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Effects of Growth Process on GaInP/GaAs/GaInP Heterointerface Structures and Device Characteristics Revealed by X-ray CTR Scattering Measurements

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The origin of the intense and deep PL peak from the GaAs/GaInP/GaAs heterostuctures was proved by X-ray CTR scattering measurement and analysis to be the In distribution into GaAs, which forms a GaInAs quantum well at the heterointerface. The growth process was modified to suppress the In distribution and the device performance was much improved.

Key words: CTR scattering, heterointerface, growth process, atomic scale

1. INTRODUCTION

The atomic level structure of semiconductor heterointerfaces and their growth process dependences (including growth technique itself) have been elucidated by the X-ray CTR (crystal truncation rod) scattering technique. When X-ray diffraction of a crystal with a flat surface is measured in detail, a line (rod)-like distribution of the X-ray intensity is observed around a Bragg point, which is called a crystal truncation rod scattering [1-3]. Since the structure of overlayers (single or multiple) grown on the surface modulates the X-ray intensity in the line-like distribution, information about the structure of the overlayers can be deduced from the X-ray CTR scattering spectra. We have successfully applied this technique to study the epitaxlially grown semiconductor interfaces and quantum wells, and demonstrated that it is a very powerful technique to reveal the atomic scale interfaces and heterostructures. Examples are listed below:

1) As/P atom exchange process at the AsH_3- and (AsH_3+PH_3)-exposed InP surface that is inevitable in the growth of InP/GaInAs/InP[4,5]
2) Composition profiles in InP/InAs/InP strained-layer heterostructures[6]
3) Layer structures and composition profiles in InP/GaInAs/InP heterosructures grown by different OMVPE processes[7]
4) Composition profiles and crystal structure of ErP in InP/ErP/InP semiconductor/semimetal heterostructures[8]
5) Diffusion coefficient of Er in InP/ErP/InP heterostructures[9]
6) Compositon profiles and thermal stability of GaAs/InAs(1ML)/GaAs strained-layer heterostructures[10]
7) Composition of top 1ML AlGaAs on GaAs[11]
8) Growth process dependence of ZnSe/GaAs heterointerface structures[12]
9) Crystal structure and polarity of nitrided sapphire surface for GaN growth[13,14]
10) Characterization of low-temperature deposited AlN buffer layer (LT-AlN) on sapphire and role of LT-AlN for GaN growth[14-16]
11) Characterization of whole structure of GaInN/GaN/LT-AlN/sapphire[14-16]

Though the growth facilities such as MBE and OMVPE have been believed to be able to fabricate heterostructures at the atomically controlled accuracy, the real structures were quite graded and very much dependent on growth processes.

In this paper, the origin of the intense and deep PL peak from the GaAs/GaInP/GaAs heterostuctures is proved to be the In distribution into GaAs, which forms a GaInAs quantum well at the heterointerface. A lower growth temperature suppressed the In distribution and this peak simultaneously. Quality of layers and device performances, especially the threshold current of GaInP/GaAs/GaInP DH lasers, are discussed with the interface structures.

2. PROBLEMS IN GaAs/GaInP/GaAs HETERO-STRUCTURE

The deep and intense PL peak from the GaInP/GaAs/GaInP DH structure is generally observed. This radiation center effectively kills carriers and suppresses the band edge transition and the electron transport across the heterostructure. We found that the growth temperature does affect the PL spectrum, i.e., creation and suppression of the radiation center.

Fig. 1 shows the layer structure of GaAs/GaInP/GaAs on GaAs substrate and the growth conditions in the inset. When the structure was grown at 580~610°C, an intense PL peak is observed below the band edge. When the same structure is grown at 540~550°C, only the near band edge emission is observed, as shown in Fig. 2. This behavior is dependent only on the growth temperature. The growth technique is the LP-OMVPE (low pressure organometallic vapor phase epitaxy) at 76 Torr, where the source materials used are listed in the inset.

