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WILEY-VCH

Phys. Status Solidi C **9**, No. 3–4, 658–661 (2012) / **DOI** 10.1002/pssc.201100365

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current topics in solid state physics

RF-MBE growth of semipolar InN(10-13) and InGaN(10-13) on GaAs(110)

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Received 8 July 2011, revised 21 December 2011, accepted 1 February 2012

Keywords InN, InGaN, MBE, semipolar

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We have studied InN and InGaN films grown on GaAs(110) substrates by RF-assisted molecular beam epitaxy. Reflection high-energy diffraction observation and X-ray diffraction (XRD) measurements revealed that the InN films were epitaxially grown with InN(10-13)// GaAs(110). From XRD pole figure measurements, only one InN(0002) peak was found at an angle of 31.8° from the pole, indicating that the semipolar InN films were free from twin crystals. This can be explained by the similarity in the anisotropic structure between InN(10-13) and GaAs(110) surfaces. By using low-temperature InN buffer layers, we could obtain semipolar InN films with a smooth surface. Polarization anisotropy in the photoluminescence peak observed at 0.67 eV from semipolar InN(10-13) was weaker than that from *a*-plane InN, which is reasonable considering the smaller angle between the *c*-axis and the perpendicular direction to the semipolar InN surface. We have also successfully grown In-rich InGaN(10-13) on GaAs(110) substrates with an InN(10-13) intermediate layer, and observed strong photoluminescence from the semipolar InGaN films.

1 Introduction InN has attracted considerable attention because of its narrow band gap of 0.6-0.7 eV [1] and a large band offset at InN/InGaN heterojunctions, which are suitable for the high-performance infrared light-emitting device applications. Since III-nitride semiconductors including InN have most commonly wurtzite structure and are grown along the [0001] orientation, piezoelectric and spontaneous polarization-induced electric fields along the *c*-axis spatially separate electrons and holes and lower the optical transition probability. Thus, nonpolar and semipolar III-nitride semiconductors have been intensively studied in recent years because they are useful for reducing the electric fields in the layers and potentially improving the performance of optoelectronic devices [2-8]. We have reported the growth of nonpolar *a*-plane InN on *r*-plane sapphire by molecular beam epitaxy (MBE) using an RF-nitrogen plasma source [6, 7]. In the present paper, we report MBE growth and characterization of semipolar InN(10-13) and InGaN(10-13) layers on GaAs(110) substrates.

2 Experimental procedures Semipolar InN(10-13) and InGaN(10-13) layers were grown on GaAs(110) substrates by MBE using an RF-nitrogen plasma source. The plasma power was kept at 350 W and N_2 flow rate was 1.6 sccm. Prior to the epitaxial growth of InN or InGaN layers, InN buffer layers were deposited at 400 °C for 10 s. By using the low-temperature InN buffer layer, we could improve the surface smoothness of InN epitaxial layers, as will be shown later. After the buffer layer deposition, InN(10-13) layers were grown at 490 °C for 60 min. The total thickness of the InN layers was 300 nm. The crystalline quality of InN was sensitive to the growth temperature, and the full widths at half maximum (FWHM) of X-ray diffraction (XRD) rocking curve decreased with increasing growth temperature, and was 54 arcmin at 490 °C. Following the epitaxial growth of InN layers, InGaN layers were grown with varying In flux from 5.0×10^{-5} Pa to 7.0×10^{-5} Pa to change the alloy composition. The Ga flux was set at 1.0×10^{-5} Pa. The InGaN layer thickness was approximately 400 nm. We observed the surface morphology of InN and InGaN using scanning electron microscopy (SEM) and atomic force microscopy (AFM). The crystal orientation and quality of the samples were investigated by using XRD. We performed photoluminescence (PL) measurements using a diode-pumped solid-state laser (λ=532 nm) and an InSb photovoltaic device as an excitation source and a detector, respectively.

