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

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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$_{x}$Ga$_{1-x}$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$_{x}$Ga$_{1-x}$N/GaN HSs have concentrated on electrical properties. So far, only a few optical studies have been reported for Al$_{x}$Ga$_{1-x}$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$_{0.4}$Ga$_{0.6}$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$_{0.4}$Ga$_{0.6}$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-°C and 300 (150) Torr, respectively. The growth in-
terrupition time between Al$_{0.4}$Ga$_{0.6}$N and GaN layers was chosen to be 3 min.\textsuperscript{8} The Al compositions of the Al$_x$Ga$_{1-x}$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$_x$Ga$_{1-x}$N/GaN heterointerface was 750 cm$^2$/V s and the sheet charge density of the 2DEG was determined to be $1.3 \times 10^{13}$ cm$^{-2}$. This high value of the sheet charge density can be attributed to the strong polarization effect.\textsuperscript{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 $\sim$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 1811 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.\textsuperscript{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.\textsuperscript{12} The emission peaks related to 1 longitudinal optical (LO) and 2 LO phonon replicas have $\sim$92 meV energy periodicity from the zero phonon peak of undoped GaN, as marked with vertical grids in Fig. 1(b).\textsuperscript{13} We clearly observed that an additional peak at $\sim$3.448 eV emerged for the Al$_{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 ($\Delta E$) 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.
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 band-gap 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. 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 ($\tau_1$) and a slower one ($\tau_2$) 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 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 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 ($\tau_2$) 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 $\tau_2$ 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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