phys. stat. sol. (c) **3**, No. 6, 2109–2112 (2006) / **DOI** 10.1002/pssc.200565288

# Carrier dynamics of optical emission from two-dimensional electron gas in undoped AlGaN/GaN single heterojunctions

**H. S. Kwack**[1], **Y. H. Cho**[*,1], **G. H. Kim**[2], **M. R. Park**[3], **D. H. Youn**[3], **S. B. Bae**[3], **K.-S. Lee**[3], **J. H. Lee**[4], and **J. H. Lee**[4]

[1] Department of Physics and Institute for Basic Science Research, Chungbuk National University, Cheongju 361-763, Korea
[2] School of Information and Communication Engineering, Sungkyunkwan University, Suwon 440-746, Korea
[3] Basic Research Laboratory, Electronics and Telecommunications Research Institute, Daejeon 305-350, Korea
[4] Department of Electric and Electronic Engineering, Kyungpook National University, Taegu 702-701, Korea

Received 7 August 2005, revised 10 April 2006, accepted 10 April 2006
Published online 22 May 2006

**PACS** 73.20.At, 77.65.-j, 78.47.+p, 78.55.Cr, 78.60.Hk, 78.66.Fd

The strucutral and optical properties of undoped AlGaN/GaN single heterojunctions (HJs) were studied by means of high-resolution x-ray diffraction, photoluminescence (PL), cathodoluminescence (CL), and time-resolved PL spectroscopy. An additional two-dimensional electron gas (2DEG)-related PL and CL emission appeared at about 40 meV below the GaN band-edge emission energy and persisted up to about 100 K, while this peak disappeared when the top AlGaN layer was removed by reactive ion etching. Depth-resolved CL spectra reveal the presence of a 2DEG at the heterointerface. The additional PL and CL emission below the GaN band-edge emission is attributed to the recombination between photogenerated holes and electrons confined at 2DEG states in the triangular-shaped interface potential. For the 2DEG emission, we observed an about 50-ps delayed rise time than the GaN and AlGaN emissions by using time-resolved PL, indicating effective carrier transfer from the GaN flatband and AlGaN regions to the heterointerface. From the results, we explained the optical properties and carrier recombination dynamics of 2DEG, GaN, and AlGaN emissions in undoped AlGaN/GaN single HJs.



## 1 Introduction

$Al_xGa_{1-x}N/GaN$ heterojunctions (HJs) have attracted much attention for their promising applications for high-voltage, high-current power, and high-temperature electronic devices. The $Al_xGa_{1-x}N/GaN$ HJs have been shown to induce high sheet carrier densities two-dimensional electron gas (2DEG) because of high sheet carrier concentration originating from the strong built-in piezoelectric and spontaneous polarization effect at the heterointerface [1–3]. Up to now, rather sophisticated HJs such as modulation-doped HJs [4] or double-barrier type HJs [5] have been mostly used to investigate optical properties of $Al_xGa_{1-x}N/GaN$ HJs, since stronger 2DEG-related emission can be obtained in these kinds of HJs. However, the optical properties and carrier dynamics for two-dimensional electrons in undoped $Al_xGa_{1-x}N/GaN$ single HJs are rare in the literature, even though the undoped and single HJs are the most fundamental HS. The optical properties and carrier dynamics in undoped $Al_xGa_{1-x}N/GaN$ single HJs are crucial not only for understanding the intrinsic properties in the unique HJs with a strong built-in internal field but also for

[*] Corresponding author: e-mail: yonghcho@chungbuk.ac.kr, Phone/Fax: +82-43-261-3342

developing the practical devices such as high-electron mobility transistors. In this work, we have investigated the structural and optical properties of two-dimensional electrons in undoped AlGaN/GaN single HJs by means of high resolution x-ray diffraction (HRXRD), photoluminescence (PL), cathodoluminescence (CL) and time-resolved PL spectroscopy.