3 Results and discussion Figure 1(a) shows a SEM image of InN grown on GaAs(110). As can be seen from this image, the surface of the InN layer is flat. A streak feature was observed by reflection high-energy diffraction (RHEED) during the growth of InN layers, also showing that the surface was smooth. Figure 1(b) shows a SEM image of InGaN grown on GaAs(110) with Ga and In fluxes of 1.0×10^{-5} Pa and 6.0×10^{-5} Pa, respectively. Compared with the surface of InN, that of InGaN layers was not uniform. Thus, a further examination of the growth conditions, for instance, growth temperature, is required to improve the surface morphology.

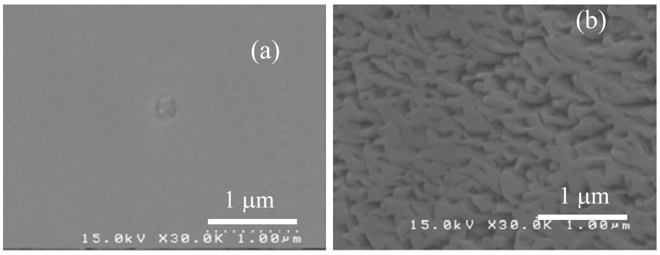

Figure 1 SEM images of (a) InN and (b) InGaN grown on GaAs (110).

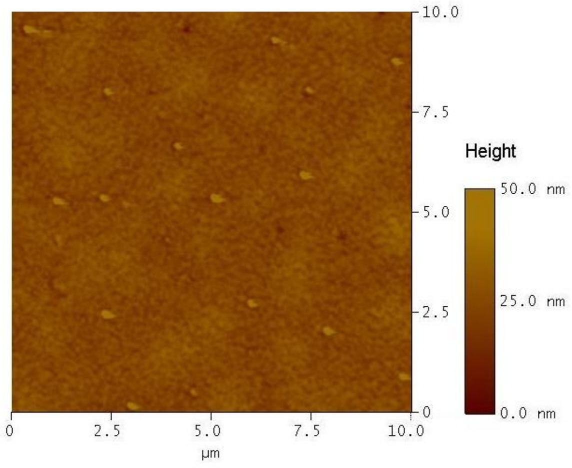

Figure 2 AFM image of InN surface.

Figure 2 shows an AFM image of InN grown on GaAs(110). The surface roughness of the InN layer was found to be 2.8 nm in RMS value from the AFM observation.

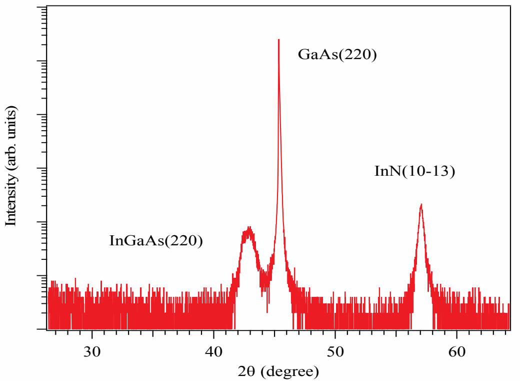

Figure 3 XRD 2θ-ω scan profile of InN grown on GaAs (110).

Figure 3 shows the XRD 2θ-ω scan profile of InN grown on GaAs (110). The XRD peak from InN (10-13) is observed at 2θ = 56.9° and no other peak related to InN is seen. A broad peak observed at 2θ = 43° is believed to come from InGaAs(220) formed by the reaction between In and GaAs. The In composition of InGaAs was estimated to be 0.94. Since the bandgap energy of $In_{0.94}Ga_{0.06}As$ is 0.45 eV, incidentally, the luminescence of InGaAs does not interfere with PL results mentioned later. We have also carried out XRD pole figure measurements, and only one InN(0002) peak was found at an angle of 31.8° from the pole, as shown in Fig. 4. These indicates semipolar InN(10-13) films were epitaxially grown with InN(10-13) // GaAs(110) [8] and were free from twin crystals. The crystal orientation relationship of between InN films and GaAs substrates can be explained by the similarity in the anisotropic surface structure between InN(10-13) and GaAs(110) surfaces, as shown in Fig. 5.

