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Optical properties and carrier dynamics of two-dimensional electrons in AlGaN/GaN single heterostructures

Ho-Sang Kwack and Yong-Hoon Cho[a]
Department of Physics and Institute for Basic Science Research, Chungbuk National University, Cheongju 361-763, Korea

G. H. Kim
School of Information and Communication Engineering, Sungkyunkwan University, Suwon 440-746, Korea

M. R. Park, D. H. Youn, S. B. Bae, and K.-S. Lee
Basic Research Laboratory, Electronics and Telecommunications Research Institute, Daejeon 305-350, Korea

Jae-Hoon Lee and Jung-Hee Lee
Department of Electric and Electronic Engineering, Kyungpook National University, Taegu 702-701, Korea

T. W. Kim
Advanced Semiconductor Research Center, Division of Electronics and Computer Engineering, Hanyang University, Seoul 133-791, Korea

T. W. Kang
Quantum-Functional Semiconductor Research Center, Dongguk University, Seoul 100-715, Korea

Kang L. Wang
Department of Electronic Engineering, University California at Los Angeles, Los Angeles, California 90095

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We have investigated the optical properties and carrier dynamics of the two-dimensional electron gas (2DEG) in $Al_{0.4}Ga_{0.6}N/GaN$ single heterostructures grown by metalorganic chemical vapor deposition by means of photoluminescence (PL), PL excitation, and time-resolved PL spectroscopy. Shubnikov-de Haas oscillations were clearly observed at 1.5 K, confirming the existence of a 2DEG. An additional 2DEG PL emission appeared at about 40 meV below the GaN band-edge emission and persisted up to about 100 K, while this peak disappeared when the top $Al_{0.4}Ga_{0.6}N$ layer was removed by reactive ion etching. We observed abrupt PLE absorption at GaN band edge energy and approximately 50-ps delayed risetime compared to GaN and AlGaN emissions, indicating effective carrier transfer from the GaN flatband and AlGaN regions to the heterointerface. Even though the 2DEG emission is a spatially-indirect (slow) recombination, a fast decay component of ~0.2 ns is found to be dominant in 2DEG emission because of the fast exhaustion of photogenerated holes in GaN flatband region via spatially-direct (fast) GaN recombination. From the results, we explain the carrier generation, transfer, and recombination dynamics and the relationships between 2DEG, GaN, and $Al_{0.4}Ga_{0.6}N$ emissions in undoped $Al_{0.4}Ga_{0.6}N/GaN$ single heterostructures. © *2005 American Institute of Physics*. [DOI: 10.1063/1.2000334]

$Al_xGa_{1-x}N/GaN$ heterostructures (HSs) have recently attracted much attention for their promising applications for high-speed, high-power, and high-temperature electronic devices (e.g., high electron mobility transistors), because of high sheet carrier concentration originating from the strong built-in piezoelectric and spontaneous polarization effect at the heterointerface.[1–3] Although both the electrical and optical properties of a two-dimensional electron gas (2DEG) in AlGaAs/GaAs HSs have been extensively studied, most of the studies for $Al_xGa_{1-x}N/GaN$ HSs have concentrated on electrical properties. So far, only a few optical studies have been reported for $Al_xGa_{1-x}N/GaN$ HSs such as modulation-doped heterojunctions (HJs)[4–7] and double HJs,[6] where a higher intensity of 2DEG emission was obtained by injection of dopant electrons and by confinement of photogenerated holes.

Undoped and single HJs are the most fundamental heterostructure in any compound semiconductors, and the studies of 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 these unique HSs with a strong built-in internal field, but also for understanding and developing practical devices such as high-electron mobility transistors. Nevertheless, reports of 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. In this letter, we have investigated the optical properties and carrier dynamics (including carrier generation, transfer, and recombination) of two-dimensional electrons in undoped $Al_{0.4}Ga_{0.6}N/GaN$ single HJs by means of photoluminescence (PL), PL excitation (PLE), and time-resolved PL (TRPL) spectroscopy.

