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RF-MBE growth of InN/InGaN quantum well structures on 3C–SiC substrates

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Abstract

$InN/In_{0.83}Ga_{0.17}N$ multiple quantum well (MQW) structures have been fabricated on 3C–SiC (0 0 1) substrates by radio-frequency plasma-assisted molecular beam epitaxy (RF-MBE). The surface morphology, structural properties, and optical properties of the samples were investigated by scanning electron microscopy (SEM), X-ray diffraction (XRD) and photoluminescence (PL), respectively. XRD satellite peaks due to the periodic structure were clearly observed in the MQW structures grown at temperatures lower than 530 °C. PL emissions from the MQW were observed around 0.85 eV.

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1. Introduction

InN has attracted much interest in recent years due to its narrow band gap of 0.6–0.7 eV [1], which makes InN suitable for photonic devices such as temperature-insensitive high-efficiency laser diodes operating at optical communication wavelengths. Although, sapphire substrates have been most commonly used for the growth of InN, SiC is an attractive alternate because of its electrical conduction and high thermal conductivity, which are helpful for device applications. We have previously reported that high-quality h-InN films were grown on 3C–SiC (0 0 1) substrates utilizing the small mismatch between h-InN $(1\bar{1}00)$ and 3C–SiC (1 1 0) [2].

In this study, we report on the growth of InN/InGaN multiple quantum well (MQW) structures on 3C–SiC (0 0 1) substrates by radio-frequency plasma-assisted molecular beam epitaxy (RF-MBE).

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2. Experimental procedures

$InN/In_{0.83}Ga_{0.17}N$ MQW structures were grown at 510–550 °C on 3C–SiC (0 0 1) substrates with an InGaN underlayer. 3C–SiC (0 0 1) epilayers were obtained by chemical vapor deposition (CVD) growth on Si (0 0 1) substrates [3,4]. The thickness of 3C–SiC (0 0 1) epilayers was 300 nm. Prior to the growth, thermal cleaning of 3C–SiC (0 0 1) substrates was carried out at 900 °C for 30 min. Following the thermal cleaning, a 10 nm thick InN buffer layer and a 150 nm-thick InN epilayers were grown at 350 and 510 °C, respectively. Then $InN/In_{0.83}Ga_{0.17}N$ MQW structures were grown at 510–550 °C on 3C–SiC (0 0 1) substrates with a 300 nm thick $In_{0.83}Ga_{0.17}N$ underlayer grown at 510–550 °C. The MQW structures were fabricated 7 pairs of 5 nm thick InN well layers and 10 nm thick $In_{0.83}Ga_{0.17}N$ barrier layers.

The surface morphology of the samples was investigated by reflection high-energy electron diffraction (RHEED) and scanning electron microscopy (SEM). Structural properties were characterized by X-ray diffraction (XRD) using PANalytical X'Pert PRO XRD system. Optical properties were investigated by photoluminescence (PL) measurements from 14 to 300 K. An InSb photovoltatic device and a frequency doubled Nd:YVO_4 laser operating at 532 nm were used as the detector and the excitation source, respectively. The optical power density used for the sample excitation was 4 W/cm^2.

3. Results and discussion

Fig. 1(a)–(f) show RHEED patterns and the SEM images observed after the growth of the MQW structures grown at 510–550 °C. As shown in these Fig. 1, the streak pattern was observed for MQW grown at 510 and 530 °C, indicating that the surface is very smooth at the atomic level. On the other hand, the spotty streak pattern was observed at 550 °C. From the SEM observation, the MQW structures grown at 510 and 530 °C have grain boundaries, which may be due to the domain boundaries of 3C–SiC, but the surface was smooth. In contrast, the MQW structures grown at 550 °C were columnar. These indicate the surface morphology is strongly affected by the substrate temperature. The dissociation of InN at a high temperature of 550 °C may cause the three-dimensional (3-D) growth mode.

Fig. 2 shows the XRD θ–2θ scan profile for the MQW structures. The peaks observed at 31.43° and 31.92° correspond to InN (0 0 0 2) and InGaN (0 0 0 2), respectively. Lattice spacing of InN (0 0 0 2) is estimated to be 5.687 Å from the Bragg angle. This value is somewhat smaller than those previously reported [1,5–11]. This discrepancy can be partly explained by in-plane tensile strain due to the misfit strain between 3C–SiC (1 1 0) and InN ($1\bar{1}00$). In addition, the thermal strain is expected to be tensile due to the differences in the in-plane the thermal expansion coefficient between InN ($3.6\times10^{-6}\,K^{-1}$) and Si ($2.4\times10^{-6}\,K^{-1}$), as compared with those of GaN ($5.6\times10^{-6}\,K^{-1}$) and sapphire ($7.5\times10^{-6}\,K^{-1}$) which lead to compressive strain in InN [12]. From the Vegard's law, the InN molar fraction of InGaN was estimated to be 0.83. XRD satellite peaks due to the periodic structure were clearly observed in the MQW structures grown at temperatures lower than 530 °C. On the other hand, XRD satellite peaks were not observed for the sample grown at 550 °C, which indicates that MQW could not be successfully fabricated at a temperature as high as 550 °C, as mentioned before in terms of the RHEED and SEM observation. Simulated curves are well fitted to the experimental curves, as shown in Fig. 2. From the simulation, the thicknesses of well and barrier layers were evaluated to be 4.5 and 10.9 nm, respectively.

