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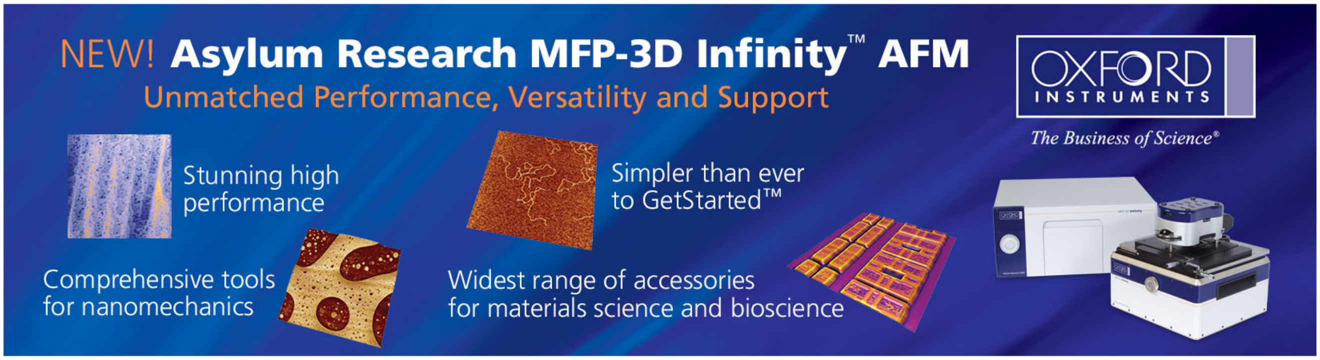

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A study of subbands in AlGaN/GaN high-electron-mobility transistor structures using low-temperature photoluminescence spectroscopy

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$Al_{0.15}Ga_{0.85}N$/GaN high-electron-mobility transistor (HEMT) structures with various δ-doping concentrations and spacer thicknesses grown on sapphire by metalorganic chemical-vapor deposition are investigated. The Hall mobility is as high as 1333 $cm^2/V\,s$ at room temperature and 6330 $cm^2/V\,s$ at 77 K. Two-dimensional electron gas (2DEG) phenomena, which have not been clearly resolved in the literature, are observed by photoluminescence (PL) spectra at low temperature in this study. The PL spectra peaks of the interband transitions from 2DEG subbands to the valence band are in the range from 3.486 to 3.312 eV. The effects of the strain caused by different Al fractions of the top layer, and that of the spacer thickness on the 2DEG phenomena are discussed. Redshifts due to temperature variations for various HEMT structures are observed in 2DEG subbands and in the band-edge emission, which is believed to be evidence of interband transitions from 2DEG subbands to valence bands. *© 2002 American Institute of Physics.* [DOI: 10.1063/1.1485310]

The AlGaN/GaN heterostructure has been extensively examined due to its attractive two-dimensional electron gas (2DEG) characteristics and has been widely employed in fabricating high-voltage and high-power electronic devices.[1–3] Unlike that of the $Al_xGa_{1-x}As$/GaAs heterostructure, for a given Al fraction, the piezoelectric effect at the AlGaN/GaN interface is very strong. As a result, the band discontinuity at the AlGaN/GaN interface is much more serious than at the $Al_xGa_{1-x}As$/GaAs interface.[4] Bergman published a work on optical properties relating to the recombination of the 2DEG subband.[5] In recent years, several groups have presented the 2DEG photoluminescence (PL) spectra of AlGaN/GaN heterostructures. A higher Al fraction ($x=0.11-0.26$) corresponds to superior 2DEG confinement.[6] Double confinement by incorporating a thin $Al_{0.12}Ga_{0.88}N$ in the bottomside of the unintentionally doped (UID) GaN layer also improves the 2DEG confinement.[7] Modifying the nucleation layer by inserting a thin AlN layer prior to *i*-GaN growth can improve both the mobility of the 2DEG and the crystal morphology.[8] The doping effect on the 2DEG PL spectra for undoped and modulation-doped $Al_xGa_{1-x}N$/GaN heterostructures has also been reported.[9] This letter elucidates the 2DEG subband photoluminescence spectra and their temperature dependence in detail for various high-electron-mobility transistor (HEMT) structures, which have not been clearly resolved in the literature.

$Al_{0.15}Ga_{0.85}N$/GaN HEMTs were grown on a (0001) sapphire substrate using low-pressure metalorganic chemical-vapor deposition (MOCVD) with an EMCORE D75 reactor. Hydrogen was employed as the carrier gas with silane, trimethylgallium, trimethylaluminum, and ammonia precursors. The HEMT structure consisted of Ohmic, Schottky, δ-doping electron donating, spacer, channel, and nucleation layers, and a sapphire substrate. All of the samples studied included a nucleation layer grown to around 400 Å at 500 °C and a 2-μm-thick undoped GaN layer grown at 1040 °C. Table I details each layer of the various samples used in this study. The Hall effect was measured using a Bio-Rad 5900+ to determine the Hall mobility (μ_H) at room temperature (300 K) and at 77 K. The PL spectra at various temperatures were obtained by 325 nm (3.815 eV) He–Cd laser excitation, the photon energy of which was sufficiently high to pump all the $Al_xGa_{1-x}N$ layers in the structures studied in this letter.