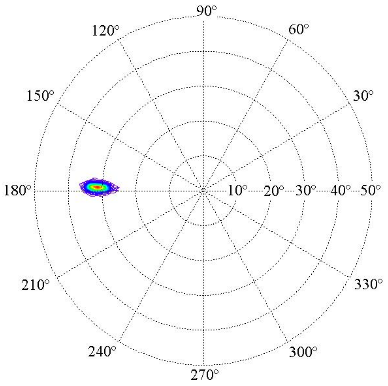

Figure 4 XRD pole figure of InN(0002). Only one peak is seen at an angle of 31.8° from the pole.

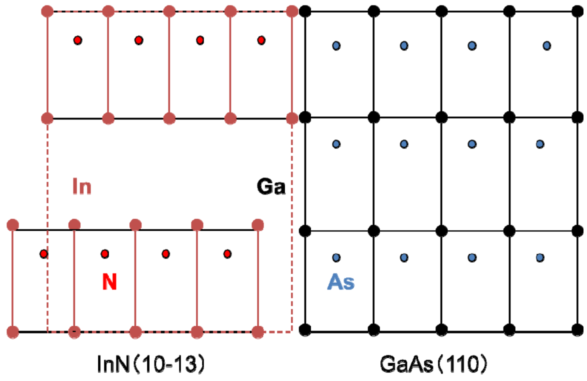

Figure 5 The similarity in the anisotropic surface structure between InN(10-13) and GaAs(110) determines the epitaxial relationship.

Figure 6 shows the XRD 2θ-ω scan profiles of InGaN(10-13) layers grown on GaAs(110) substrates with InN(10-13) intermediate layers. In addition to the XRD peak from InN(10-13) observed at 2θ = 56.9°, the XRD peak from InGaN(10-13) can be seen around 2θ = 58°, indicating that semipolar InGaN was grown with InGaN (10-13) // InN(10-13). With increasing In flux from 5.0×10^{-5} Pa to 7.0×10^{-5} Pa, the XRD peak shifts to lower angles, which corresponds to the increase in In composition of InGaN from 0.78 to 0.85. It was also found from XRD rocking curve measurements that the FWHM of the InN(10-13) peak varied from 78 to 174 arcmin with decreasing In composition. The increase in the XRD peak width is probably due to larger lattice mismatch between InGaN and InN.

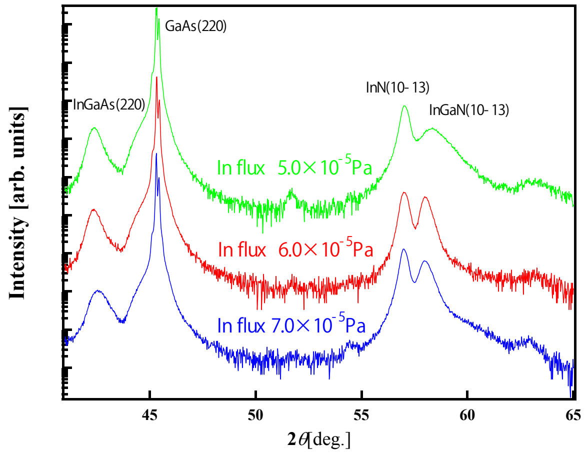

Figure 6 XRD 2θ-ω scan profiles of InGaN(10-13) grown with varying In fluxes from 5.0×10^{-5} to 7.0×10^{-5} Pa. The Ga flux was set at 1.0×10^{-5} Pa.