## 2 Experiments

AlGaN/GaN single HJ structures consisting of a 25-nm-thick $Al_xGa_{1-x}N$ ($x \le 0.3$) layer grown on a 1.45-µm-thick undoped GaN were prepared by metalorganic chemical vapor deposition on (0001) sapphire substrates with a 30-nm thick GaN buffer layer. Trimethylgallium, ammonia, and trimethyl-aluminum were used as the Ga, N, and Al precursors, respectively. The growth temperature and the reactor pressure of the undoped GaN (the AlGaN) layer were 1020 (1030) $^{o}$C and 300 (150) Torr, respectively. Shubnikov-de Haas oscillations were clearly observed in the AlGaN/GaN single HJs, which indicates the existence of 2DEG in the AlGaN/GaN heterointerface [6]. The electrical properties were measured by Hall-effect measurement at room temperature. The Hall mobility of 750 $cm^2$/V·s and the sheet charge density of $1.3\times10^{13}$ $cm^{-2}$ were obtained for the AlGaN /GaN HJ. PL spectra were measured as a function of temperature ranging from 10 to 300 K using the 325 nm line of a He–Cd laser. CL measurements were carried out using a scanning electron microscope system. All CL spectra were taken from 8 to 30 keV at 5 K using currents from 0.8 to 1.5 nA, respectively. Time-resolved PL spectra were measured using a frequency-tripled picosecond mode-locked Ti:sapphire laser (280 nm) for excitation and a multichannel plate photomultiplier tube for detection.

## 3 Results

Figure 1 shows (a) the HRXRD diffraction curve for the (00·4) direction of and (b) the PL spectrum of the $Al_xGa_{1-x}N$/GaN single HJ (solid line), and those of the GaN layer after removing the top AlGaN layer by reactive ion etching (RIE) (dotted line). The etched depth was found to be about 243.8±2.7 nm by using atomic force microscopy, as shown in the inset of Fig. 1(a). The absence of AlGaN top layer after RIE is also confirmed by the disappearance of AlGaN peak of the HRXRD data. The PL emissions due to free exciton A ($FX_a$), free exciton B ($FX_b$) and bound exciton ($BX$) are observed at 3.481, 3.487, and 3.498 eV, respectively. The emission peaks related to 1 longitudinal optical (LO) and 2 LO phonon replicas have ~ 92 meV energy periodicity from the zero phonon peak of undoped GaN, as marked with vertical grids in Fig. 1(b). We observed that an additional peak emerged for the AlGaN/GaN HJ, while this peak disappeared at PL when the top AlGaN layer was etched off. We note that this peak is typically not observable for as-grown undoped GaN single layers.

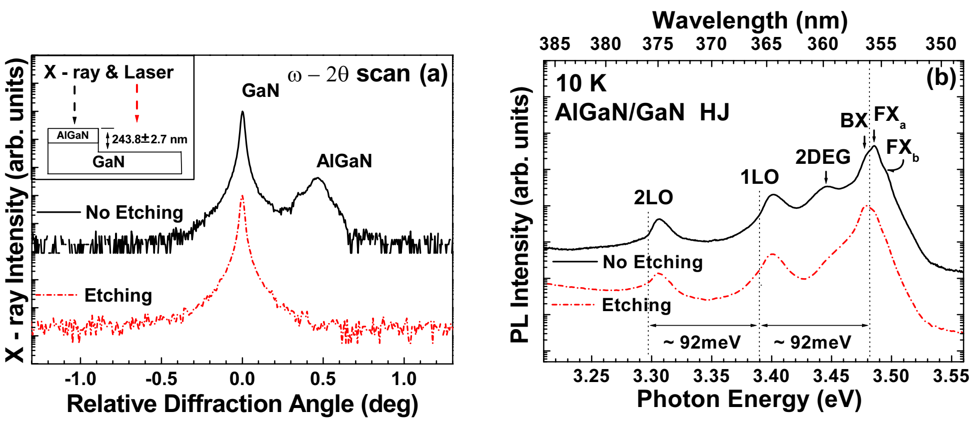



**Fig. 1** (a) Comparison of the ω-2θ diffraction curve of and (b) 10 K PL spectra of the AlGaN/GaN HJ and that of the GaN layer after removing the AlGaN top layer by RIE.

