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Structural anisotropy of InGaAs/GaAs(001) quantum dot chains structures

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We have studied the structural properties of ordered InGaAs/GaAs(001) quantum dot chains multilayer by high-resolution X-ray diffraction. Two systems of lateral satellites, one of which being inclined with respect to the sample surface normal, i.e. the growth direction [001], were observed. The measured inclination of 30.0° ± 2.5° does not affect the diffraction profile from planar superlattice (SL), i.e. SL peaks are not inclined with respect to the GaAs substrate peak. We identify the splitting of coherent SL satellites for all orders as well as for two perpendicular directions. This splitting most likely indicates that two discrete periods exist in SL structure.

1 Introduction

High-Resolution X-ray diffraction (HRXRD) is a non-destructive method for investigation of periodical nanoscale structures like quantum dots (QDs) or quantum wires (QWRs) synthesized using the Stranski–Krastanow growth mode in highly mismatched systems [1–3]. Application of this technique allows to estimate both technological parameters (layer thickness, composition) and structural ones such as strain in the layers and the ordering degree of QDs or QWRs in vertical and lateral directions [4–7]. However, despite great amount of experimental and theoretical studies, there are a lot of questions about interpretation of X-ray data obtained from self-ordered structures with QDs or QWRs. In particular, the splitting of coherent superlattice (SL) satellites was observed in [1, 2]. This effect was explained by the existence of two different spatially separated structural areas, appearing either due to the lateral composition modulations (LCM) in short-periodical superlattices [1] or the presence of two superlattices with slightly different periods [5]. Nevertheless, the detailed mechanism of the satellites splitting is absent.

The aim of our work was to apply coplanar high-resolution X-ray reciprocal space map (HR-RSM) measurements around the symmetrical 004 and asymmetrical 224, 113 reciprocal lattice points (RLPs) to explain the splitting of both coherent SL satellites and diffuse scattering peaks of QDs in InGaAs/GaAs QD multilayer structures with QD chains.

2 Experiment

The InGaAs/GaAs QD chains were grown by molecular-beam epitaxy on semi-insulating GaAs(100) substrate with a miscut angle smaller than 0.1°, using procedure similar to that described in Ref. [8].

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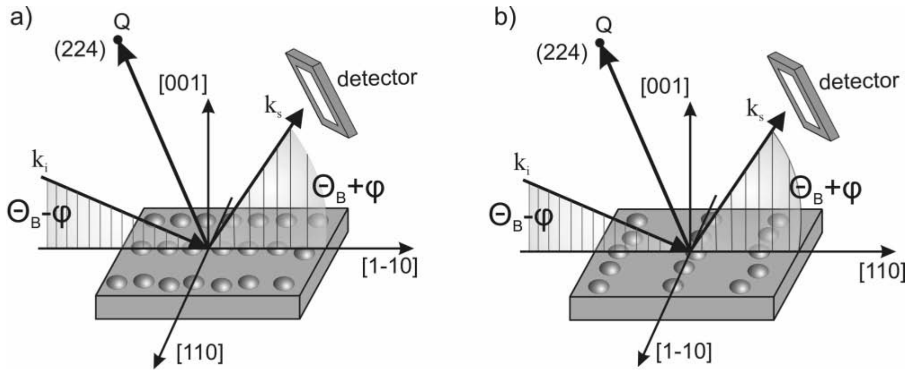

Fig. 1 Coplanar diffraction geometry. Diffraction plane is parallel (a) and perpendicular (b) to the QDs chains direction. φ is the angle between surface and diffraction plane, θ_B is Bragg angle. $\boldsymbol{k}_i$ and $\boldsymbol{k}_s$ are the incident and scattered X-ray beams respectively, $\boldsymbol{Q}$ is the diffraction vector. Scattering plane (shaded area) is perpendicular to the sample surface.

After growing a 0.5 μm GaAs buffer layer at 580 °C, the temperature was reduced to 540 °C for the growth of 17-period (7.6 monolayers (MLs) $In_{0.4}Ga_{0.6}As$/60 MLs GaAs) multilayer dot structures.

Radial scans were measured by high-resolution "X'Pert PRO MRD XL" diffractometer with a Bartels four-crystal Ge(220) monochromator using Cu K_a radiation. Three-crystal Ge(220) analyzer with 12 arcsec angular divergence was used to measure the HR-RSMs. Experimental data were obtained for various azimuthal directions: scattering plane was $(\bar{1}10)$ and (110), i.e. perpendicular (Φ = 90°) and parallel (Φ = 0°) to the QD chains direction, respectively (Fig. 1). Symmetrical 004, asymmetrical 113 and 224 diffraction geometries were used.