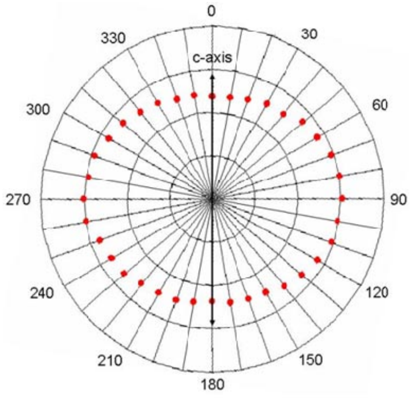

Figure 7 Polarized PL intensity of the semipolar InN(10-13) film grown on GaAs(110) measured at 15 K. The PL peak energy was 0.67 eV.

We have observed PL peak at 0.67 eV from the semipolar InN(10-13) film. Figure 7 shows the polarized PL intensity of InN(10-13) measured at 15 K. The PL polarized vertical to the *c*-axis (θ = 90° or 270°) is stronger than that polarized to θ = 0° or 180°. The polarization anisotropy percentage for the semipolar InN was 13% and was smaller than that for nonpolar *a*-plane InN (72%) [7]. This result is reasonable considering that the angle between the *c*-axis and the perpendicular direction to the sample surface for the semipolar InN (31.8°) is smaller than that for nonpolar InN (90°).

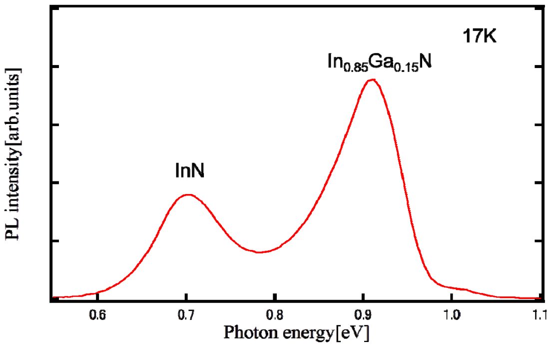

Figure 8 PL spectrum obtained from semipolar InGaN grown on an InN intermediate layer with In and Ga fluxes of 7.0×10^{-5} Pa and 1.0×10^{-5} Pa, respectively. A strong PL peak from semipolar InGaN is seen at 0.91 eV.

Figure 8 shows a PL spectrum obtained from semipolar $In_{0.85}Ga_{0.15}N$ grown on an InN(10-13) intermediate layer with In and Ga fluxes of 7.0×10^{-5} Pa and 1.0×10^{-5} Pa, respectively. The PL spectrum was measured at 17 K. Along with a PL peak seen at 0.69 eV due to the semipolar InN intermediate layer, we could observe a strong PL peak at 0.91 eV from the semipolar InGaN layer, showing that the crystalline quality was quite good, although the surface was not flat. The FWHM of the PL peak was 95 meV for both InN and InGaN. From the XRD measurements, the crystalline quality of InGaN is not believed to be better than that of InN. However, the PL from InGaN was stronger as shown in Fig. 8. This is because the InGaN layer thickness is comparable to the penetration depth of the laser used for the PL measurements.

4 Conclusions We investigated MBE growth of InN and InGaN(10-13) films on GaAs(110) substrates. RHEED observation and XRD measurements showed that semipolar InN films were epitaxially grown with InN(10-13) // GaAs(110). It was found from XRD pole-figure measurements that the semipolar InN films were free from twin crystals. The crystalline quality of semipoar InN was sensitive to the growth temperature, and the FWHM of X-ray rocking curve decreased with increasing growth temperatures. By using low temperature InN buffer layers, we could drastically improve the surface smoothness of semi polar InN films. Polarization anisotropy in the photoluminescence spectra obtained from semipolar InN(10-13) was weaker than that from *a*-plane InN. This result is reasonable considering the smaller angle between the *c*-axis of InN(10-13) and the perpendicular to the surface. We could successfully grow In-rich InGaN(10-13) films on GaAs(110) substrates with an InN(10-13) intermediate layer, and observe strong PL from the semipolar InGaN films.

Acknowledgements The authors would like to thank Mr. Jun-ichiro Suzuki, Mr. Naoki Yokoyama, and Mr. Taihei Otsuka for their technical assistance.

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