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Recombination Dynamics in GaN and InGaN/GaN Multiple Quantum Wells on Air-bridged Lateral Epitaxial Grown GaN Layers

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Recombination dynamics in GaN and InGaN/GaN 3 quantum wells (QWs) on air-bridged lateral epitaxial grown (ABLEG) GaN have been studied by means of spatial and time-resolved photoluminescence spectroscopy. Internal quantum efficiencies (η_{int}) of luminescence measured in macroscopic photo-excitation were 2 % and 9 % for ABLEG-GaN and ABLEG-InGaN/GaN 3QWs at room temperature (RT). It was found that threading dislocations are not major nonradiative recombination center in both samples. However, comparing the ratio of the difference between PL lifetime at the wing [dislocation density (DD)=10^6 cm^{-2}] and seed (DD=10^9 cm^{-2}) regions, the values of InGaN/GaN 3QWs and GaN are 8 % and 40 %, respectively, indicating that threading dislocations affect less carrier recombination process in InGaN than in GaN. These phenomena can be understood in terms of the model of carrier localization in InGaN active layers. The origin of localization in InGaN active layers is thought to be the fluctuation of well width and/or In mole fluctuation.

KEYWORD: spatial and time-resolved spectroscopy, ABLEG-GaN, threading dislocation, localizaion

1. Introduction

Currently, the growth technique of GaN-based semiconductors has been developed rapidly for the fabrication of light emitting devices and robust electron devices. Actually, an epitaxial lateral overgrowth (ELO) method and a pendeo-epitaxy method have been carried out with the aim of achieving good crystallinity of GaN or InGaN with low dislocation density (DD). More recently, Kidoguchi et al. 1) accomplished a new crystal growth technique which is called air-bridged lateral epitaxial growth (ABLEG).

As for the correlation between threading dislocation and recombination pathway, Sugahara et al. 2) showed by the comparison between transmission electron microscopy (TEM) and cathodoluminescence (CL) mapping that dislocations act as nonradiative recombination centers (NRC). On the other hand, Mukai et al. 3) reported that the efficiency of blue LED, whose defect density is lowered by the ELO technique, is almost the same as that of conventional LEDs grown directly on sapphire. And it was reported that the lifetime of photoluminescence (PL) depended hardly on DD in ELO-GaN by selective-photo-excitation using a metal-masking technique 4), and by site-selective time-resolved PL (TRPL) spectroscopy with spatial resolution less than a few microns 5). Furthermore, Nakamura et al. reported that the difference in the emission efficiency between LEDs grown on sapphire and ELO-GaN substrates becomes smaller with increasing indium (In) mole fraction in InGaN 6). Therefore, it is of great significance to assess the detailed recombination dynamics in InGaN active layers with different In mole fractions and different DDs.

In this paper, we report optical properties of GaN-based layers grown by the ABLEG technique using TRPL spectroscopy with spatial resolution of a few microns.

2. Experimental procedure

We used two types of samples grown by MOCVD using the ABLEG-technique 1). One is (a) ABLEG-GaN and the structure of the ABLEG-GaN (sample (a)) which consists of two regions, one is seed region having high DD (10^9 cm^{-2}) and another is wing region having low DD (10^6 cm^{-2}) is schematically depicted in Fig. 1. Another sample is (b) InGaN (35 Å) / GaN (105 Å)-3QWs which is grown on the ABLEG-GaN.

For PL and TRPL measurements, the pulsed

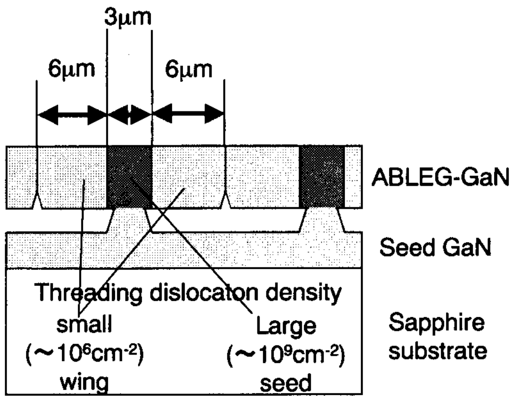

Fig. 1. The cross section of ABLEG-GaN (sample (a)).

