Composition and Strain of Semiconductor Quantum Dots

Quantum dots exhibit confinements of electronic carriers and have been a major focus of research interest in the last decade. The confinement resulted from the dot dimension, which is typically in the range of 10 nm to 50 nm. Although new fabrication techniques for various dots have greatly advanced, our fundamental knowledge of quantum dots in terms of equilibrium and kinetic properties of formation remains limited. Compared to bulk crystals or epitaxial films, the concepts of equilibrium crystal shape, surface segregation, and phase diagram all need to be developed for different quantum dot systems. To be able to experimentally determine the exact atomic positions of the dot is one of the critical steps in this research.

The method we have employed to study the structure of quantum dots is an extension of the conventional grazing incidence surface X-ray diffraction technique. The basic idea is that the dots can be divided into iso-strain slabs, which are regions with constant lateral lattice parameters [1]. X-rays scattered by different iso-strain slabs at different heights will distribute to different parts of the reciprocal space (Fig. 1). Therefore, from the detailed profile of the X-ray intensity distribution around surface Bragg peaks, we are able to reconstruct the shape and the strain field within the dots. The methodology is called Reciprocal Space Mapping (RSM) [1]. In this work, we further explore the resonant X-ray effect in RSM to study quantum dots.

For semiconductor systems, the fabrication techniques of different quantum dots have been well developed to the extent that opto-electronic devices can be commercialized. Nowadays, the most effective way to fabricate semiconductor quantum dots is by the self-assembled growth mode, which relies on strain-induced island formation via a Stranski-Krastanow epitaxial growth. Interestingly, such quantum dots are dislocation free and often exhibit a preferred shape with narrow size distribution [2]. We applied RSM to uncapped InGaAs quantum dots grown on a GaAs(001) substrate. The surface topology of a typical sample studied is shown in Fig. 2(a).

The X-ray scattering measurements were conducted at both the bending magnet beamline **BL12B2** at SPring-8 and the wiggler beamline BL17B of Taiwan Light Source. The grazing incident scattering geometry was set with $\alpha_i < \alpha_c$ of GaAs. With this scattering geometry, we explored an illuminated area of a few mm^2 containing ~10^6 quantum dots. The results obtained by non-resonant RSM of the strain and compositional distributions of the InGaAs dots are shown in Fig. 2(b) [3].

The resonant RSM method incorporates the anomalous X-ray effect near the absorption edges [4], where the dispersion corrections f' and f" make a rather large contribution to the atomic scattering factors and vary drastically with the energy of the incident X-rays. This variation is further enhanced for weak reflections and provides a highly sensitive means to determine the composition (x) of each iso-strain slab. One can better understand the sensitivity of the method by

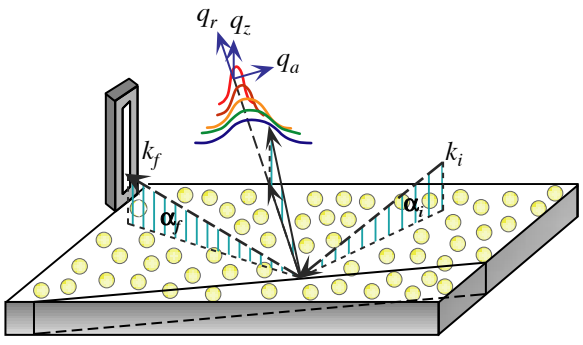

Fig. 1. A schematic of the grazing incidence scattering geometry employed in the Reciprocal Space Mapping method.

examining the structure factor of even reflections of $In_xGa_{1-x}As$, which has the zinc-blend structure, as given by

$$F_{InGaAs} = [x F_{InAs} + (1-x) F_{GaAs}]$$
$$= 4 [x (f_{In} \pm f_{As}) + (1-x) (f_{Ga} \pm f_{As})],$$

where F's and f's are the structure factors and the atomic scattering factors and the plus (minus) sign is for strong (weak) reflection, respectively. Figure 3(a) illustrates the energy dependence of normalized scattered intensities for the $In_xGa_{1-x}As$ (200) and (400) reflections with In composition x of 0.1 and 0.4. These calculated profiles agree qualitatively to the experimental ones as shown in Fig. 3(b). The obtained height-strain and composition-strain dependence clearly indicate that the In concentration is much lower than the nominal composition 0.5 near the dot/substrate interface region and grows with increasing lattice mismatch. Detailed results will be published [4].