We already knew that the radiation center is formed in the top GaAs layer, near the GaAs/GaInP interface, since the deep PL peak disappears when top GaAs is etched off [17].

We assumed that the origin of the deep PL peak must be related with the interface structure because it depends only on the growth temperature and no impurities are intentionally doped. This assumption was made from

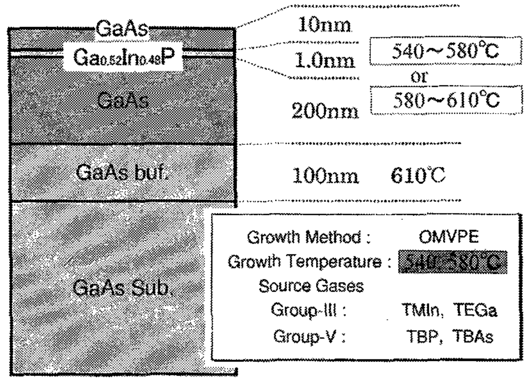


Fig. 1 Layer structure of GaAs/GaInP/GaAs on GaAs substrate. Thicknesses and growth conditions are also shown. The growth temperature is the most effective parameter to change the optical properties as shown in Fig. 2.

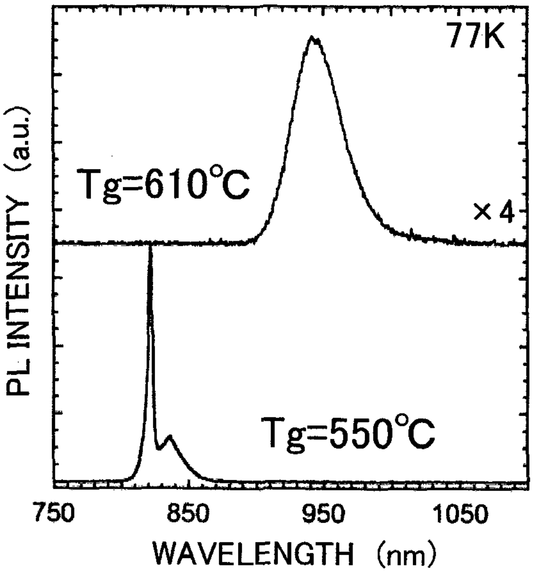


Fig. 2 When GaAs/InP/GaAs is grown at 610°C, an intense PL peak is observed below the band edge. When the same structure is grown at 550°C, only the near band edge emission is observed.

our previous experience in heterostrucutre analysis of InP/GaInAs/InP where unexpectedly wide distribution of group-III elements was observed in the heterostructure grown by OMVPE [7].

3. SAMPLE PREPARATION AND X-RAY CTR SCATTERING MEASUREMENTS

3.1 Sample preparation

Three different sequences were employed to grow GaAs/GaInP/GaAs heterostructures by OMVPE in our laboratory. In sample A all three layers were grown at 540°C, in sample B only GaInP was grown at 580°C and in sample C all the layers were grown at 580°C, as shown in Fig. 3. The layer thicknesses are also listed. The GaAs cap layer thickness was designed to be 10nm to obtain the oscillatory CTR spectrum that helps analysis with rich of information.

3.2 X-ray CTR scattering measurements

The X-ray CTR scattering was conducted at the beamline BL18B of Photon Factory at Tsukuba. The wavelength of the X-ray was set at 1.600Å by a Si(111) double-crystal monochromator. A Weissenberg camera was used to record the X-ray CTR scattering intensity around the 002 Bragg diffraction spot of GaAs with a CCD camera as a detector. The obtained data for the three samples and the best-fit curves are shown in Fig. 4. The theoretical curves of CTR spectra were generated from crystal models that contain parameters such as layer thickness, alloy composition (and lattice distortion), interface gradation, and surface roughness.