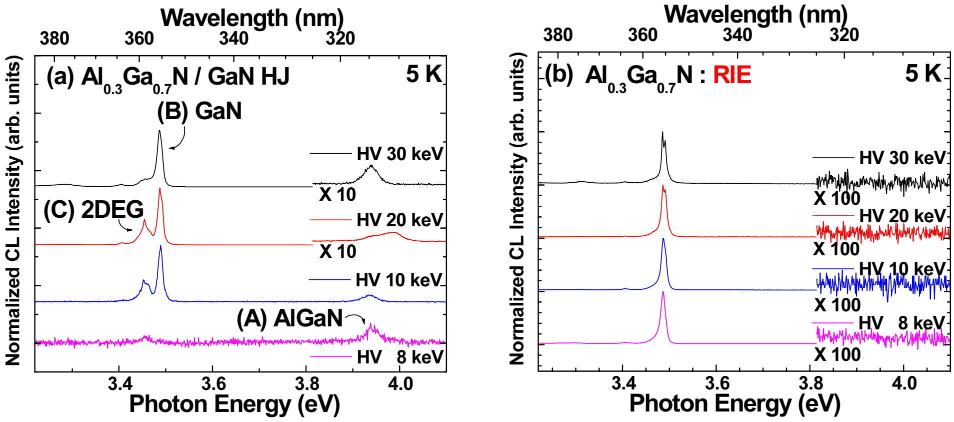



**Fig. 2** Depth-resolved CL spectra of (a) the AlGaN/GaN HJ and (b) the GaN layer after removing the AlGaN top layer. The AlGaN (A), GaN (B) and 2DEG (C) emissions are indicated by arrows.

To further investigate the properties of the 2DEG related emission, we obtained depth-resolved CL spectra of the (a) AlGaN/GaN HJ and (b) the GaN after removing AlGaN layer with increasing accelerating voltage from 8 to 30 keV. The CL technique allows us to probe the emission properties of different depths in the material by varying electron beam energy (accelerating voltage). Based on the CL depth profiling data of GaN for different electron-beam voltages ranging from 8 to 30 keV [7], we can investigate the properties of a 2DEG located at the heterointerface with accelerating voltages. The AlGaN (A), GaN *BX* (B), and 2DEG (C) related emissions from AlGaN/GaN single HJ are clearly observed in Fig. 2(a). The 2DEG related emission was seen at ~ 3.45 eV and the AlGaN layer at ~ 3.94 eV, whose peak intensity appears to increase gradually with increasing accelerating voltage, as shown in Fig. 2(a). However, these CL peaks disappeared when the top AlGaN layer was etched off. Therefore, the additional PL and CL emission below the GaN band-edge emission is attributed to the recombination between photogenerated holes and electrons confined at 2DEG states in the triangular-shaped interface potential. The separate peaks for GaN (especially at 20 and 30 keV) can be attributed to GaN bound and free exciton emissions.

Figure 3 shows the excitation power (circles) and the temperature dependence of the energy separation ($\Delta E$) between the 2DEG and the GaN $FX_a$ peaks. The GaN band-edge peak shifts to lower energy while the 2DEG peak does not change much with increasing temperature, resulting in a gradual decrease of $\Delta E$ from about 39 to 37 meV with varying temperature from 10 to 70 K. We also performed excitation-power dependent PL experiments ranging from 0.01 to 10 mW at 10 K, and observed that $\Delta E$ decreases from about 41 to 39 meV with increasing excitation power. These results can be explained by the screening effect of carriers in a triangular potential well at the AlGaN/GaN heterointerface [5].

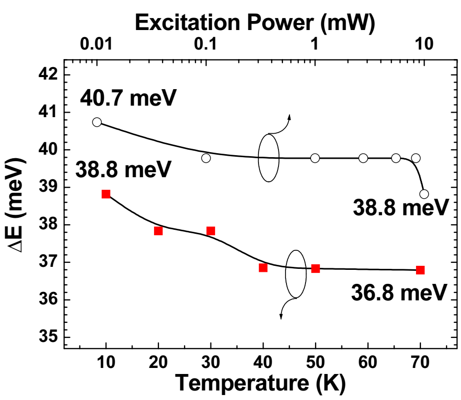
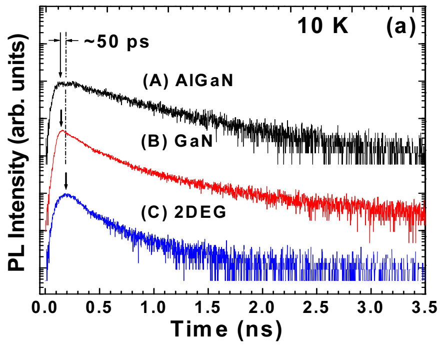



**Fig. 3** Excitation power and temperature dependences of the energy separation ($\Delta E$) between the 2DEG and the GaN $FX_a$ peaks.



