Mat. Res. Soc. Symp. Proc. Vol. 722 © 2002 Materials Research Society

Structural and Optical Properties of InGaN/GaN Multi-Quantum Well Structures with Different Well Widths

Young-Hoon KIM [2], Chang-Soo KIM, Sam-Kyu NOH, Jae-Young LEEM, Kee-Young LIM [1], Byung-Sung O [2] and Jay P. SONG [3]
National Research Laboratory on Quantum Dot Technology, Materials Evaluation Center, Korea Research Institute of Standards and Science, Taejon, Korea 305-600
[1] Semiconductor Physics Research center and Department of Semiconductor Science and Technology, Chonbuk National University, Chonju, Korea 561-756
[2] Department of Physics, Chungnam National University, Taejon, korea 305-764
[3] SongJee Industrial Corporation, Sungnam, Korea 463-500

ABSTRACT

The structural and the optical properties of 10-period $In_{0.15}Ga_{0.85}N$/GaN multiple quantum wells (MQWs) have been investigated using HRXRD (high-resolution X-ray diffraction) and PL (photoluminescence). For the samples, the barrier thickness was kept constant, 7.5 nm and the well thicknesses were varied, 1.5, 3.0, 4.5, and 6.0 nm. For the structural characterization, an $\omega/2\theta$-scan and an ω-scan for GaN (00 2) reflection and a reciprocal space mapping (RSM) around the GaN (10 5) lattice point were employed. The average strain for the MQWs increased as the well thickness increased. The MQW with a 6.0 nm well thickness experienced lattice relaxation and the crystallinity of the sample was poor compared to that of the other samples. MQWs with well thicknesses of 1.5, 3.0 and 4.5 nm, however, maintained lattice coherency with the GaN epilayers underneath, and the critical well thickness for lattice relaxation of the MQWs used in the study was 6.0 nm. The PL spectra showed that the relative emission intensity of the sample with a 6.0 nm well thickness was lower than for the others, a fact consistent with the X-ray results. The emission intensity, therefore, is considered to be affected by defects due to lattice relaxation of the epilayer.

INTRODUCTION

The III-V nitrides such as GaN, InN and AlN are candidate materials for light-emitting diodes (LEDs), laser diodes (LDs) and high power transistors due to their wide band gaps, thermal stability and strong bond strength [1]. InGaN/GaN multiple quantum wells (MQWs) have been used as active layers for blue LDs. For InGaN/GaN quantum well structures, two different radiative recombination mechanisms are generally accepted [2].

For a GaN epilayer, heteroepitaxial growth on a sapphire substrate has commonly been employed. It has been very difficult to grow a high quality GaN film with a smooth surface because of the large lattice and thermal mismatches between GaN and sapphire. The InGaN layer grown on GaN experiences a compressive biaxial strain. As the thickness of the strained layer exceeds a critical value, the accumulated elastic energy is relieved by the formation of misfit dislocations at the interface [3]. The induced strain can, also, cause additional piezoelectric fields and will influence the optical and electrical properties of films and devices.

High-resolution X-ray diffraction (HRXRD) has been proved to be a very convenient and nondestructive method for evaluating the structural properties of thin semiconductor epilayers and superlattices (SLs). Important structural parameters such as lattice mismatch, residual strain, alloy composition and superlattice period can be routinely obtained with the appropriate HRXRD.

In this work, the structural and the optical properties of 10-period InGaN/GaN MQWs have been investigated using HRXRD and low temperature photoluminescence (LT-PL).

EXPERIMENTAL DETAILS

The 10-period $In_{0.15}Ga_{0.85}N$/GaN MQW structures used in this study were grown on c-plane sapphire substrates by metalorganic chemical vapor deposition (MOCVD). Prior to the growth of the MQWs, a 25 nm thick low-temperature GaN nucleation layer and a 1 μm thick GaN buffer layer were grown. The well thicknesses were varied, 1.5, 3.0, 4.5 and 6.0 nm while maintaining the barrier thickness constant, 7.5 nm. Table 1 lists the well and barrier thicknesses for the designed MQWs and also shows sample codes used in the text.

Table 1. The period (D) and the average strain ($<\varepsilon^{\perp}>$) for the MQWs (d_w: well thickness, d_b: barrier thickness).