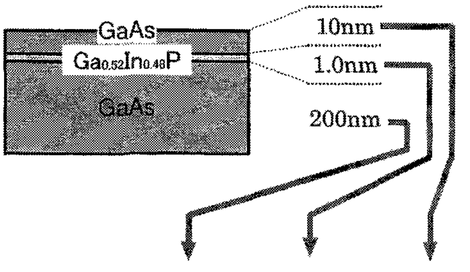
4. RESULTS AND DISCUSSION

4.1 Composition profiles

The composition profiles are plotted in Fig. 5. Those profiles were constructed using those parameters obtained from the best-fit curves as shown in Fig. 4.

As is clear in Fig. 5 (a), the gradation of P is quite abrupt, which is not always the case in the usual OMVPE growth system and growth sequence. In our growth system 4-barrel reactor is used to supply As-source and P-source in a different barrel by rotating the susceptor from barrel to barrel [18,19].

On the other hand, the In distribution looks dependent on the growth temperature sequence. Especially in sample C grown at the higher temperature, the gradation is deep into GaAs upper layer. This distributed In together with Ga and As forms a thin GaInAs layer that has a narrower energy gap than GaAs or GaInP. Then, it is easily understood that the GaInAs quantum well formed adjacent to GaInP is an efficient recombination area for a deeper PL emission. Since the In distribution is not necessarily uniform, the depth and the width of the GaInAs well must fluctuate from place to place. This fluctuation give a broader peak of the PL spectra. In sample A grown at the lower temperature, the gradation is much suppressed. Even though there is some



Sample Name	200nm GaAs Buffer Layer	1nm GaInP Layer	10nm GaAs Cap Layer
A	540℃	540℃	540℃
B	540℃	580℃	540℃
C	580℃	580℃	580℃

Fig. 3 Growth temperatures for GaAs/GaInP/GaAs layers. Three different sequences were employed; in sample A all three layers were grown at 540°C, in sample B only GaInP was grown at 580°C and in sample C all the layers were grown at 580°C.

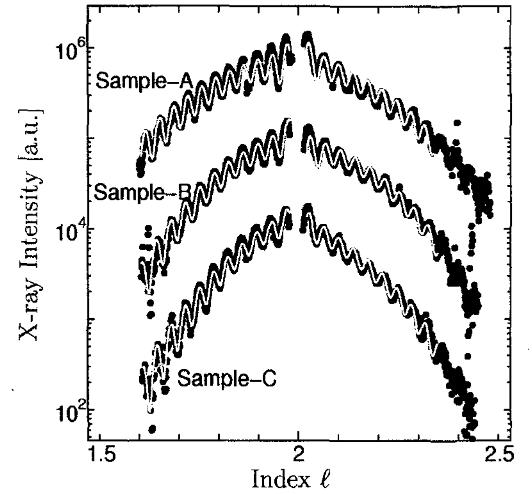


Fig. 4 Experimentally obtained CTR data (•) and the best-fit curves for analysis (—). They are shifted upward by one order each for clarity.

distribution of In into GaAs, the quantum well is narrow enough to have a quantum level at the well edge, giving no deep emission.

4.2 Effects on device performances

We fabricated GaInP/GaAs/GaInP DH lasers to investigate the effects of the growth temperature, e.g., the effects of the In distribution into GaAs layers.

In the growth process of GaAs(cap)/GaInP(barrier)/ GaAs(active)/GaInP(barrier) structures, similar temperature sequences as in Fig. 3 were employed. To fabricate DH1, the lower temperature of 540°C was used for all the top 3 layers (GaAs/GaInP/GaAs). To fabricate DH2, only the GaInP barrier layer was grown at 580°C. To fabricate HD3, the GaInP barrier layer was grown at 580°C but the temperature was once lowered to 540°C to grow the GaAs/GaInP interface and then raised to 580°C for the GaAs cap layer growth.

In Fig. 6, the symbols are ○: DH1, □: DH2, △: DH3 and ●: all the layers were grown at 580°C. Here, the distribution of the threshold current density (Jth) of laser oscillation is shown. It is very clear that the lower temperature growth gives the lowest Jth and the lowest scatter in the distribution (○). On the other hand, higher temperature growth gives the highest Jth and the highest scatter in the distribution (●).

