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The optical polarization of AlN/$Al_xGa_{1-x}N$ single quantum wells ($x = 0.65$) has been studied by means of photoluminescence (PL) spectroscopy. The predominant polarization component of the band-edge PL switched from $E \parallel c$ to $E \perp c$ at a well width around 2 nm. The emission intensity with polarization of $E \perp c$ and the degree of polarization were found to decrease with increasing well width. The emission intensity with polarization of $E \parallel c$ was found to increase with increasing well width. © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4737941]

Al-rich AlGaN alloys have attracted much interest as a promising material for deep ultraviolet (UV) light emitting diodes (LEDs) and laser diodes (LDs). These devices have potential applications like water purification, UV curing, photospectroscopy, bioanalysis, and high-density optical recording.[1–3] However, despite the enormous progress that group-III nitride-based UV LEDs have recently made,[4–9] the emission efficiency in those devices rapidly decreases as the wavelength decreases.[10] This is generally attributed to the difficulty in growing high crystal quality and the presence of deep acceptor energy level in Al-rich AlGaN epilayers.[11] However, change in the light extraction efficiency can also be a significant contributing factor. The optical transition between the conduction and the topmost valence bands in AlN (GaN) is polarized along (perpendicular to) the c-axis owing to the negative (positive) crystal field splitting energy.[12–15] Accordingly, the dominant polarization component of band-edge emission from AlGaN ternary alloys switches from $E \perp c$ to $E \parallel c$ with increasing Al composition, where E is the electric field vector of the emitted light. This polarization phenomenon affects light extraction in AlGaN-based light emitters. For AlGaN-based light emitters grown on c-plane substrates, several studies indicate that the polarization of the emitted light switches from transverse electric (TE) polarization to transverse magnetic (TM) polarization as the wavelength decreases.[16–18] A crossover from TE to TM polarization at short wavelengths is an issue for light extraction from top or bottom emitting UV LEDs grown on the c-plane because light that propagates along the c-axis must have TE polarization. It is, therefore, desirable to engineer the active region so that TE polarization is achieved.[19–21] Similarly, polarization control is also a critical issue in AlGaN UV laser diode design.

In this work, the optical polarization anisotropy in AlN/$Al_{0.65}Ga_{0.35}N$ single quantum wells (QWs) grown on c-plane sapphire substrates is systematically investigated using low temperature (10 K) deep UV photoluminescence (PL) emission spectroscopy. We demonstrate that the polarization of the light in these QWs can be switched from TM to TE by decreasing well width (L_w), which means that the TE polarization of the emission can be achieved at wavelengths as short as 220 nm.

A set of AlN/$Al_xGa_{1-x}N$ ($x \sim 0.65$) QW samples with L_w varying from 1 to 3 nm and a fixed barrier width of 10 nm were grown on sapphire (001) substrates by metalorganic chemical vapor deposition (MOCVD). The growth temperature and pressure were 1150 °C and 100 Torr, respectively. For each of the five samples, prior to the growth of $Al_{0.65}Ga_{0.35}N$ QW, a thin AlN buffer layer and a 1-μm undoped AlN epilayer were grown on the sapphire substrate. It was then followed by the growth of $Al_{0.65}Ga_{0.35}N$ QW and a 10 nm AlN barrier. The targeted L_w of these samples was 1, 1.5, 2, 2.5, and 3 nm. The barrier and well widths were determined by the growth rates of the AlN and $Al_xGa_{1-x}N$ epilayers.[22] The samples were mounted on a low temperature (10 K) stage with a cold finger in a closed–cycle helium refrigerator. The deep UV PL spectroscopy system consists of a frequency quadrupled 100 femtosecond Ti: Sapphire laser with an average power of 3 mW and repetition rate of 76 MHz at 196 nm and a 1.3 m monochromator with a detection capability ranging from 185 to 800 nm. The experimental geometry used to measure the polarization PL is depicted in the inset of Fig. 1(b), where the PL emission with either $E \parallel c$ or $E \perp c$ polarization orientation can be collected using a polarizer in front of the monochromator.

Figure 1(a) shows a schematic diagram for the general layer structure of AlN/$Al_{0.65}Ga_{0.35}N$ QWs grown on $\sim 1\ \mu$m undoped AlN template. Figure 1(b) shows polarization (10 K) PL of AlN which was used as a template in our structure. The calculated degree of polarization (P) was -0.7, where P is defined by $P = (I_\perp - I_\parallel)/(I_\perp + I_\parallel)$, where $I_\perp$ and $I_\parallel$ are the integrated intensities for the polarization components of $E \perp c$ and $E \parallel c$, respectively. This quantity indicates a strong polarization along the c-axis, which is consistent with previous reports[14] and verifies the experimental setup.

