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Grazing Incidence X-ray Diffraction Measurements of Columnar InAs/GaAs Quantum-Dot Structures

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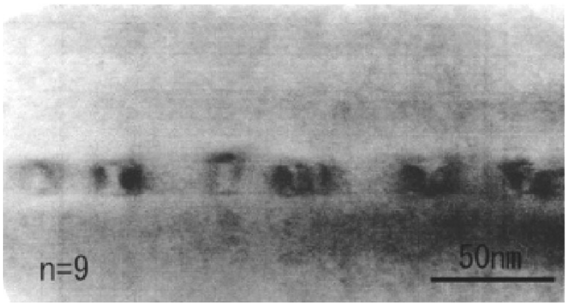
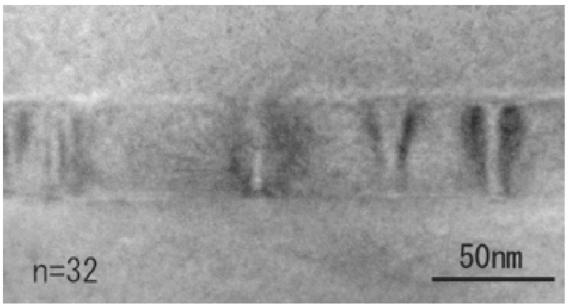
1. Introduction

In terms of the development of quantum dot (QD) devices for optical telecommunication and quantum information processing, it is important to control the symmetry of the QD structure that determines the polarization properties of photon emission. The well-known Stranski-Krastanow (SK)-type QD is known to be elongated in the [1-10] direction on a (001) substrate. The development of a technique for growing a closely stacked (columnar) QDs has led to a QD structure with improved symmetry [1, 2]. The evaluation technique influences the efficiency of QD development. We have succeeded in obtaining grazing incidence X-ray diffraction (GIXD) measurements of QD structures using the laboratory equipment [3]. In this work, the lattice constant distribution inside the columnar InAs/GaAs QD and its crystal orientation dependence were evaluated with the GIXD method.



(a)



(b)

Figure 1 Cross-sectional TEM images of columnar QD; (a) number of stacking units, n, = 9, and (b) n = 32.

2. Experimental

Columnar QDs were grown by stacking SK-type QDs directly in the growth direction. To realize a single columnar form, 0.7-monolayers of InAs QDs were stacked with 3-monolayer intervals of GaAs layers after 1.8 monolayers of InAs had been mounted on a GaAs (001) substrate. We prepared four samples where the number of InAs stacking units, n, varied from 9 to 32. Optical evaluation has suggested that the form of the columnar QD became elongated and inclined in the [1-10] direction with increases in QD height [4]. Figure 1 compares cross-sectional transmission electron microscope (TEM) images of QD samples grown with n = 9 and 32. The aspect ratio of the n = 9 sample is almost 1 and the symmetry of the QD form is high. With the n = 32 sample, the QD form of the upper part changes, and some QDs are leaning.

The lattice constant was evaluated by GIXD measurement. Figure 2 shows the experimental setup. An incident X-ray beam was located at a very small angle close to the total-internal-reflection angle to the (001) plane surface. Most of the incident beam was reflected at the surface. We set the samples so that diffraction might be caused by the (220) and (2-20) planes. The diffraction caused by the (220) and (2-20) plane provides the lattice information parallel to the surface in the (1-10) and (110) directions, respectively. The diffracted X-ray beam was irradiated on an imaging plate (IP) and detected as two-dimensional information.

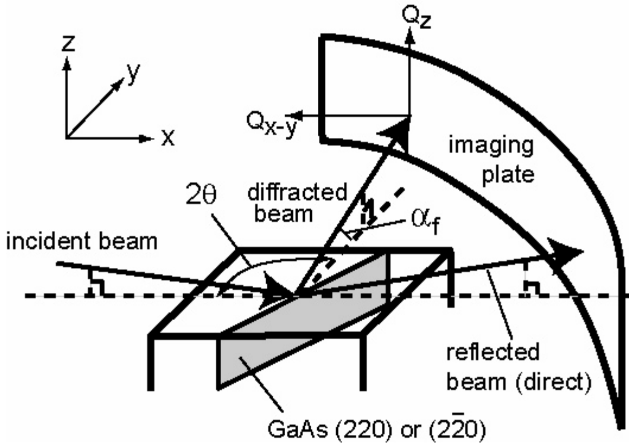


Figure 2 Schematic of GIXD measurement setup.