3 Results and discussion

Figure 2 presents the radial line scans measured near 004 Bragg peak at Φ = 0° and Φ = 90° together with simulation assuming perfect tetragonally distorted layer system. These diffraction profiles contain GaAs substrate peak, average superlattice (SL) peak of zeroth order SL_0 and coherent $SL_{\pm n}$ satellites peaks, which appear due to the interference between InGaAs layers and GaAs spacer layers. The SL

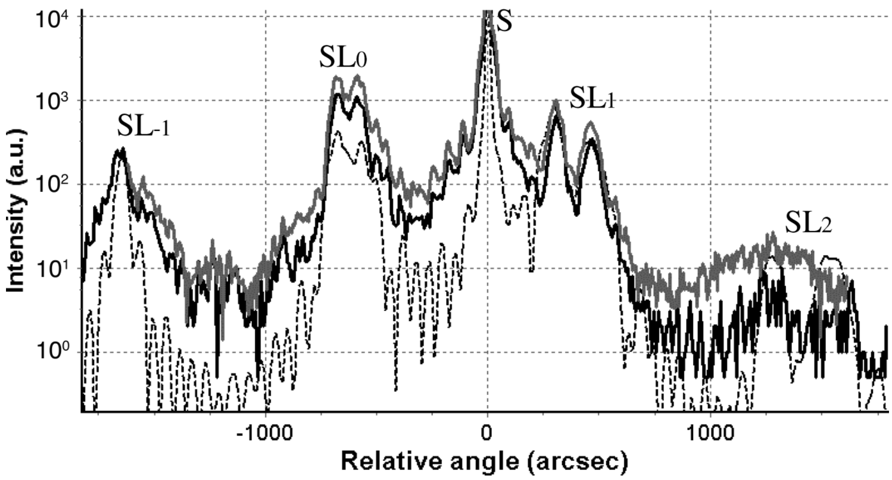

Fig. 2 HRXRD radial scans near 004 Bragg peak at Φ = 0° (gray) and Φ = 90° (black) together with simulation (dashed line) which uses dynamical theory.

peaks show a systematic splitting for both azimuthal directions. It has to be pointed out that we did not observe the missing of odd numbered coherent satellite peaks as it was reported in [1].

To obtain information on structural parameters of the buried InGaAs QDs, we performed reciprocal space map measurements. QDs give rise to the diffuse scattering in the vicinity of the coherent SL satellites. Figure 3 presents typical HR-RSMs performed near 224 Bragg peak for two mutually perpendicular directions, which show satellite peaks corresponding to both vertical and lateral structure. These maps as well as the maps measured for the asymmetrical 113 reflection (not shown) indicate that SL is fully strained with respect to the substrate and GaAs buffer layer. Moreover, measurements of 004, 224 and 113 HR-RSMs for $\Phi = 90°$ have confirmed the splitting of coherent SL satellites. Lateral satellites of diffuse scattering from InGaAs QDs were observed both near SL_0 and near high order peaks.

Periodical modulation of the intensity along crystal truncation rod (CTR) is well observed on the sections of the experimental maps representing SL vertical periodicity (Fig. 2). As can be clearly seen, there are two systems of coherent SL satellites in radial scans. These two systems were observed on HR-RSMs for 004, 113, 224 reflections. Two vertical periods of SL were estimated from the radial scans and equal $L_1 = 19.7 \pm 0.1$ nm and $L_2 = 19.02 \pm 0.08$ nm. In contrast to [9], the performed simulations indicate that lateral composition modulations that appear due to the presence of QDs chains cannot explain the observed splitting for both [110] and $[1\bar{1}0]$ directions. Lattice distortions also cannot completely explain this phenomenon as it was reported in [10] because this effect is azimuthally dependent. The splitting of vertical SL satellites most likely indicates that two discrete periods exist in SL structure [11]. This was proved by simulation shown in Fig. 2 (dashed line). The superlattice period is formed only by thicknesses of wetting layer and the GaAs spacer layer. Breakdown correlation of the dots positions gives a small contribution to the formation of the coherent superlattice structure, but is manifested in the redistribution of elastic strain fields. Therefore, the presence of two different SL periods corresponding to the vertical and inclined alignment of QDs is caused only by the change of wetting layer thickness in these periods.

Scattered intensity outside CTR is concentrated in so-called resonant diffuse scattering streaks (Fig. 3a, dash-dot line). The peculiar properties of these streaks are determined by QDs vertical and lateral ordering degree. If the scattering plane is perpendicular to $[\bar{1}10]$ direction (Fig. 3a), they are repre-