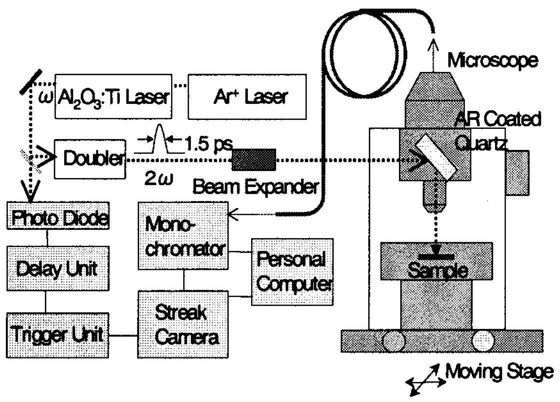

Fig. 2. TRPL measurement system in conjumction with UV-optical microscope.

excitation source was second or third harmonic generation (SHG or THG) of a mode-locked Al_2O_3 : Ti laser which was pumped by Ar^+-laser. The pulse width and the repetition rate were 1.5 ps and 80.0 MHz, respectively. The excitation wavelength was selected as 266 nm (THG) or 353 nm (SHG) for sample (a) and 370 nm (SHG) for (b) in order to excite only InGaN active layers. PL detection was carried out using a multi-channel analyzer and TRPL detection system was composed of a streak camera in conjunction with a 25 cm monochromator. In order to avoid the multiexcitation for sample (b), repetition rate of the source (80.0 MHz) was selected to 4.0 MHz by the acoustic optic (AO) modulator. Fig. 2 shows TRPL measurement system with micro spatial resolution, the beam was focused down by using an air-gapped object lens.

3. Result and discussion

Fig. 3 shows PL spectra of two samples at room temperature (RT). The PL main peak of Sample (a) is located at 3.41 eV. The PL spectrum of sample (b) is oscillated owing to the effect of thin layer interference.

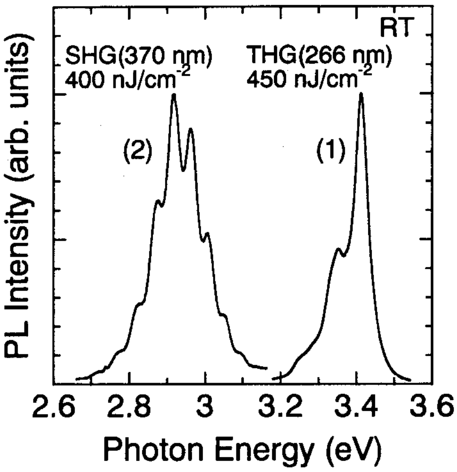

Fig. 3. PL spectra of (1) sample (a) and (2) sample (b) at RT. The excitation source was THG (266 nm) for sample (a) and SHG (370 nm) for sample (b).

Therefore, the real PL main peak energy without this effect would be between the energies of two peaks (2.918 eV and 2.962 eV) suiting to 2.940 eV. From this PL peak energy, we calculated the In mole fraction of InGaN active layers of sample (b) using following equation,

$$E_{InGaN} = E_{GaN}(1-x) + E_{InN}x - bx(1-x), \qquad (1)$$

where x is the In mole fraction and E_{InGaN}, E_{GaN} and E_{InN} are the band gap of InGaN, GaN and InN, respectively. And b is bowing parameter. Furthermore, we considered the effect of blue shift due to quantum confinement, as well as the effect of the red shift due to the piezo-electric field in the active layer. Using the reported value of b=2.0 eV, the In mole fraction of sample (b) was estimated to be 17 %.

