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Improvement of the surface morphology of *a*-plane InN using low-temperature InN buffer layers

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We report on the improvement of the surface morphology of *a*-plane InN films grown by RF molecular beam epitaxy. By using low-temperature (LT) InN buffer layers, we could successfully obtain InN films with a smooth surface. The full width at half maximum values of the x-ray diffraction (11-20) rocking curve along the [0001] InN direction were 2870 arcsec and 3410 arcsec for *a*-plane InN samples grown at 500°C with and without LT-InN buffer layers, respectively. Thus, we could improve also the crystalline quality of *a*-plane InN films by using LT-InN buffer layers. We observed strong polarization anisotropy in the photoluminescence spectra of *a*-plane InN, which is typical of nonpolar wurtzite III-nitride films.

1 Introduction Recently, the growth of nonpolar III-nitrides has been studied because of its potential improvement of the performance of III-nitride-based optoelectronic devices [1-9]. InN and other III-nitrides have hexagonal wurtzite crystal structure and are most commonly grown along the (0001) orientation. Spontaneous and piezoelectric polarization-induced electric fields along the polar *c*-axis in the layers, however, adversely affect the performance of optoelectronic devices. A useful approach for reducing the deleterious effects of the built-in fields is to grow along the nonpolar directions, because the polar *c*-axis lies in the plane. The growth of nonpolar GaN, such as *m*-plane (1-100) and *a*-plane (1-120) GaN, has been intensively studied for improving the performance of light-emitting devices. On the other hand, there have been a few reports concerning the growth of nonpolar InN [10-12], whose quality has still left room for improvement. In addition, nonpolar wurtzite nitrides show optically polarized emission [13, 14] and absorption [14, 15], which is explained by the crystal field along the *c*-axis of wurtzite nitrides and its effect on the valence band structure. This unique property of polarized light emission could be desirable for the backlighting of liquid crystal displays by improving power consumption and compactness. In this study, we have improved considerably the surface morphology of nonpolar (11-20) *a*-plane InN films grown on (1-102) *r*-plane sapphire substrates using low-temperature (LT) InN buffer layers. LT-InN buffer layer has been demonstrated to be an effective approach for the improvement of the crystal quality in c-plane InN grown by molecular beam epitaxy (MBE) [16-18]. We also report on the strong polarization anisotropy in the photoluminescence (PL) spectra observed for *a*-plane InN films.

2 Experimental Nonpolar (11-20) *a*-plane InN films were grown on (1-102) *r*-plane sapphire substrates by MBE using an RF-N_2 plasma source. Prior to the growth of *a*-plane InN layers, *a*-plane GaN layers were grown on *r*-plane sapphire at 900°C. Following the GaN layer growth, InN layers were grown for 1 hour at between 400 and 600°C with and without LT-InN buffer layers. LT-InN buffer layers were deposited for 5 min at between 250 and 400°C to investigate the effect of LT-InN buffer layers on the surface morphology of the InN films.

The crystalline quality was examined by high-resolution x-ray diffraction (HR-XRD), and the surface morphology was observed by scanning electron microscopy (SEM), and atomic force microscopy (AFM). We carried out PL measurements at between 15 K and 300 K for *a*-plane InN films and polarized PL measurements at 15 K for *a*- and *c*-plane InN films. The 532 nm frequency doubled line of a Nd:YVO_4 laser was used as an excitation source, and an InSb photovoltaic device was used as a detector.

3 Results and discussion As can be seen from the SEM images shown in Fig. 1, the surface of InN grown at 450-550°C without LT-InN buffer layers was not uniform at all. Fig. 2 shows the SEM images of InN films grown at 500 °C with a LT-InN buffer layer deposited at various temperatures. These images clearly show that the surface morphology of *a*-plane InN films is improved by depositing LT-InN buffer layers. As a result, we could obtain *a*-plane InN films with a flat surface when the LT-InN buffer layer was deposited at 300 °C. Thus, we set a deposition temperature of 300 °C for LT-InN buffer layers.

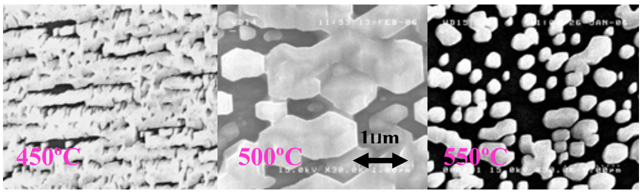

Figure 1 SEM images of *a*-plane InN grown at different temperatures without a LT-InN buffer layer.

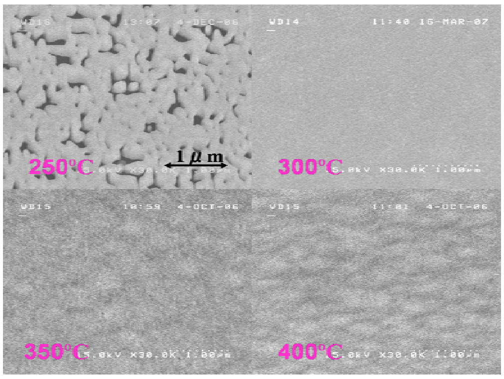

Figure 2 SEM images of *a*-plane InN grown at 500 °C with LT-InN buffer layers deposited at various temperatures.