Sample	**d_w+d_b = D (nm)**		**$< \varepsilon^{\perp} > \times 10^{-3}$**
	Designed	**XRD result**	
W15	1.5+7.5=9.0	10.91	4.04
W30	3.0+7.5=10.5	11.20	6.30
W45	4.5+7.5=12.0	12.32	7.90
W60	6.0+7.5=13.5	13.84	9.48

HRXRD scans were performed in a Philips MRD with a four-crystal Ge (220) monochromator and a crystal analyzer. With the analyzer between the sample and the detector, the different orientation distributions of the scattering intensities from sample can be resolved. To evaluate the structural parameters such as the crystalline quality, the lattice relaxation, the strain and the period of the MQWs, an ω/2θ-scan and an ω-scan for GaN (00 2) reflection and a reciprocal space mapping around the GaN (10 5) reciprocal lattice point were employed for each sample. For the optical characterization LT-PL spectra were obtained at 23 K using a He-Cd laser.

DISCUSSION

Figure 1 shows ω/2θ-scans for the (00 2) reflections of the $In_{0.15}Ga_{0.85}N$ /GaN MQWs with different well thicknesses. For the measurements 1 mm receiving slit was used in front of the detector. As the well thickness increases from 1.5 nm to 6.0 nm, the satellite peak separation for each sample decreases, and the angular separation between the zeroth order satellite and the GaN peak increases. The period D of a SL is given by

$$D = (L_i - L_j)\lambda / 2(\sin\theta_i + \sin\theta_j) \qquad (1)$$

where L_i, L_j are diffraction orders and θ_i, θ_j the corresponding Bragg angles of the satellites L_i, L_j, and λ is the X-ray wavelength used. From the angular position of the zeroth order satellite with respect to the GaN layer peak, the average strain $<\varepsilon^{\perp}>$ of the quantum well can be determined [4]. To separate the zeroth order satellite peak from the GaN peak for samples W15 and W30, a

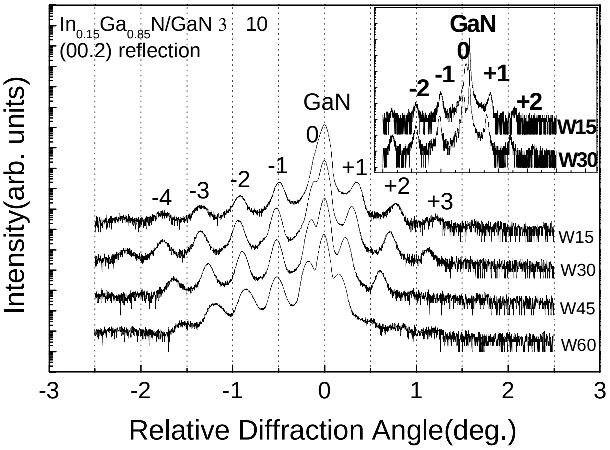

Figure 1. ω/2θ diffraction curves for (00·2) reflection of the MQWs with different well thicknesses.

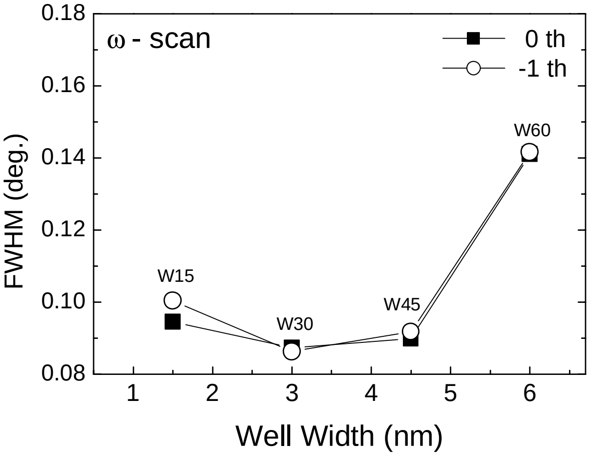

Figure 2. Variations in the FWHMs of the zeroth order and –1st order satellites.

crystal analyzer was used, and the scan results are inserted in Figure 1. The period and the average strain determined for the samples are summarized in Table 1. The result shows that the average strain of the quantum well increases, as the well thickness increases. Figure 2 shows the variations in the full width at half maximum's (FWHMs) of the zeroth order and –1st order satellite peaks for the ω-scans as the well thickness increases. An ω-scan can provide information on the mosaicity, i.e., the crystalline quality of a film [5]. The FWHMs for samples W15, W30 and W45 are almost constant, but that of sample W60 increases sharply. This means that the crystallinity of W60 is relatively poor in contrast to the quality of other samples.