The Hall measurements in Table I reveals that samples (a), (b), and (c) show high mobility at room temperature and at 77 K but sample (d) exhibits very low mobility. This result suggests that the enhanced 2DEG phenomena exist in samples (a), (b), and (c) but not in (d). Figure 1 shows the PL spectra of all samples measured at 10 K. Note that some peaks are present below D^0X(3.486 eV) for all samples, but samples (a), (b), and (c) seem to show more peaks than sample (d). We propose that these extra peaks are related to 2DEG subband emission. Sample (d) has a low Hall mobility (546 $cm^2/V\,s$) and does not exhibit 2DEG subband emission, perhaps due to the thin barrier layer causing a Coulombic interaction between the dopant and carriers. Sample (a), with Hall mobilities of 1221 and 5613 $cm^2/V\,s$ at 300 and 77 K, respectively, exhibits weak 2DEG subband emission and strong $Al_{0.06}Ga_{0.94}N/Al_{0.20}Ga_{0.80}N$ PL emission (~3.60 eV),

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TABLE I. Sample structures and Hall mobilities.

Structure\sample (No).	(a)	(b)	(c)	(d)
Ohmic layer/Schottky layer /δ-doping/spacer	300/200/30/60 (Å)	100/100/30/60 (Å)	100/100/30/60 (Å)	100/100/60/30 (Å)
Ohmic layer thickness $Al_{0.06}Ga_{0.94}N$	300 (Å)	100 (Å)	100 (Å)	100 (Å)
Schottky layer thickness $Al_xGa_{1-x}N$	200 (Å) $x=0.15$	100 (Å) $x=0.15$	100 (Å) $x=0.2$	100 (Å) $x=0.2$
δ-doping thickness concentration (cm^{-3})	30 (Å) 10^{19}	30 (Å) 10^{18}	30 (Å) 10^{18}	60 (Å) 10^{18}
Spacer thickness $Al_{0.1}Ga_{0.9}N$	60 (Å)	60 (Å)	60 (Å)	30 (Å)
Channel layer UID GaN	2 μm	2 μm	2 μm	2 μm
μ_H 300 K/77 K	1221/5613	1117/5506	1333/6530	564
Sheet N (cm^{-2})	9.00×10^{12}	8.91×10^{12}	9.30×10^{12}	1.16×10^{13}

as shown in Fig. 1. This is believed to be due to absorption by the thick Ohmic and Schottky layers. Sample (c) has a higher Al fraction in the electron Schottky layer, $x=0.2$, than sample (b). A higher Al fraction corresponds to a smaller lattice constant. Thus, a stronger compression strain is induced across the 2DEG well, increasing the sheet concentration of the channel.[11,12] The increase in the Al fraction in the Schottky contact layer compresses the barrier; increases the band gap of the spacer, and thus, increases the ΔE_v across the interface of the 2DEG well.

The 2DEG is present at the interface of the AlGaN/GaN structure that is exactly at the interface of the spacer and the channel layer of the HEMT. So, the PL spectra of UID GaN observed at low temperature must be compared, given that UID GaN is the thickest layer in these samples. UID GaN has a Hall mobility of 131 cm^2/V s with $N_s=2.41\times10^{13}$ cm^{-2}. Figure 2 shows the PL spectra of the UID GaN. The near-band-edge emission split into four subbands. The peak at 3.468 eV, corresponding to a neutral donor-bound exciton, referred to as D^0X, can be observed in the UID GaN and all the HEMTs structures in Fig. 1. The peaks in Fig. 2 differ greatly from that in Fig. 1, this is due to the polarization effect of PL measurement in UID GaN.[10] As Reynolds *et al.* reported, for $\mathbf{E}\perp c$ (making the electric field of a polarized laser beam normal to the c axis), D^0X dominates the near-band-edge emission of an UID GaN in the shape shown in Fig. 1. At the appropriate arrangement of sample orientation, making $\mathbf{E}\perp c$, causes Γ_5 and Γ_6 to dominate the near-band-edge emission with a new A_L subband, implying that the grown UID GaN is of a very high-quality material.[10] The first phonon replica of the neutral donor-bound exciton (D^0X-1LO) is present in the UID GaN and broadens as the temperature increases. In contrast, for sample (c), as shown in Fig. 3, the peaks close to 3.406 eV do not vary with the measured temperature of the HEMT. In particular, the peak at 3.406 eV does not appear in sample (b), as shown in Fig. 1. The shift of peak D^0X exceeds that of the 2DEG subbands when the PL-measuring temperature of sample (c) rises, since the triangular potential well varies little as the band gap narrows. This result has been reported

