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Growth and optical properties of a-plane AlN and Al rich AlN/$Al_xGa_{1-x}N$ quantum wells grown on r-plane sapphire substrates

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A-plane AlN epilayers and AlN/$Al_{0.65}Ga_{0.35}N$ quantum wells (QWs) have been grown on r-plane sapphire substrates by metal organic chemical vapor deposition. The growth surface and high crystalline quality were confirmed by x-ray diffraction. Photoluminescence (PL) spectroscopy has been employed to probe the optical quality of the grown templates and QWs. The PL emission intensity of a-plane AlN has been compared with that of c-plane AlN. It was shown that the surface emission intensity of a-plane AlN epilayers is comparable to that of c-plane AlN. The PL emission properties of a- and c-plane AlN/$Al_{0.65}Ga_{0.35}N$ QWs were studied and compared. It was found that the low temperature PL characteristics of *a*-plane QWs are primarily governed by the quantum size effect, whereas those of *c*-plane QWs are significantly affected by the polarization fields. The PL decay time was found to be only weakly dependent on the well width, L_w, for *a*-plane QWs, whereas a strong dependence of the PL decay time on L_w was observed for *c*-plane QWs.

1 Introduction AlN is emerging as an active material for deep ultraviolet (DUV) optotelectronic devices for many applications because of its large direct bandgap ~ 6.1 eV [1, 2]. AlN has strong chemical bonds, which makes AlN based devices very stable and highly resistant to degradation when operating under harsh conditions. AlN also plays an important role as a template for the subsequent epitaxial growth of nitride optoelectronic device structures, in which the high quality AlN epilayer serves as a dislocation filter [3].

Usually, nitride-based epitaxial structures are grown on (001) *c*-plane sapphire and SiC substrates. Due to the nonsymmetric nature of nitrides grown in the (001) direction, a large built-in electrostatic field occurred perpendicular to the AlGaN/InGaN heterointerfaces because of spontaneous and piezoelectric polarization. The polarization induced electric fields are known to significantly reduce the electron-hole wavefunction overlap and hence the radiative recombination efficiency in III-nitride quantum wells (QWs). Our previous studies on AlN/AlGaN QWs grown on *c*-plane sapphire substrates showed that the AlN/AlGaN QW structures possess a built-in polarization field of ~ 4 MV/cm [4]. The growth on nonpolar plane, such as *a*-plane nitrides, is a potential solution to this problem [5]. It is also known that for DUV emitters utilizing *c*-plane AlGaN alloys as active layers, the dominant emission has a polarization of **E**//**c** and this unique optical property significantly reduces the surface emission intensity in DUV emitters based on *c*-plane AlGaN alloys [6]. The growth of nonpolar nitrides on GaN templates has been reported by several groups [7, 8]. For optoelectronic devices operating at short wavelengths (λ < 300 nm), the growth on *a*-plane AlN template would provide reduced effects of polarization fields as well as enhanced surface emission. However, very little work dealing with epitaxial growth [9] and no work on optical properties of *a*-plane AlN and AlN/AlGaN QWs have been previously reported.

2 Experimental AlN epilayers were grown on *r*-plane sapphire substrates in horizontal reactor by MOCVD with a growth temperature and pressure of 1300 ^{0}C and 40 Torr, respectively. Trimethylaluminum (TMAl) and Ammonia (NH_3) were used as the Al and N sources, respectively. A 45 nm AlN low temperature buffer layer was first grown to serve as a nucleation layer followed by the growth of a 1µm AlN epilayer. AlN/$Al_xGa_{1-x}N$ ($x \sim 0.65$) QWs were grown on top of a- and c-plane AlN/Al_2O_3 templates. The growth temperature and pressure were 1120 °C and 50 Torr, respectively. This was then followed by the growth of a 10 nm AlN barrier with same temperature as QW layer. The barrier and well widths were determined by the growth rates of the AlN and $Al_xGa_{1-x}N$ epilayers. 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 fs Ti:sapphire laser with an average power of 3 mW and a repetition rate of 76 MHz at 196 nm, a 1.3 m monochromator with a detection capability ranging from 185 to 800 nm, and a streak camera detector with 2 ps time resolution [10]. X-ray diffraction (XRD) was used to determine the crystalline quality and orientation of AlN epilayers.

3 Results and discussion The growth surface of the AlN epilayers was determined to be *a*-plane using XRD θ-2θ scan, which detected sapphire (102), (204), and *a*-plane AlN (110) reflections, as illustrated in Fig. 1(a). Only the *a*-plane reflection peak at $2\theta = 59.4^0$ was observed. Since the AlN (002) reflection at $2\theta = 36.02^0$ was not detected, we believe that instabilities in the AlN growth orientation are not a concern [11]. As shown in Fig. 1(b), the measured FWHM of XRD rocking curve of the (110) reflection peak is about 940 arcsec, which to our knowledge is the narrowest value reported for a-plane AlN.