Undoped $Al_{0.4}Ga_{0.6}N/GaN$ single HJs were grown by metal-organic chemical vapor deposition on (0001) sapphire substrates with a 30-nm thick GaN buffer layer. The growth temperature and the reactor pressure of a 1.45-μm-thick undoped GaN (a 25-nm-thick $Al_{0.4}Ga_{0.6}N$) layer were 1020 (1030) °C and 300 (150) Torr, respectively. The growth in-

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[a] Electronic mail: yonghcho@chungbuk.ac.kr

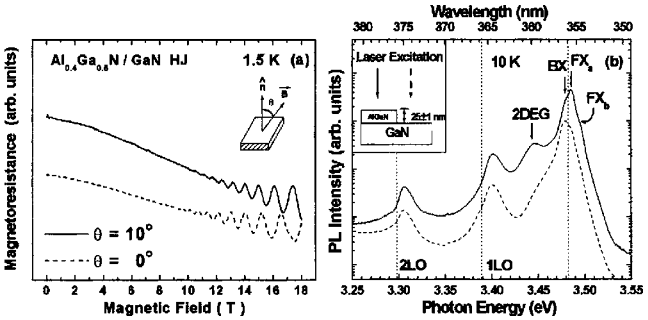

FIG. 1. (a) SdH oscillations taken at 1.5 K for an undoped $Al_{0.4}Ga_{0.6}N/GaN$ single HJ with $\theta=0°$ (dotted line) and $\theta=10°$ (solid line). (b) 10 K PL spectra for an undoped $Al_{0.4}Ga_{0.6}N/GaN$ single HJ (solid line) and the GaN layer (dotted line). For the GaN sample, the top $Al_{0.4}Ga_{0.6}N$ layer is removed by RIE. The spectra of free excitons (FX_a, FX_b) and bound exciton (BX) indicated by arrows.

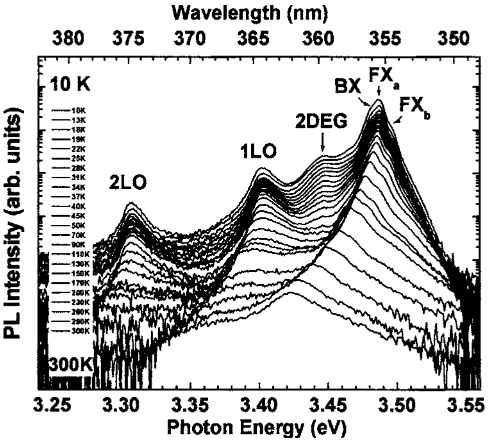

FIG. 2. Temperature dependent PL spectra of the undoped $Al_{0.4}Ga_{0.6}N/GaN$ single HJs in the temperature range from 10 to 300 K.

terruption time between $Al_{0.4}Ga_{0.6}N$ and GaN layers was chosen to be 3 min.[8] The Al compositions of the $Al_xGa_{1-x}N$ layer were determined to be about 40% by high-resolution x-ray diffraction. The electrical properties were measured by Hall-effect measurement. The room temperature mobility of the 2DEG at the $Al_{0.4}Ga_{0.6}N/GaN$ heterointerface was 750 $cm^2/V\ s$ and the sheet charge density of the 2DEG was determined to be $1.3\times10^{13}\ cm^{-2}$. This high value of the sheet charge density can be attributed to the strong polarization effect.[9] 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 with a power of ~10 mW. Low-excitation-power PL and PLE spectra were also measured using the quasimonochromatic light dispersed by a monochromator from a xenon lamp. TRPL spectra were measured using a frequency-tripled picosecond mode-locked Ti:sapphire laser for excitation and a multi-channel plate photomultiplier tube for detection.

Shubnikov-de Haas (SdH) measurements were performed for an undoped $Al_{0.4}Ga_{0.6}N/GaN$ single HJ at 1.5 K in magnetic fields up to 18 T in an Oxford superconducting magnet system by using a Keithley 181 nanovoltmeter. SdH oscillations were clearly observed as shown in Fig. 1(a). The 2DEG behavior of the free-electron carriers giving rise to the SdH oscillations was substantiated by using magnetic fields oriented at 0° and 10° to the normal to the surface, which confirms the existence of 2DEG.[10,11] Figure 1(b) shows the PL spectrum of an undoped $Al_{0.4}Ga_{0.6}N/GaN$ single HJ with GaN thickness of 1.45 μm (solid line), and that of the GaN layer after removing the top $Al_{0.4}Ga_{0.6}N$ layer by reactive ion etching (RIE) (dotted line). The etched depth was found to be about 25±1 nm by using an alpha-step with a resolution of 0.8 nm (KLA-Tencor Alpha Step IQ), as shown in the inset of Fig. 1(b). The emissions due to bound exciton (BX), free exciton A (FX_a), and free exciton B (FX_b) are observed at about 3.481, 3.487, and 3.498 eV, respectively.[12] 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).[13] We clearly observed that an additional peak at ~3.448 eV emerged for the $Al_{0.4}Ga_{0.6}N/GaN$ HJ, while this peak disappeared when the top $Al_{0.4}Ga_{0.6}N$ layer was etched off. We also note that this peak is typically not observable for as-grown undoped GaN single layers. Therefore, the additional PL 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.