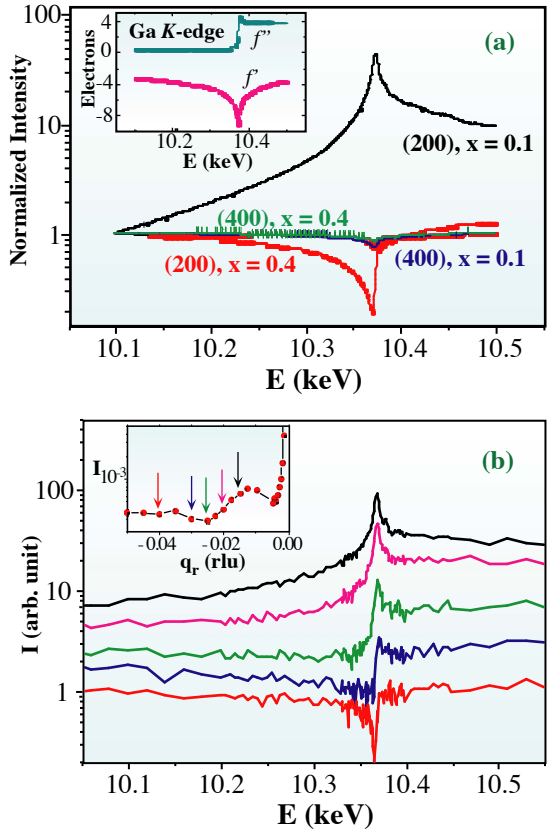

*Fig. 3. **(a)** The energy dependence of normalized scattered intensities for the $In_xGa_{1-x}As$ (200) and (400) reflections with In composition x of 0.1 and 0.4. Inset: the energy dispersion corrections f' and f'' near Ga K-edge. **(b)** The experimental energy-scanned profiles at different q_r positions as indicated in the inset. Different profiles correspond to quantum dot layers with different In concentration. The curves are offset vertically for clarity.*

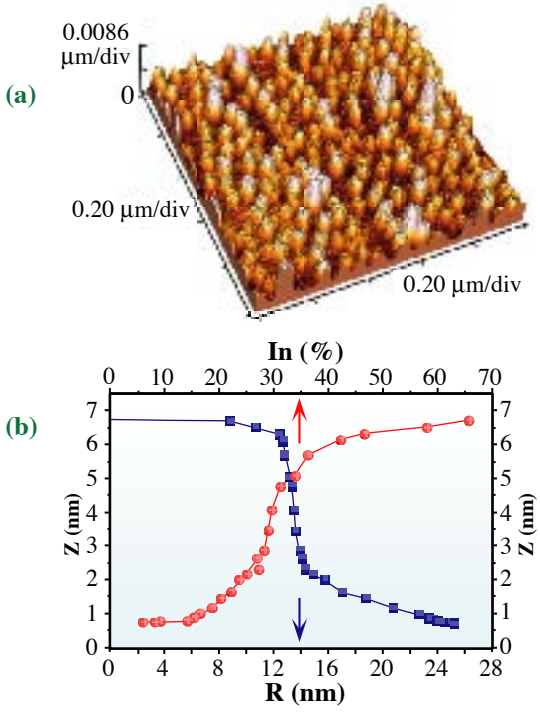

*Fig. 2. **(a)** An AFM image of uncapped $In_xGa_{1-x}As$ quantum dots formed on GaAs(001) surface with a nominal x = 0.5. **(b)** The variations of radius and In content of InGaAs quantum dots obtained by non-resonant RSM method.*

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References

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