3. Results and discussions

Figure 3 shows an IP image of an n = 32 sample in the GIXD measurement. The deepest signal is GaAs substrate

(220) diffraction, and the upper right signal is QD (220) diffraction. The IP images were sliced and converted to rocking curves at each diffraction angle, α_f, to analyze the in-plane lattice constant distribution. The value of 2θ is decided on the basis of GaAs diffraction. We can see that the QD signal extends greatly in the 2θ direction, suggesting a large lattice constant distribution inside the QD. The diffraction angle was converted to height, z, by

$$z = \frac{\lambda}{2\pi\alpha_f}\cos^{-1}\frac{\alpha_f}{\alpha_c}, \qquad (1)$$

where α_c is the total-internal-reflection angle and λ is X-ray wavelength [5]. The in-plane lattice constant was investigated as a function of QD height.

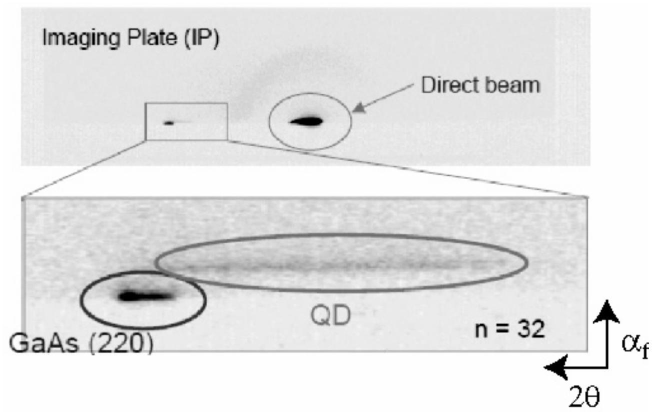


Figure 3 IP image of n = 32 sample in a GIXD measurement.

We found that the in-plane lattice constant depended on the height and that the dependence is influenced by the crystal orientation. We also found that the dependence changed greatly as n increased. The lattice constant distribution in n = 9 and n = 32 QDs is compared in Figure 4. Since all the clear diffraction peaks in the rocking curves are plotted, there are two or more symbols at the same height. The data interval depends on the IP signal resolution. With the n = 9 sample, the lattice constants differ in the (110) and the (1-10) directions, but are almost fixed in the height direction. On the other hand, with the n = 32 sample, the lattice constants become small in the (110) direction and large in the (1-10) direction as the height increases. The direction in which the lattice constant increased at a high position inside the QD agrees with the direction in which the elongation and inclination of the QD form occurred.

4. Conclusions

The GIXD measurements of columnar InAs/GaAs QDs were performed with laboratory equipment to evaluate the structure inside the QDs in detail. Using an IP as a detector, QD-related signals were observed around the GaAs(220) peak. We found that the height dependence of the lattice constant inside the QD changed as the number of stacking units during the QD growth changed, and the dependence differed in the (110) and the (1-10) directions.

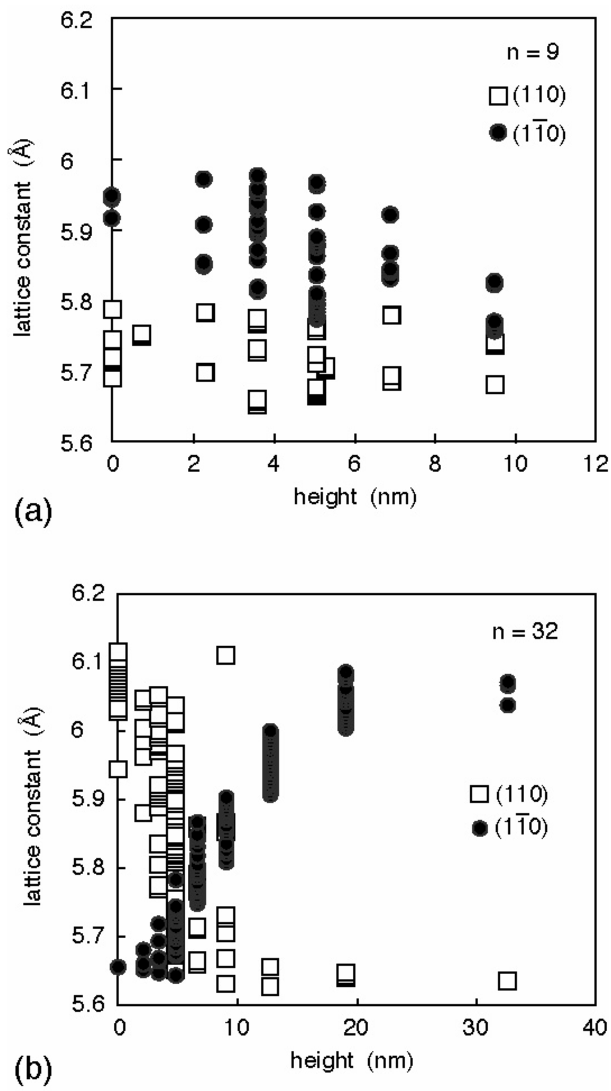


Figure 4 In-plane lattice constant as a function of height obtained by GIXD analysis; (a) n = 9 and (b) n = 32.

Acknowledgements

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