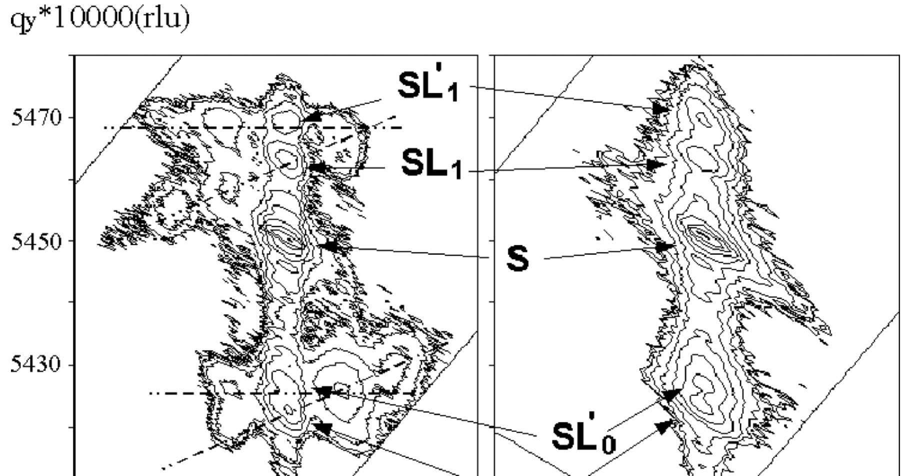

Fig. 3 224 HR-RSMs measured for InGaAs/GaAs QDs chain sample at $\Phi = 90°$ (a) and $\Phi = 0°$ (b). S denotes the substrate peak, and SL_0, SL_1, SL_0', SL_1' are the coherent satellites for two subsuperlattices.

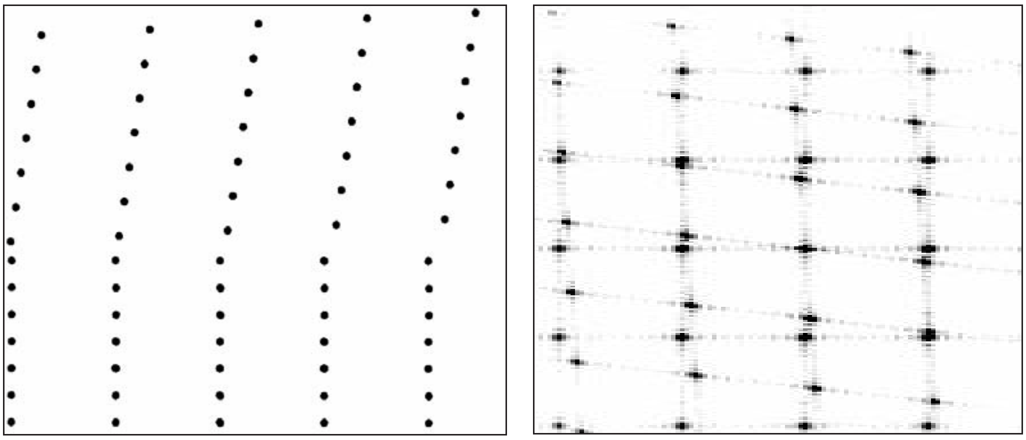

Fig. 4 Correlation between scattering centers in real space (left) and satellite structure in reciprocal space (right) for strongly vertical and inclined inheritance of the scattering centers.

sented as two systems of lateral satellites, one of which is inclined with respect to the sample surface normal, i.e. the growth direction [001]. In order to explain the observed arrangement of lateral satellites the model pattern of QDs position in the structure and its Fourier transformation are shown in the Fig. 4. The measured inclination is 30.0° ± 2.5°.

Only HR-RSMs data analysis has given information about the presence of buried QDs chains and their inclined character in the structure. Using a well known ratio of periodicity in the real and reciprocal spaces $\Delta\vartheta = 2\pi/\Delta L$, we evaluated the average distance between neighbour QDs chains (i.e. for $\Phi = 90°$) to be equal to $L_{LCM} = 82 \pm 0.3$ nm, while the atomic-force microscopy (AFM) gives the value $L_{LCM} \approx 80$ nm on the surface. We should mention that X-ray measurements are averaged over the whole sample volume, which in our case includes all SL periods, while the AFM measurements characterize only the surface morphology.

One should notice considerable difference between reciprocal space maps near 224 RLPs for mutually perpendicular crystallographic directions (Fig. 3a, b). If diffraction plane is perpendicular to QDs chains, the lateral satellites are clearly observed (Fig. 3a), while it is parallel to QDs chains, there is only wide diffuse scattering halo on the left and right of the main truncation rod for SL (Fig. 3b). This is due to the weak correlation of QDs positions in chains or great dispersion of QDs sizes.

The vertical width of the lateral satellites depends on vertical correlation of QDs chains position. By using the technique described in [4] the vertical correlation length can be easily evaluated, and for this sample it equals to 200–250 nm.

The comparison of various order satellites intensity and the experimental HR-RSMs allows to estimate the standard deviation of the magnitude L_{LCM}. In our case it is $\sigma_{LCM} = 5$ nm.

4 Conclusions

We have observed two systems of vertical coherent satellites on HR-RSMs for 004, 113, 224 reflections and for any azimuthally oriented sample. It is explained by the presence of two independent periods in SL structure with values of $L_1 = 19.7 \pm 0.1$ nm and $L_2 = 19.02 \pm 0.08$ nm. It was shown that two independent SL periods arise due to the difference in wetting layers thickness in two spatially separated structural regions with various character of QDs alignment in the growth direction.

When diffraction plane is perpendicular to $[\bar{1}10]$ direction, the direction of QDs chains, two systems of lateral satellites are observed on HR-RSMs for all measured reflections. One of the systems is parallel to the sample surface and the other is inclined to the surface normal by the angle of 30.0° ± 2.5°. The measured distance between QDs chains is $L_{LCM} = 82 \pm 0.3$ nm.

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