Fig. 4 shows PL decay spectra of ABLEG-GaN [sample (a)] monitored at A free exciton (E_{XA}) from seed region (DD=10^9 cm^{-2}) (a) and wing region (DD=10^6 cm^{-2}) (b) at RT. Both decay spectra showed double exponential curves. Both first component (τ_1) and second component (τ_2) are limited by the channel of nonradiative recombination[5]. Therefore, we discuss how τ_1 value changes with regions in a sample because the fast process limits the PL decay process compared with the slow one. It was found that PL lifetime (τ_{PL}) measured at a wing region is 130 ps which is larger than the value monitored at a seed region (90 ps) whose DD is three orders of magnitude larger than that in the wing region. This indicates that the larger DD makes τ_{PL} shorter, but τ_{PL} did not differ so largely between two regions having the DD difference of three orders of magnitude, as suggested previously [5]. It is noted that the double exponential behavior in PL decay is changed to single exponential one as a result of the elimination of the first component (τ_1) if a small amount of indium (less than a few % in mole fraction) is added to the layer.

Fig. 5 shows PL decay spectra of sample (b) at RT. It was found that τ_{PL} values measured at a wing region and at a seed region were 1.74 ns and 1.60 ns, respectively. The tendency that the larger DD makes τ_{PL} shorter is similar to the result for sample (a). Therefore, threading dislocation affects emission efficiency in InGaN as well as in GaN. Fig. 6 shows the picture of fluorescence micro-image taken at sample (b) (ABLEG-InGaN/GaN 3QWs) through the 420 nm band pass filter. In fact, the intensity of blue emission in the wing region is more intense than that in the window region [7]. Comparing the ratio of the difference between τ_{PL} at the wing and seed regions, however, the values for sample (a) and (b) are 40 % and 8 %, respectively. Considering that internal quantum efficiencies (η_{int}) of luminescence measured in macroscopic photo-excitation were 2 % and 9 % for ABLEG-GaN and ABLEG-InGaN/GaN 3QWs at

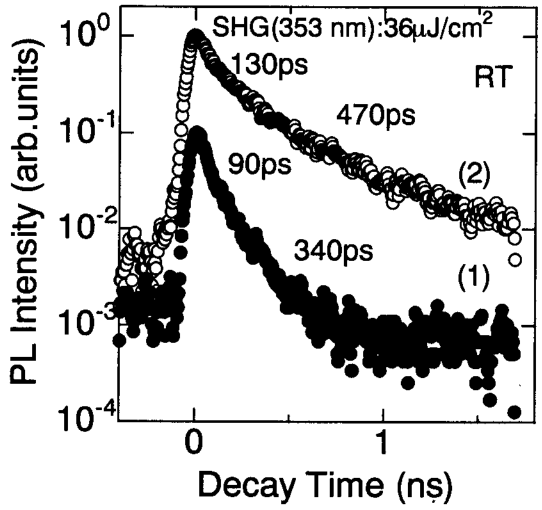

Fig. 4. PL decay spectra of sample (a) at (1) seed region (DD = 10^9 cm^{-2}), and at (2) wing region (DD = 10^6 cm^{-2}).

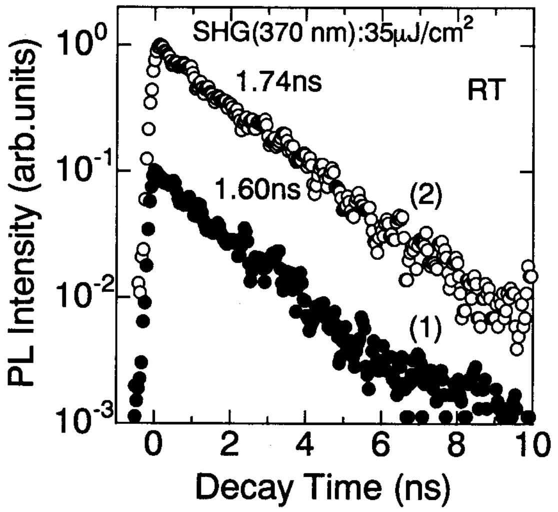

Fig. 5. PL decay spectra of sample (b) at (1) seed region (DD = 10^9 cm^{-2}), and at (2) wing region (DD = 10^6 cm^{-2}).