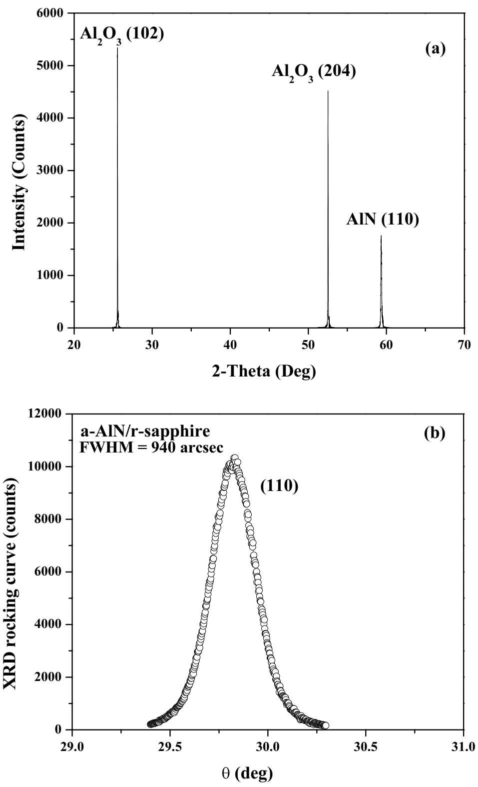

Figure 1 (a) XRD θ-2θ scan of an *a*-plane AlN epilayer. (b) XRD rocking curve of (110) reflection peak of an *a*-plane AlN epilayer. Full width at half maximum (FWHM) is 940 arcsec.

Figure 2 compares the room temperature (300 K) PL spectra of *c*-plane and *a*-plane AlN epilayers covering a broad spectral range from 2 to 6.2 eV. The peak position of the band-edge transition in *a*-plane AlN epilayer is at 5.95 eV, which is about 30 meV below that in *c*-plane AlN epilayer (5.98 eV). This redshift of the band-edge transition could be related to the anisotropy of the in-plane strain in *a*-plane AlN epilayer, in which the strain induced band-gap shift depends on all three strain components [12]. In spite the fact that the growth technology for *a*-plane AlN is much less mature than that for *c*-plane AlN, the intensity of the band-edge emission in *a*-plane AlN is comparable to that in *c*-plane AlN. This is partly due to the unique polarization property of the optical emission (***E//c***) in *c*-plane AlN, which tends to reduce the surface emission intensity [6]. Thus, we believe that the band edge emission intensity from *a*-plane AlN epilayers is expected to be much higher than that from *c*-plane AlN of the same optical quality. The PL emission spectrum of the a-plane AlN epilayer also comprises of a deep level impurity transition, which could be due to the recombination between shallow donors and cation complexes with two-negative charges [13]. The emission intensity of this deep level transition is relatively weak and can be suppressed with further improvement in material quality.

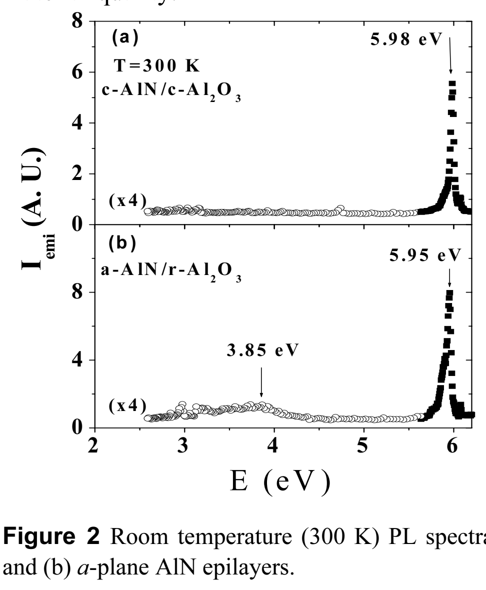

Figure 2 Room temperature (300 K) PL spectra of (a) *c*-plane and (b) *a*-plane AlN epilayers.