Fig. 3 shows the PL spectra of the MQW structures grown at 510 °C, where each curve was measured at temperatures from 14 to 300 K. As shown in Fig. 3, the PL peaks and shoulders were observed at 0.71 and 0.85 eV, respectively. We assigned the peak at 0.71 eV to the emission from InN, although the PL peak was observed at somewhat higher energy than that previously reported [2]. Because it is conceivable that carriers generated by photoexcitation in a 300 nm thick InGaN layer flow into a 150 nm thick InN layer and result in the Burstein–Moss shift. The PL emission around 0.85 eV became weaker with increasing temperature from 14 to 100 K and disappeared at temperatures higher than 100 K.

In order to identify the origin of the emission around 0.85 eV, we show residual PL emissions obtained by subtracting the peak at 0.7 eV, which is assumed to have almost the same shape at temperatures from 14 to 120 K,

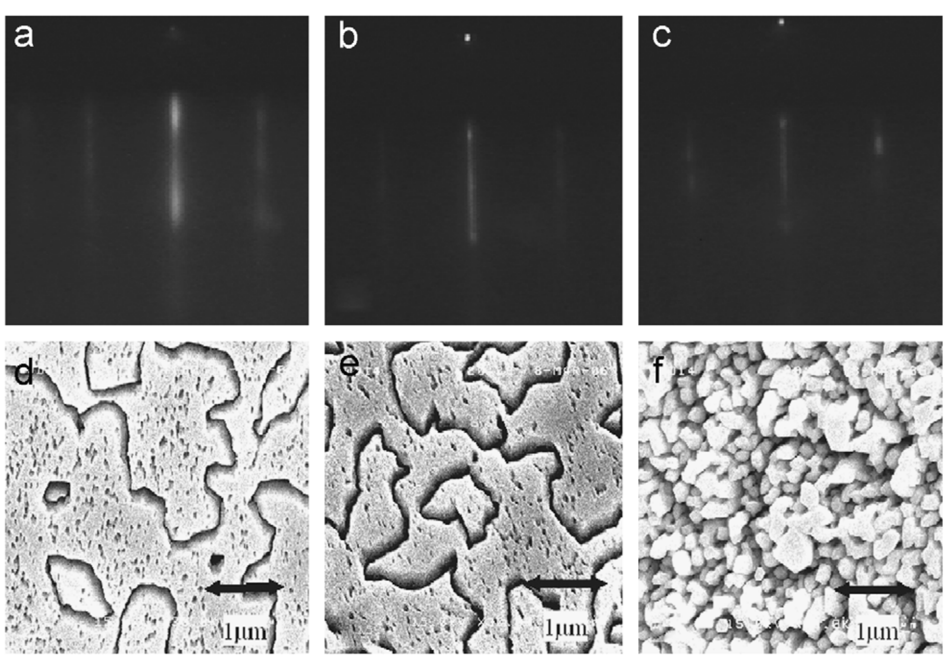

Fig. 1. RHEED patterns and SEM images of the MQW structures at (a), (d) 510 °C, (b), (e) 530 °C, and (c), (f) 550 °C.

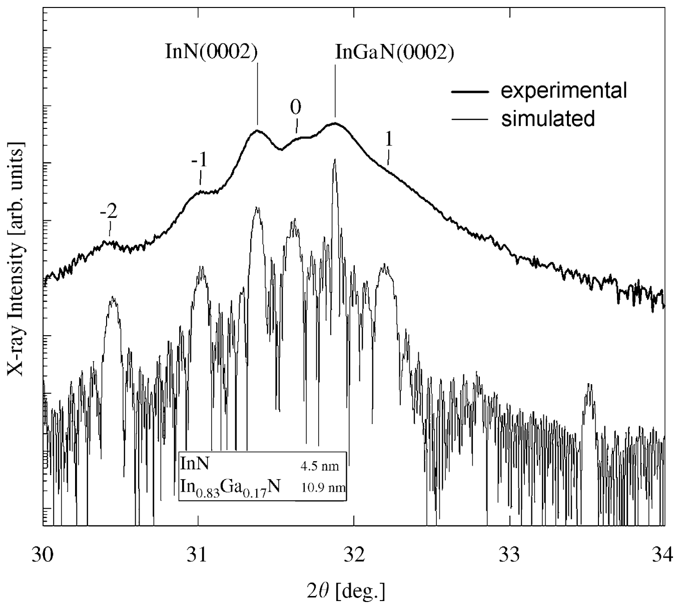

Fig. 2. The XRD curves from InN/ $In_{0.83}Ga_{0.17}N$ MQW structure grown at 510 °C on 3C–SiC (0 0 1). The thick and thin lines indicate the experimental and simulated results, respectively. From the simulation, the thicknesses of well and barrier layers were evaluated to be 4.5 and 10.9 nm, respectively.