To discuss the well width (L_w) dependence of the polarization properties, Fig. 2 shows the 10 K PL spectra of AlN/$Al_{0.65}Ga_{0.35}N$ QW samples with well width varying from 1 to 3 nm and a fixed barrier width of 10 nm. We attribute the dominant PL emission lines to the localized exciton recombination in the AlGaN QW regions.[23] With respect to the band edge transition at 4.969 eV in $Al_{0.65}Ga_{0.35}N$ epilayers, the PL peak energy is red-shifted for QWs with $L_w = 2.5$ and 3 nm and blue-shifted for QWs with $L_w = 1$, 1.5, and 2 nm. This indicates that the PL peak energy is defined by the quantum confinement as well as by the

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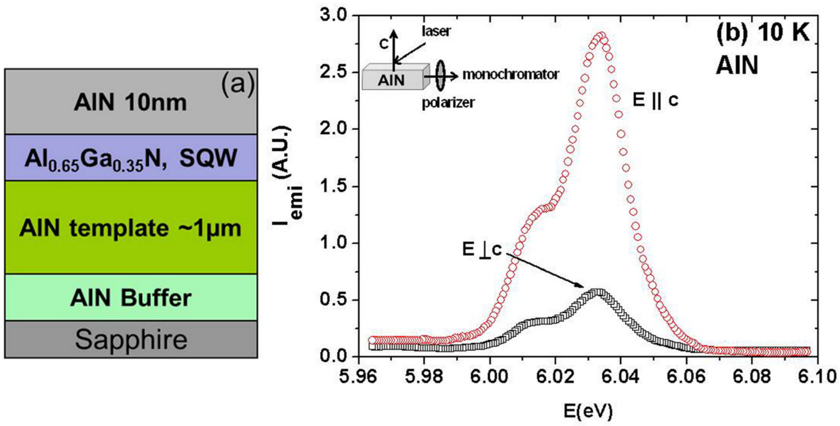

FIG. 1. (a) Schematic diagram for the general layer structure of AlN/$Al_{0.65}Ga_{0.35}N$ QWs. (b) Polarization PL spectra of AlN template. The experimental geometry was depicted in the inset, where the electrical field of PL emission (E) can be selected either parallel (||) or perpendicular (⊥) to the **c** axis.

induced fields along the growth direction, the detailed PL properties are discussed in our previous report.[22] In the figure, as the well width decreases from 3 to 1 nm, the predominant polarization switched from E ∥ c to E ⊥ c at $L_w \sim$ 2 nm. The emissions from QWs thicker than 2 nm show E ∥ c polarization, whereas that of QWs thinner than 2 nm show E ⊥ c polarization, indicating that quantum confinement affects the valence-band order and, consequently promotes E ⊥ c polarization.

Figure 3 plots P as a function of L_w. P decreases almost linearly with increasing L_w, this trend confirms the theoretical prediction that decreasing L_w of the QW enhances the TE polarization at the expense of the TM polarization, which cause band-crossing and change the character of the topmost band.[19] Also shown in Fig. 3 that the degree of polarization is almost zero for QW with well width of around 2 nm, which means that the integrated intensities of the TE polarized light and the TM polarized light are almost the same. At this point, the heavy-hole, light-hole, and split-off-hole bands are energetically degenerated.[14]

Figure 4 shows the variation of the integrated PL emission intensity of these AlN/$Al_xGa_{1-x}N$ QWs versus L_w measured at 10 K for both polarization orientations of E ⊥ c and E ∥ c. The emission intensity for E ⊥ c component increases with decreasing L_w, while the emission intensity for E ∥ c component decreases with decreasing L_w.

In summary, we have studied the effects of well width on the polarization properties of c-plane AlN/$Al_{0.65}Ga_{0.35}N$ single quantum wells by means of PL spectroscopy. The predominant polarization switched from E ∥ c to E ⊥ c at $L_w \sim$ 2 nm. The emissions from QWs thicker than 2 nm show E ∥ c polarization, whereas that of QWs thinner than 2 nm show E ⊥ c polarization. This indicated that the topmost valence band changed from split-off-hole band to heavy-hole band with decreasing well width. The degree of polarization decreases with increasing well width. Furthermore, the emission intensity with polarization of E ⊥ c decreases with increasing well width, meanwhile, the emission intensity with polarization of E ∥ c increases with increasing well width. These findings will serve as a guideline for designing optimal deep UV light emitter structures.