The (10 K) PL spectra of the *c*- and *a*-plane AlN/$Al_{0.65}Ga_{0.35}N$ QWs are shown in Figs. 3(a) and 3(b), respectively. Independent of the crystal orientation, the QW PL emission peak shifts to lower energies with increasing well width (L_w), due to the weakening of the quantum confinement effect. In particular, the emission peak energies of the *a*-plane QWs steadily approach but do not redshift beyond the band edge transition of the

$Al_{0.65}Ga_{0.35}N$ epilayer with increasing L_w. Conversely, the *c*-plane QW emission peak energy redshifts with L_w and becomes even lower than the band edge transition peak of the $Al_{0.65}Ga_{0.35}N$ epilayer at L_w > 2 nm. This strong dependence of the PL emission energy on L_w in *c*-plane QWs is due to the strong spontaneous and strain-induced piezoelectric fields ~ 4MV/cm [4], in addition to the quantum size effect. These polarization fields are much weaker in *a*-plane QWs [14].

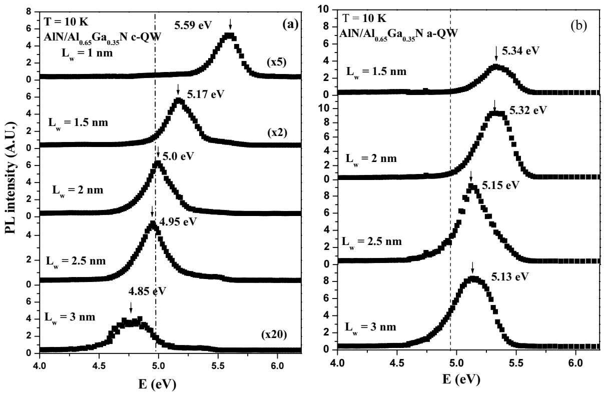

Figure 3 Low temperature (10 K) PL spectra of (a) *c*-plane AlN/$Al_{0.65}Ga_{0.35}N$ QWs with well width L_w, varying from 1 to 3 nm and (b) *a*-plane AlN/$Al_{0.65}Ga_{0.35}N$ QWs with well width L_w, varying from 1.5 to 3 nm. All samples have a fixed barrier width of 10 nm. The vertical dashed lines represent the emission peak position of $Al_{0.65}Ga_{0.35}N$ epilayers.

The PL decay characteristics of the *a*- and *c*-plane QWs for two representative well widths (L_w = 1.5 and 3 nm) were measured and the results are shown in Figure 4. The PL decay transients show nonexponential decay with a slower component at longer decay times. For *c*-plane QWs the PL decay time strongly depends on L_w. This can be explained by presence of the strong polarization fields (~ 4 MV/cm) in the polar QWs. The electrostatic fields spatially separate the electron and hole wave functions, thereby reducing the oscillator strength for their radiative recombination. At low temperatures, the measured decay time corresponds mainly to the radiative lifetime, which is inversely proportional to the oscillator strength. Conversely, for *a*-plane QWs the PL decay time exhibits only a weak dependence on L_w, which is consistent with the presence of much week polarization field.

4 Conclusion *a*-plane AlN epilayers have been grown on *r*-plane sapphire substrates by MOCVD. PL studies showed that the bandedge emission intensity of a-plane AlN is comparable to that of *c*-plane AlN. A- and c-plane AlN/$Al_{0.65}Ga_{0.35}N$ QWs have been grown by MOCVD on r- and c-plane sapphire substrates and their PL emission characteristics were measured and compared. It was found that the low temperature PL characteristics of *a*-plane QWs are primarily governed by the quantum size effect. In contrast, the emission characteristics of *c*-plane

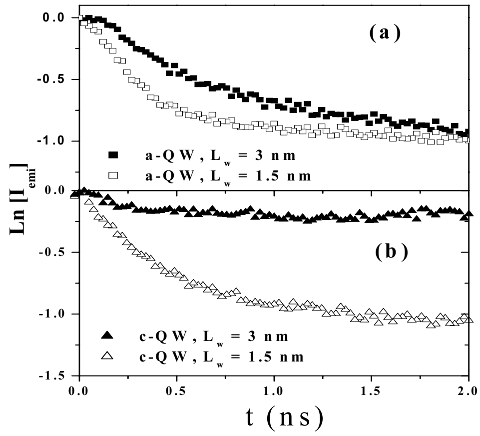

Figure 4 Low temperature (10 K) PL decay transients of two representative (a) *a*-plane and (b) *c*-plane AlN/$Al_{0.65}Ga_{0.35}N$ QWs with L_W = 1.5 and 3 nm.

QWs are affected by strong polarization fields in addition to the quantum confinement effect. The PL decay time was found to be weakly dependent on the well width, L_w, for *a*-plane QWs. However, a strong dependence of the PL decay time on L_w was observed for *c*-plane QWs, which is caused by the variation of the polarization fields in QWs due to varying L_w.

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