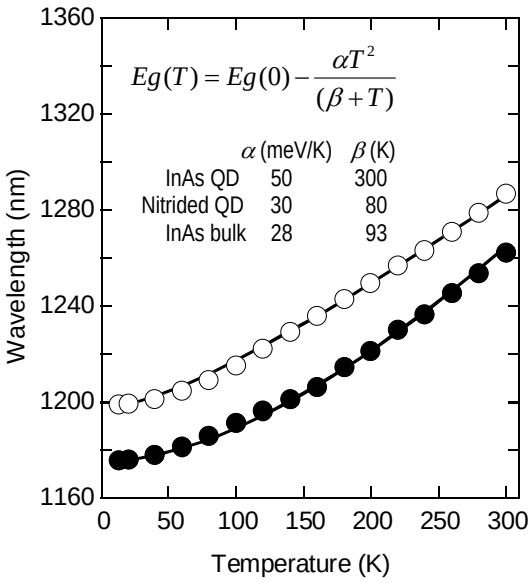

Fig. 4 PL-temperature dependence of InAs QDs nitrided for 0 s (closed ciecles) and 4 s (open circles).

3. Conclusions

Structural properties of the atomic-layer nitrided InAs QDs have been investigated by HRTEM. The nitridation causes a steep variation of the material composition, because of reduced In-segregation effects, which suggest formation of a nitrogen-containing thin layer protecting QD. The PL-temperature dependence of the nitrided QDs supports the model of QDs covered by a “shell”.

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References

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