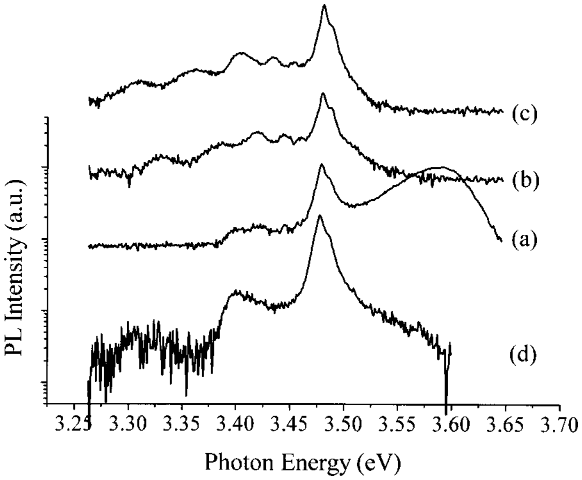

FIG. 1. PL Spectra at 10 K for different structures of $Al_{0.06}Ga_{0.94}N/Al_xGa_{1-x}N/\delta$-doping/$Al_{0.15}G_{0.85}N$/GaN HEMTs.

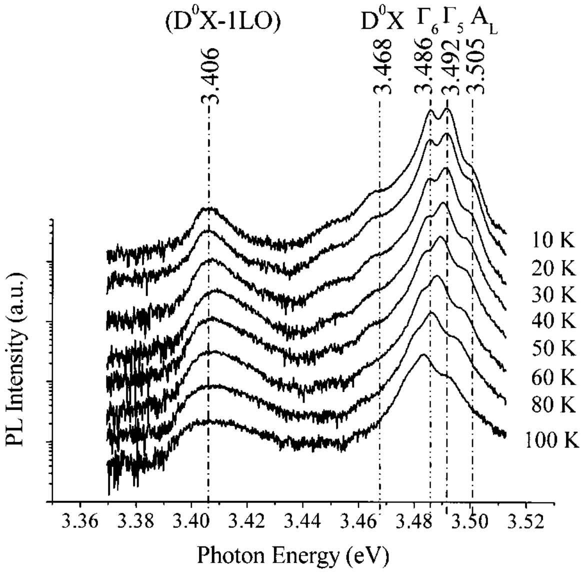

FIG. 2. PL spectra of high-quality UID GaN at different temperatures.

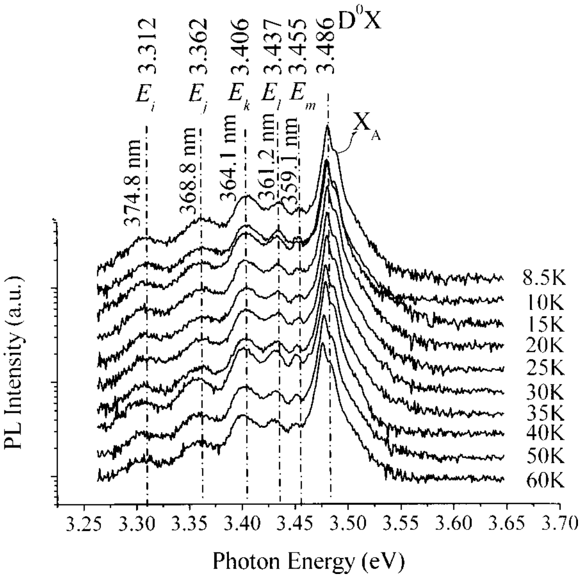

FIG. 3. Temperature-dependent PL spectra for sample (c). Notice that the peak redshift of the GaN D^0X is larger than that in the 2DEG.

by other groups.[7] This suggests that peaks below the D^0X correspond to transitions from 2DEG subbands to the valence band.

Figure 4 shows the energy separation (ΔE) of 2DEG subbands from the GaN D^0X emission. Figure 3 clarifies the symbols. The two peaks nearest to D^0X, ΔE_m and ΔE_l, correspond to the observed 2DEG peaks in other reports.[4–9] Shen has demonstrated the temperature dependence of ΔE and found a downshift of around 3.5 meV from 10 to 60 K. In the observed spectra, the shifts in ΔE_m and ΔE_l are approximately 4 and 1.2 meV, respectively, which is consistent with Shen's report.[7]

In summary, we have demonstrated highly resolved PL spectra of 2DEG subbands in AlGaN/GaN HEMT structures that are consistent with Hall measurements. There are at least five subbands observed in the HEMT structures in this study. The energy separation in the PL spectra between the interband transitions and near-band-edge transition are in the range of 25.1–172 meV. Strain has less effect on the subband transition than the near-band-edge transition, which is consistent with other reports.[11,12]

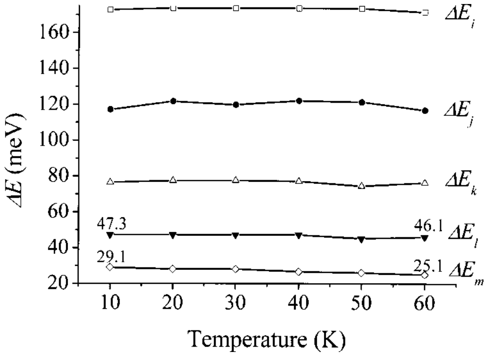

FIG. 4. Temperature dependence of the energy separation (ΔE) of the 2DEG subband PL peak from the GaN D^0X emission, where $\Delta E_i = E_{D^0X} - E_i$, and so on.

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