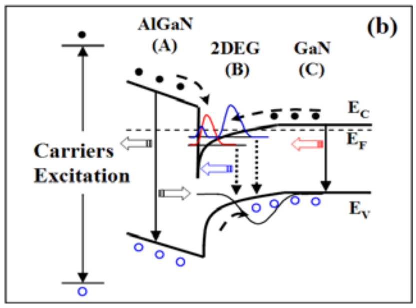




**Fig. 4** (a) Temporal evolution of PL intensities monitored at AlGaN (A), GaN (B), and 2DEG (C) PL peaks. (b) Schematic band diagram and related carrier dynamics of (A), (B), and (C).

Figure 4(a) shows time evolutions of PL related to the AlGaN (A), GaN (B), and 2DEG (C) emissions, which were vertically shifted for clarity. We observed a longer decay time of ~ 0.7 ns for the AlGaN-related emission than those for the GaN and 2DEG-related emissions [8]. A single exponential decay profile was seen for the AlGaN emission, while not for the GaN and 2DEG emissions. A dominant faster decay time and a slower one were extracted out to be ~ 0.2 ns and ~ 0.7–0.8 ns, respectively, for both GaN and 2DEG emissions by fitting of two exponential functions. We note that the rising time of 2DEG emission is delayed ~50 ps with respect to those of the AlGaN and GaN emissions [Fig. 4(a)]. This indicates that the electrons photongenerated in the GaN flat-band region efficiently transfer to the triangular well region at the heterointerface. Since the photogenerated holes are used for both the GaN recombination and the 2DEG recombination, the first stage of the decay of the 2DEG emission can be determined by the fast GaN recombination. After running out the most photogenerated holes, the 2DEG emission is affected by the slow recombination between 2DEG and remaining holes [Fig. 4(b)].

## 4 Conclusions

The 2DEG-related optical properties of AlGaN/GaN single HJs have been examined. An additional 2DEG emission appeared at about 40 meV below the GaN band-edge emission energy. The presence of the 2DEG at the heterointerface was also confirmed by depth-resolved CL spectra. The delayed rise time of the 2DEG emission indicates an effective carrier generation in the GaN flat-band region and a successive carrier transfer from the GaN and AlGaN regions to the heterointerface.

**Acknowledgements** The authors would like to acknowledge the help of Dr. Dang and Mr. Lim for the CL and time-resolved PL experiments, respectively. This work was supported by the research grant of the Chungbuk National University in 2005.

## References

[1] R. Gaska, J. W. Yang, A. D. Bykhovski, M. S. Shur, V. V. Kaminski, and S. M. Soloviov, Appl. Phys. Lett. **72**, 64 (1997).
[2] T. Nishida, H. Saito, and N. Kobayashi, Appl. Phys. Lett. **79**, 711 (2001).
[3] D.-W. Kim, K.-S. Chea, Y.-J. Park, I.-H. Lee, and C.-R. Lee, phys. stat. sol. (a) **201**, 2686 (2004).
[4] J. P. Bergman, T. Lundstron, B. Monemar, H. Amano, and I. Akasaki, Appl. Phys. Lett. **69**, 3456 (1996).
[5] B. Shen, T. Someya, O. Moriwaki, and Y. Arakawa, Appl. Phys. Lett. **76**, 679 (2000).
[6] H.-S. Kwack, Y.-H. Cho, G.-H. Kim, M. R. Park, D. H. Youn, S. B. Bae, K.-S. Lee, J.-H. Lee, and J.-H. Lee, Appl. Phys. Lett. **87**, 041909 (2005).
[7] K. Fleischer, M. Toth, M. R. Phillips, J. Zou, G. Li, and S. J. Chua, Appl. Phys. Lett. **74**, 1114 (1999).
[8] Y. H. Cho, G. H. Gainer, J. B. Lam, J. J. Song, W. Yang, and W. Jhe, Phys. Rev. B **61**, 7203 (2000).