Figure 3 exhibits the SEM images of InN films grown between 400 °C and 580 °C with a LT-InN buffer layer deposited at 300 °C. Lower growth temperature leads to smoother surface, and the surface of the InN film grown at 400 °C was the smoothest in these films. The surface roughness of the film grown at 400 °C was found to be 1.2 nm in root-mean-square (rms) value from AFM observation.

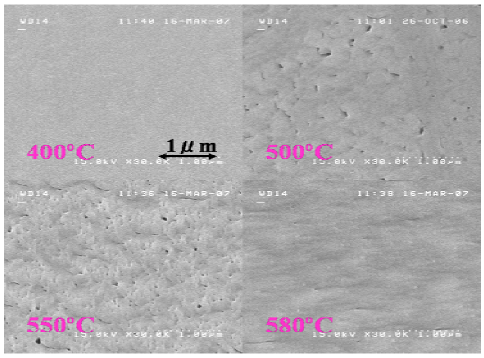

Figure 3 SEM images of *a*-plane InN grown at different temperatures with a LT-InN buffer layer deposited at 300 °C.

The full widths at half maximum (FWHM) of the XRD (11-20) rocking curves of InN films grown with and without LT-InN buffer layers along the [0001] InN direction were characterized. The FWHM of the XRD rocking curves of InN films grown with LT-InN buffer layers tends to decrease at higher growth temperatures, indicating that the crystalline quality is not always compatible with the surface morphology. The FWHM along the [0001] was smaller than that along the [1-100]. In-plane anisotropy of the FWHM of the XRD (11-20) rocking curve along the [0001] and [1-100] direction has been reported also for a-plane GaN [19, 20]. The FWHMs of the XRD (11-20) rocking curve along the [0001] direction were 2870 arcsec and 3410 arcsec for *a*-plane InN samples grown at 500 °C with and without LT-InN buffer layers, respectively. Thus, the crystalline quality of *a*-plane InN was also improved by using the LT-InN buffer layer as well as the surface morphology.

Figure 4 shows the temperature dependence of PL spectra from *a*-plane InN grown at 500 °C with a LT-InN buffer layer. PL was clearly observed even at room temperature. The PL peak was located at ~0.63 eV, which is the same result reported in our previous paper [11] for *a*-plane InN films grown without LT-InN buffer layers.

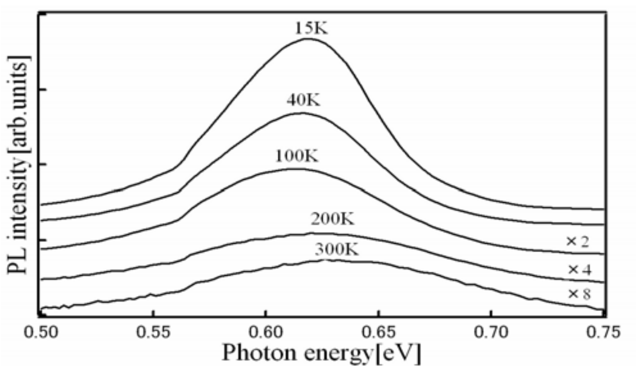

Figure 4 Temperature dependence of PL spectra observed from *a*-plane InN grown at 500 °C with a LT-InN buffer layer.

Figure 5 shows the polarized PL intensity of *a*- and *c*-plane InN. For *c*-plane InN, there was no significant polarization anisotropy in the polarized PL intensity, as expected. For *a*-plane InN, on the other hand, unambiguous polarization anisotropy with twofold symmetry was seen in the polarized PL intensity, which is consistent with the report by Bhattacharyya *et al*. [14]. The emission for $\boldsymbol{E}\perp\boldsymbol{c}$ was stronger than that for $\boldsymbol{E}//\boldsymbol{c}$. The anisotropy percentage was ~72%, which is defined as $100\%\times(I_{\perp}-I_{//})/(I_{\perp}+I_{//})$, where $I_{\perp}$ and $I_{//}$ are PL intensities for $\boldsymbol{E}\perp\boldsymbol{c}$ and $\boldsymbol{E}//\boldsymbol{c}$, respectively. This anisotropy percentage is higher than that reported by Bhattacharyya *et al*. [14], which is presumably due to the difference in anisotropic in-plane strain caused by using the LT-InN buffer layer.

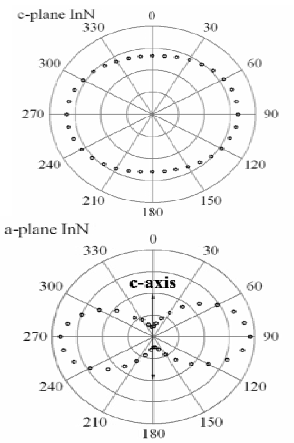

Figure 5 Polarized PL signal with the polarization angle Φ for the *c*- and *a*-plane InN film measured at 15 K.

4 Conclusion We could successfully improve the surface morphology of *a*-plane InN films grown by RF-MBE using LT-InN buffer layers. Although the surface of InN films grown without LT-InN buffer layers was rather rough, we could obtain *a*-plane InN films with a smooth surface whose roughness was 1.2 nm by using LT-InN buffer layers. The FWHM of the XRD (11-20) rocking curve was decreased by using LT-InN buffer layers. Thus, we could improve the crystalline quality as well as surface morphology of *a*-plane InN films by using LT-InN buffer layers. Strong PL was observed from *a*-plane InN films with LT-InN buffer layers even at room temperature. In addition, clear polarization anisotropy was observed in the emission spectra of *a*-plane InN, which is typical of nonpolar wurtzite nitrides.

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