To better understand the specific mechanism of peak broadening as well as to assess the overall strain state (coherent versus relaxed) of the SL with respect to the GaN layer, a reciprocal space map (RSM) was obtained for the asymmetric (10 5) reflection of the GaN layer. The measured RSMs around the (10 5) reciprocal lattice points are shown in Figure 3. In contrast to the others, the RSM for sample W60 shows the distribution of the diffusely scattered intensity around the GaN reciprocal lattice point and the SL satellites resulting from structural defects. In addition, for samples W15, W30 and W45 the straight line connecting the centers of the SL satellites passes through the center of the GaN reciprocal lattice point. The fact suggests that the InGaN/GaN MQWs were grown coherently on GaN layers. In contrast, for sample W60 the connecting line deviates from the center of the GaN reciprocal lattice point, indicating that the InGaN/GaN MQW experienced lattice relaxation. From the RSM in terms of the reciprocal lattice coordinate (q-space), the average in-plane lattice constant, a_L, of the MQW can be determined using the following eq. (2). The parallel mismatch is given by

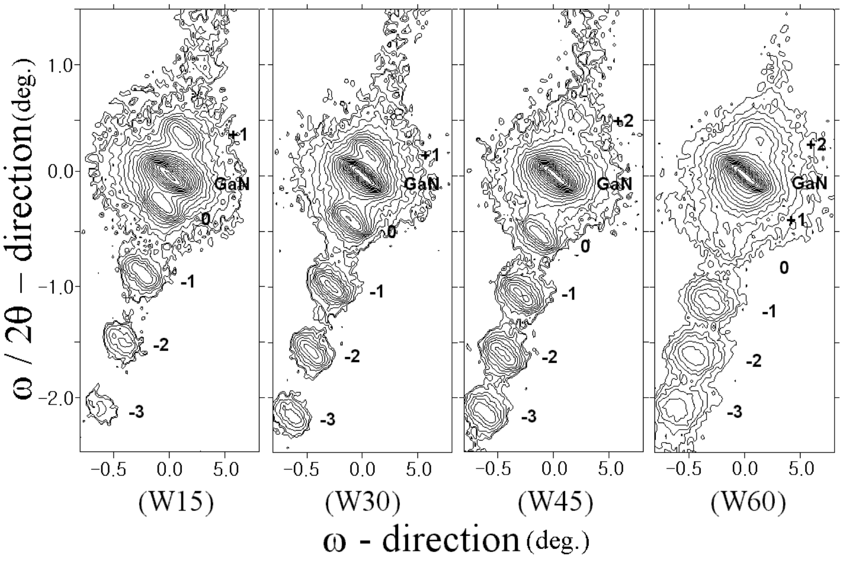

Figure 3. RSMs for the GaN (10·5) reflection of the InGaN/GaN MQWs.

$$M_{parallel} = \frac{\Delta X}{X - \Delta X} = \frac{a_L - a_S}{a_S} \qquad (2)$$

where X is the absolute location of the GaN reciprocal lattice point, ΔX the difference in the in-plane positions between the zeroth order satellite and the GaN reciprocal lattice point and a_S (=3.189 Å) the in-plane lattice constant of GaN [1,6,7].

Figure 4 shows the variation of the average in-plane lattice constants with well thickness. The lattice constant for sample W60 increases sharply while the others for samples W15, W30 and W45 remain nearly constant. This indicates that for W15, W30 and W45 lattice coherency of the MQWs is maintained with the GaN substrate along in-plane direction, the MQW for W60, however, suffered strain relaxation. The degree of relaxation along in-plane direction for W60 is about 2.8%. The peak broadening, therefore, for W60 in Figure 2 and 3 is attributed to the defects generated by lattice relaxation, and the critical thickness of the InGaN/GaN MQW for lattice relaxation is about 6.0 nm. The critical thickness determined in the study exists between the values estimated from the Matthews and Blackeslee model and the Fisher model [3,8].

Figure 5 shows the PL spectra measured at 23 K for the MQWs and the insert shows the variation in the PL intensity ratio of the yellow band at 560 nm (2.2 eV) to the peak intensity. As the well thickness increases the intensity ratio for samples W15, W30 and W45 remains nearly constant, while the ratio for W60 increases sharply. The yellow band is reported to originate from defects in the crystal [9]. The sharp change in the relative intensity for W60 suggests that the sample experienced lattice relaxation, and the fact is consistent with the XRD results.