Figure 2 shows the PL spectra of the undoped $Al_{0.4}Ga_{0.6}N/GaN$ single HJ in the temperature range of 10–300 K. The 2DEG peak is clearly distinguishable up to 90 K, and becomes merged with the higher energy tail of 1 LO phonon replica of the free exciton after 110 K. The GaN band-edge peak shifts to lower energy while the 2DEG peak does not change much with increasing temperature, resulting in the energy separation (ΔE) between the 2DEG and the GaN FX_a peaks gradually decreasing from about 39 to 37 meV with varying temperature from 10 to 70 K. Figure 3 shows low-excitation-power PL and PLE spectra for the undoped $Al_{0.4}Ga_{0.6}N/GaN$ single HJs taken at 10 K. In this PL spectrum, the GaN BX peak becomes dominant than GaN FX_a peak due to low excitation condition. The PLE experiments were carried out with the detection energies of 3.449 and 3.441 eV for the higher and lower energy side of the 2DEG peak, respectively. For PLE spectra measured at both detection energies, PLE absorption edges are clearly observed near the GaN band-edge emission. This indicates that carriers responsible for the 2DEG-related emission are mostly supplied by carrier generation in the GaN flat-band region and successive carrier transfer to the heterointerface, rather than by the direct formation of 2DEG near the heterointerface.

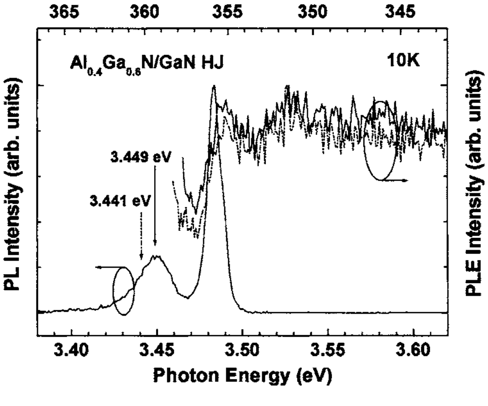

FIG. 3. 10 K PL and PLE spectra of the undoped $Al_{0.4}Ga_{0.6}N/GaN$ single HJs. The intensity of PLE signal abruptly decreases near the GaN band edge energy with decreasing excitation energy.

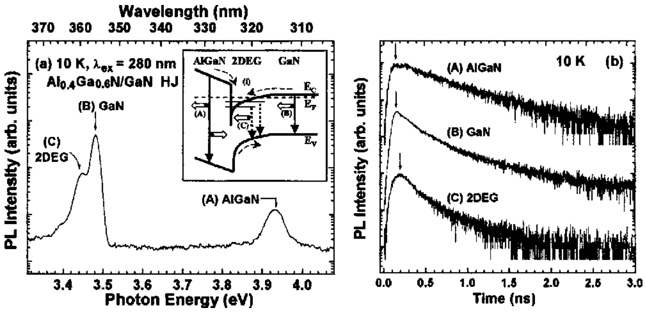

FIG. 4. (a) 10 K time-integrated PL spectrum of the undoped $Al_{0.4}Ga_{0.6}N/GaN$ single HJs. A schematic band diagram and the related carrier dynamics are shown in the inset of (a). (b) Temporal evolution of PL intensities monitored at AlGaN (A), GaN (B), and 2DEG (C) PL peak energies. All spectra in (b) are normalized, and then shifted in the vertical direction for clarity.