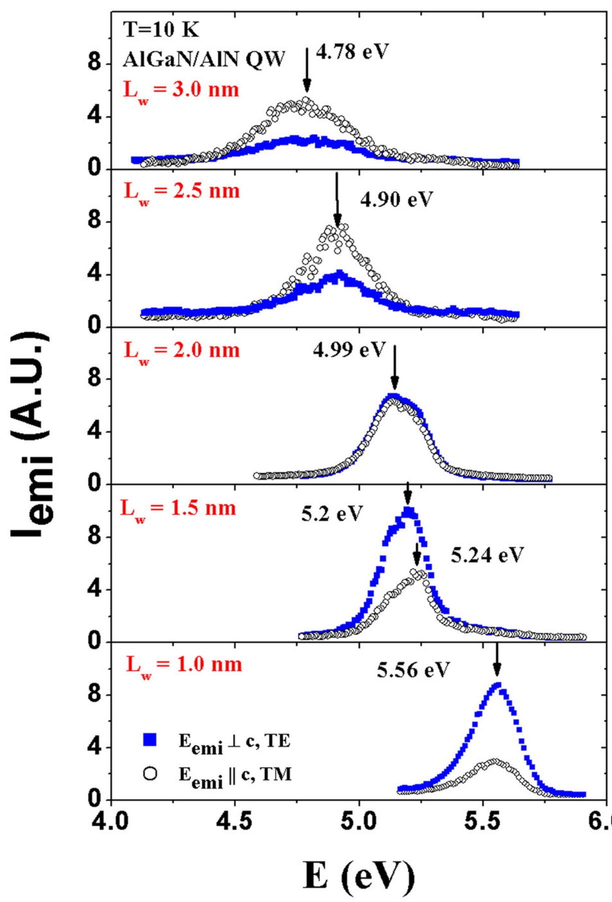

FIG. 2. Polarization low temperature (10 K) PL spectra of AlN/$Al_{0.65}Ga_{0.35}N$ QW samples with well width varying from 1 to 3 nm and a fixed barrier width of 10 nm.

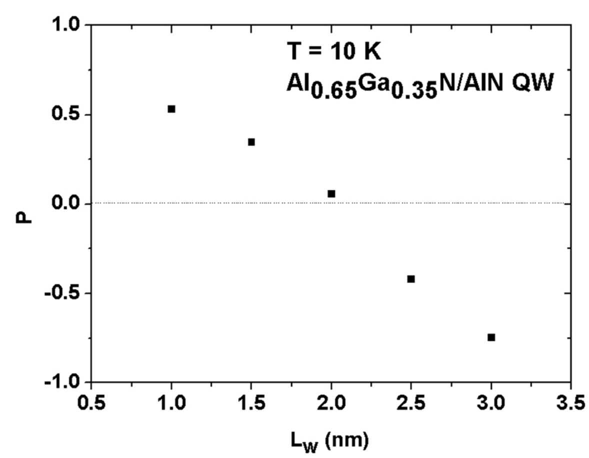

FIG. 3. The degree of polarization P as a function of well width in AlN/$Al_{0.65}Ga_{0.35}N$ QWs.

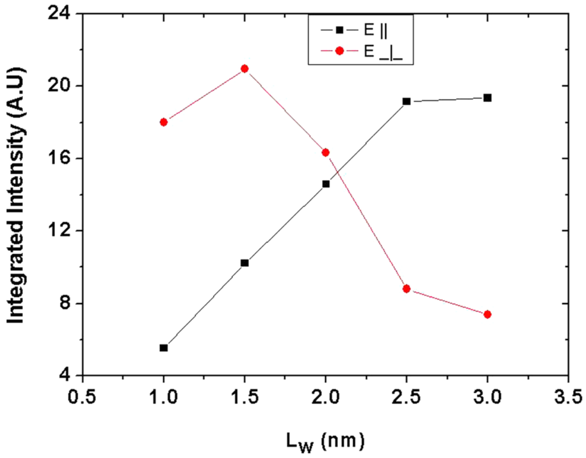

FIG. 4. Integrated PL emission intensities for E ⊥ c and E ∥ c as a function of well width of $AlN/Al_{0.65}Ga_{0.35}N$ QWs measured at 10 K.

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