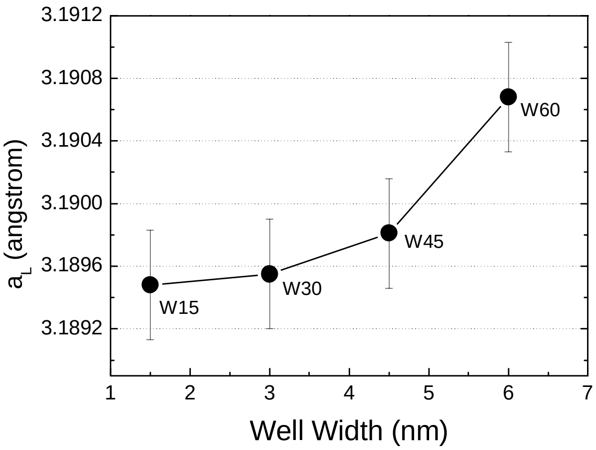

Figure 4. Variation of the average in-plane lattice constants of the MQWs with well thickness.

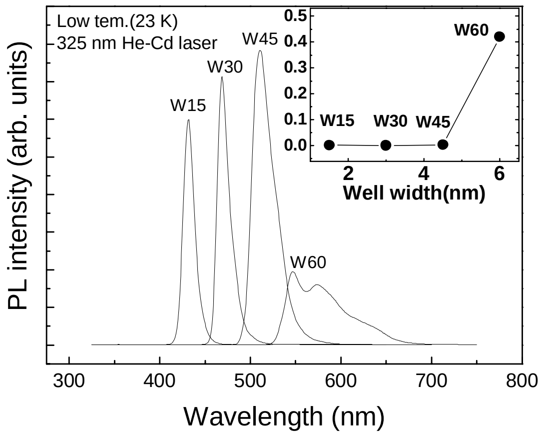

Figure 5. LT-PL spectra for the MQWs. The inset shows the variation in the intensity ratio of the yellow band to the peak intensity.

CONCLUSIONS

In this work, we investigated the structural and the optical properties of 10-period $In_{0.15}Ga_{0.85}N$/GaN MQWs using HRXRD and PL. The barrier thickness of the MQWs was kept constant, 7.5 nm and the well thicknesses were varied, 1.5, 3.0, 4.5, and 6.0 nm. The average strain of the MQW increased as the well thickness increased. The MQW with a 6.0 nm well thickness experienced lattice relaxation. MQWs with well thicknesses of 1.5, 3.0 and 4.5 nm, however, maintained lattice coherency with the GaN epilayers, and the critical well thickness for lattice relaxation of the MQWs used in the study was 6.0 nm. The PL spectra showed that the relative emission intensity of the sample with a 6.0 nm well thickness was lower than for the others, a fact consistent with the X-ray results. The emission intensity, therefore, is considered to be affected by defects due to lattice relaxation of the epilayer.

ACKNOWLEDGEMENTS

This work was supported by the Ministry of Science and Technology, Korea.

REFERENCES

1. O Ambacher, J. Phys. D: Appl. Phys. **32**, 2653 (1998).
2. J. Bai, T. Wang, and S. Sakai, J. Appl. Phys. **88**, 4729 (2000).
3. J. W. Matthews and A. E. Blackeslee, J. Crystal Growth **32**, 256 (1974).
4. Wei Li, Peder Bergman, Ivan Ivanov, Wei-xin Ni, H. Amano and I. Akasa, Appl. Phys. Lett. **69**, 3390 (1996).
5. D. Kapolnek, X. H. Wu, B. Heying, S. Keller, B. P. Keller, U. K. Mishra, S. P. DenBaars and J. S. Speck, Appl. Phys. Lett. **67**, 1541 (1995).
6. Gunther Bauer and Wolfgang Richter, *Optical Characterization of Epitaxial Semiconductor Layer* (Springer, New York, 1996), pp. 294-298.
7. Paul F Fewster, *X-Ray Scattering from Semiconductors* (Imperial College Press, London, 2000), pp. 244-253.
8. A. Fischer, H. Kuhne and H. Richter, Phys. Rev. Lett. **73**, 2712 (1994).
9. H. Liu, J. G. Kim, M. H. Ludwig and R. M. Park, Appl. Phys. Lett. **71**, 347 (1997).