The GaInAs quantum well formed at the GaAs/GaInP/GaAs heterointerface is not necessarily uniform in its depth or width. This would affect the quality of GaAs grown on top of the GaInAs quantum well. This was proved by observing the surface morphology of each layer revealed by selective etching. The surface morphology of the top GaAs and GaInP grown at higher temperature was clearly degraded, while those gown at lower temperature was mirror-like smooth. The higher value of and the higher scatter in the Jth distribution must come from the lower quality of the overlayers and degraded heterointerfaces.

5. SUMMARY

The X-ray CTR scattering measurements on GaAs/

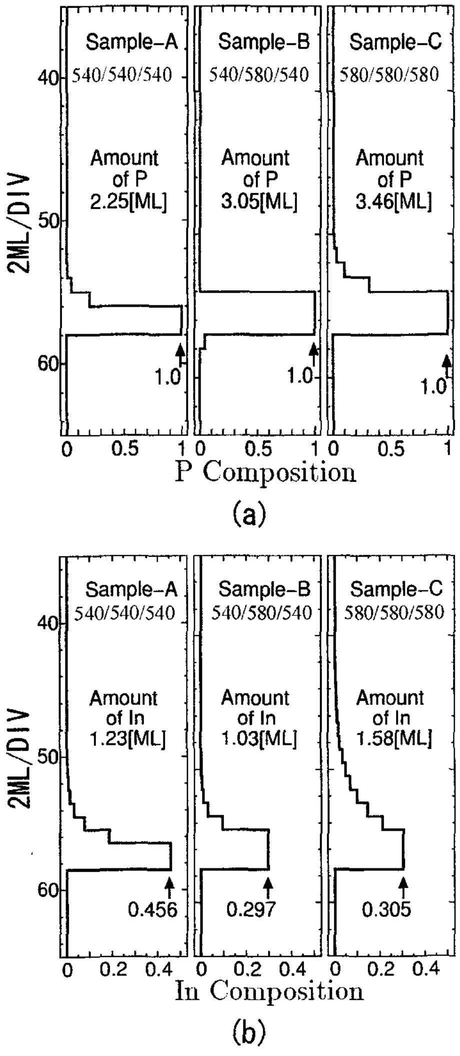


Fig. 5 P composition profiles (a) and In composition profiles for the samples A, B, and C.

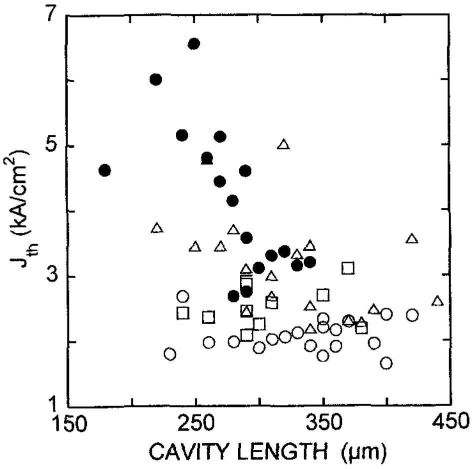


Fig. 6 Distribution of threshold current density Jth of GaInP/GaAs/GaInP DH lasers. ○: DH1, □: DH2, △: DH3 and ●: higher temperature growth (see the text).

GaInP/GaAs heterostructures revealed the P and In composition profiles in the atomic scale. From this profiles the origin of the intense and deep PL peak from the GaAs/GaInP/GaAs heterostuctures was proved to be the In distribution into GaAs, which forms a GaInAs quantum well at the heterointerface. The growth process was modified to suppress the In distribution. Crystal quality of the overlayers and the device performance of the GaInP/GaAs/GaInP laser diodes were much improved.

The X-ray CTR scattering technique that is a nondestructive and of atomic level resolution will be used to improve quality of heterostructures and devices of various combinations of materials. A simpler and much quicker measurements and analysis by this technique (that is in progress) will encourage people to use in the industrial applications.

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