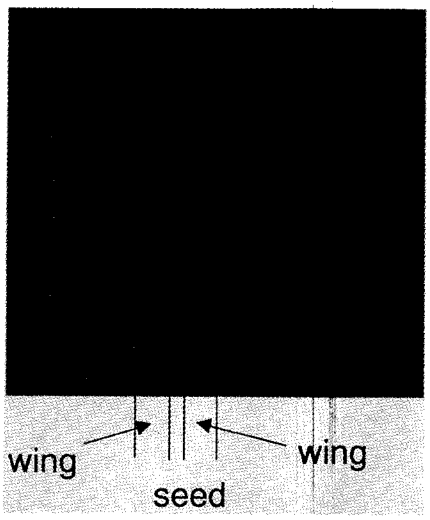

Fig. 6. Fluorescence micro-image taken at sample (b).

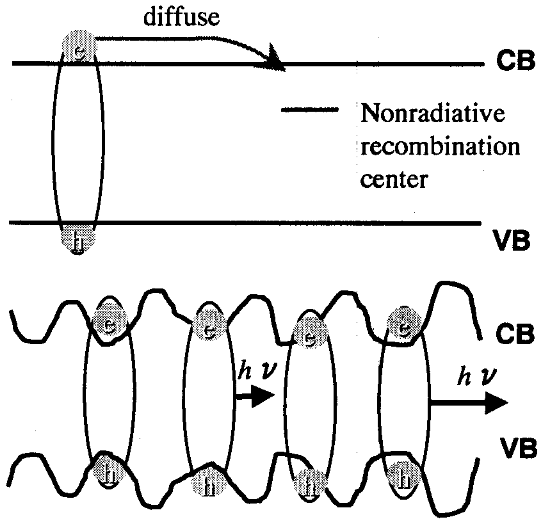

Fig. 7. The model of the carrier in (i) in GaN and (ii) InGaN active layers.

(i) In GaN, the potential fluctuation is so small that carriers can diffuse easily, so that the carriers are captured at nonradiative recombination centers.

(ii) In InGaN active layers, the potential fluctuation is too large for carriers to diffuse over the potential barriers, therefore it is difficult for carriers to be captured at nonradiative recombination centers.

room temperature (RT), threading dislocation is not major NRC at RT and this tendency is more clearly in sample (b) than in sample (a).

These phenomena can be understood in terms of the model of carrier localization depicted in Fig. 7. The potential fluctuation in GaN is so small that carriers can diffuse easily, so that the carriers are captured at NRC and recombine nonradiatively. On the other hand, in InGaN active layers the potential fluctuation is too large for carriers to diffuse over the potential barriers. Therefore, it is difficult for carriers to be captured at NRC caused by threading dislocations. The origin of localization in InGaN layers is thought to be the fluctuation of well width and/or In mole fluctuation. The effect of potential fluctuation on the recombination pathway seems to be generally applied independent on the growth technology because the results obtained at ABLEG-samples do not conflict with those at ELO samples [4),5)].

4. Conclusion

We have studied the recombination dynamics in GaN and InGaN/GaN 3QWs fabricated by air-bridged lateral epitaxial growth (ABLEG) technique by employing spatial and time-resolved photoluminescence spectroscopy. The spatial resolution with less than about 1 micron has been achieved by using air-gapped object lens. It was found that threading dislocations are not major nonradiative recombination center in either ABLEG-GaN or InGaN/GaN 3QWs on ABLEG-GaN at room temperature. However, comparing the ratio of the difference between PL lifetime at the wing and seed regions in ABLEG-InGaN/GaN 3QWs (8 %) and ABLEG-GaN (40 %) indicated that threading dislocations affected less carrier recombination process in InGaN than in GaN. And it was found that these phenomena could be understood in terms of the model of carrier localization in InGaN active layers. And it was also found that the effect of potential fluctuation on the recombination pathway found in the ELO-grown samples could also be applied to the layers grown by the ABLEG technique.

Acknowledgment

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7) It is interesting to note that the coalescence region between wing and window shows the most intensive blue emission. This is probably because the internal reflection is hindered at this region, resulting in the enhancement of photo-extraction efficiency out of semiconductors.