To further elucidate the carrier dynamics related to the 2DEG emission, we carried out TRPL measurements at 10 K. Figure 4(a) shows a time-integrated PL spectrum of the undoped $Al_{0.4}Ga_{0.6}N/GaN$ single HJ excited at 280 nm (an higher energy excitation than the top $Al_{0.4}Ga_{0.6}N$ bandgap energy) by a frequency-tripled, pulsed Ti:sapphire laser with an average power of ~0.1 mW. The $Al_{0.4}Ga_{0.6}N$ (A), GaN *BX* (B), and 2DEG (C) related emissions from $Al_{0.4}Ga_{0.6}N/GaN$ single HJ are clearly observed in Fig. 4(a). Figure 4(b) shows time evolutions of PL related to the $Al_{0.4}Ga_{0.6}N$, GaN, and 2DEG emissions. We observed a longer decay time of ~0.7 ns for the $Al_{0.4}Ga_{0.6}N$-related emission than those for the GaN and 2DEG-related emissions, probably due to carrier localization effect caused by alloy potential fluctuations of the AlGaN ternary system.[14] A single exponential decay profile was seen for the $Al_{0.4}Ga_{0.6}N$ emission, while not for the GaN and 2DEG emissions. By fitting of two exponential functions $I(t)=A_1\exp(-t/\tau_1)+A_2\exp(-t/\tau_2)$, a dominant fast component (τ_1) and a slower one (τ_2) of decay times for both GaN and 2DEG emissions were extracted out to be ~0.2 ns and ~0.7–0.8 ns, respectively. Interestingly, we clearly observed that the rising time of 2DEG emission is delayed about 50 ps with respect to those of the AlGaN and GaN emissions, as indicated by vertical arrows in Fig. 4(b).

Based on the PLE and TRPL results, we can explain the carrier generation, transfer, and recombination dynamics of the 2DEG-related emission in undoped AlGaN/GaN single HJs as follows [see the inset of Fig. 4(a)]: (i) After photogeneration of carriers via laser excitation, effective carrier transfer from the GaN (and also possibly from AlGaN) region to the triangular potential well at the heterointerface occurs with the help of a strong built-in internal field. This plays an important role for 2DEG-related emission in undoped AlGaN/GaN single HJs, resulting in an abrupt PLE absorption edge at GaN band-edge energy (Fig. 3) and the ~50-ps delayed risetime for the 2DEG emission [Fig. 4(b)]. (ii) Since the high density of electrons exists in the 2DEG states by residual and transferred electrons, the decay of the 2DEG recombination relies on the lifetime of the photogenerated holes. Most photogenerated holes must exist in the GaN flatband region due to the strong built-in internal electric field near the heterointerface, and contribute not only to the "spatially-indirect" (slower) 2DEG-related recombination (between electrons in 2DEG states at heterointerface and holes in GaN flatband region) but also to the "spatially-direct" (faster) GaN recombination (between electrons and holes in GaN flatband region). Therefore, the decay of the 2DEG-related emission (that is intrinsically spatially-indirect and slow recombination) is predominantly determined by the GaN recombination (that is direct and fast recombination), leading to almost the same decay time (τ_1) of the 2DEG emission as the fast GaN band-edge recombination. (iii) After exhaustion of most photogenerated electrons in the GaN flatband region via the fast GaN recombination process, recombination between the electrons in the 2DEG states and remaining holes in the GaN flatband region can still proceed to the 2DEG emission with a slower decay time of τ_2 at the last stage of the recombination. In addition, the longer decay time of $Al_{0.4}Ga_{0.6}N$ layer may allow the excess carriers to be transferred from the $Al_{0.4}Ga_{0.6}N$ top layer to the GaN region (or to be regenerated in GaN region via a photon-recycling reabsorption process), which may result in a similar profile at the last stage of all the decays.

In conclusion, we have examined the carrier dynamics of 2DEG for undoped $Al_{0.4}Ga_{0.6}N/GaN$ single HJs. The abrupt PLE absorption edge at GaN band-edge energy and the delayed risetime of the 2DEG emission strongly indicates an effective carrier generation in the GaN flatband region and a successive carrier transfer from the GaN and AlGaN regions to the heterointerface. Although the 2DEG emission itself is a spatially-separated indirect recombination, a fast decay of ~0.2 ns is found to be dominant in 2DEG recombination because of the fast exhaustion of photogenerated holes in the GaN flatband region via spatially-direct (fast) GaN recombination.

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