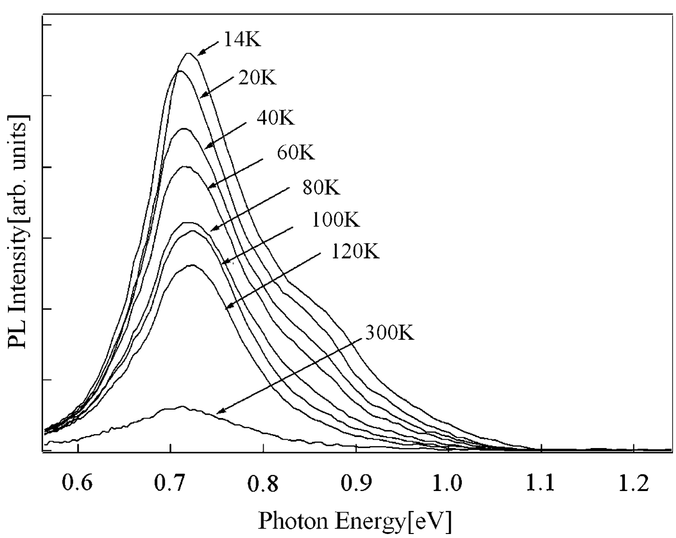

Fig. 3. The PL spectra of the MQW structures grown at 510 °C. The measuring temperature ranged from 14 to 300 K.

from the whole PL spectrum in Fig. 4. As shown in Fig. 4, the PL shoulders were observed at 0.95 eV in addition to the PL peak at 0.85 eV. We assigned the PL peak at 0.85 eV to the emission from InN MQW because this emission was located at lower energy side than the emission of $In_{0.83}Ga_{0.17}N$. Thus, we attributed the PL shoulder at 0.95 eV to the emission from the $In_{0.83}Ga_{0.17}N$ barrier layers. As found from the broad XRD satellite peaks shown in Fig. 2, the InN well width is not expected to be so uniform. This can explain the PL peak of InN MQW is broad. It should be noted that the PL peak of InN MQW

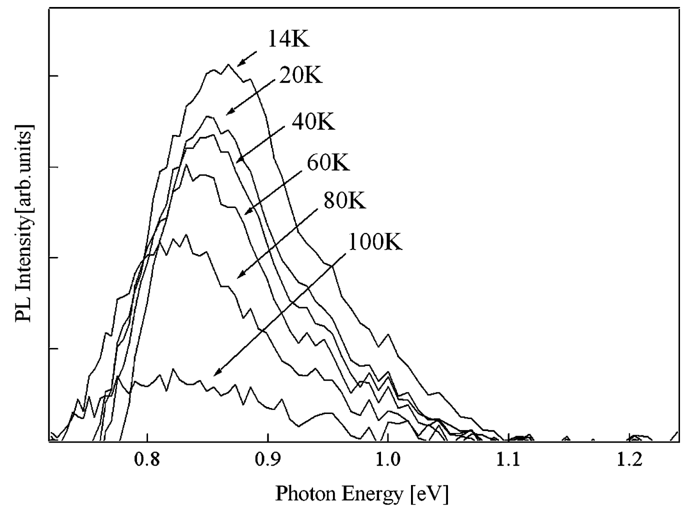

Fig. 4. Each curve were obtained by subtracting the PL emission around 0.7 eV from the whole PL spectra to identify the origin of those around 0.85 eV observed up to 100 K in Fig. 3.

shifts to lower energies with increasing temperature. This is probably because the carriers at the higher energy side easily escape from the well layers with increasing temperature.

4. Conclusion

We have fabricated InN/$In_{0.83}Ga_{0.17}N$ MQW structures on 3C–SiC (0 0 1) substrates with an InGaN underlayer. The MQW structures grown at 510 and 530 °C exhibited the 1st and 2nd satellite XRD peaks, showing that the periodic structures were successfully fabricated. Simulated curves were well fitted to the experimental curves. From the simulation, the thicknesses of well and barrier layers were evaluated to be 4.5 and 10.9 nm, respectively. We carried out PL measurement for the MQW structure and observed the PL shoulder at 0.85 eV, which was attributed to the emission from InN MQW.

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