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Photoluminescence study of hexagonal InN/InGaN quantum well structures grown on 3C-SiC (001) substrates by molecular beam epitaxy

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We have studied photoluminescence from hexagonal InN/InGaN multiple quantum well structures grown on 3C-SiC (001) substrates with an InGaN underlayer by plasma assisted molecular beam epitaxy. We have observed photoluminescence spectra of InN/InGaN MQWs with various well widths. The photoluminescence peak related to quantum wells was clearly observed even at room temperature and found to shift to higher energies with decreasing well width due to the quantum confinement effect. We also discuss the effect of the built-in electric fields on the PL peak energy.

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 high performance photonic devices such as temperature-insensitive laser diodes operating at optical communication wavelengths. Although sapphire substrates have been widely 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 molecular beam epitaxy growth of high-quality hexagonal InN (h-InN) films on 3C-SiC (001) substrates with h-InN (0001) || 3C-SiC (001) and h-InN (1-100) || 3C-SiC (110) utilizing the small mismatch between h-InN (1-100) and 3C-SiC (110) [2]. In addition, we have reported the growth of InN/InGaN multiple quantum well (MQW) structures on 3C-SiC (001) substrates [3]. In this study, we report on the photoluminescence from hexagonal InN/InGaN multiple quantum well (MQW) structures grown on 3C–SiC (001) substrates by radio-frequency plasma-assisted molecular beam epitaxy (RF-MBE).

2 Experimental

Samples used in this study were InN/$In_{0.82}Ga_{0.18}N$ MQW structures grown on 3C-SiC (001) substrates with an InGaN underlayer. 3C-SiC (001) was obtained by chemical vapor deposition on Si (001) substrates [4, 5]. The layer thickness of 3C-SiC (001) was 300 nm. Prior to the growth, thermal cleaning of 3C-SiC (001) was performed at 800°C for 30 min. After the thermal cleaning, a 10-nm InN buffer layer and a 150-nm InN epilayers were grown at 350 and 490 °C, respectively. In our previous study, we found that lower temperature growth leads to smoother surface morphology in the temperature range between 510 and 550 °C. In this study, therefore, InN/$In_{0.82}Ga_{0.18}N$ MQW structures were grown at 470-510°C on 3C-SiC (001) substrates with a 300-nm-thick $In_{0.82}Ga_{0.18}N$ underlayer. The MQW structures consisted of 7 pairs of InN well layers (1-4.5 nm) and 12-nm $In_{0.82}Ga_{0.18}N$ barrier layers, and a 25-nm $In_{0.82}Ga_{0.18}N$ cap layer.

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

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(XRD) using PANalytical X'Pert PRO XRD system. Optical properties were investigated by photoluminescence (PL) measurements at 14 to 300 K. An InSb photovoltatic device and a frequency doubled Nd:YVO4 laser operating at 532 nm were used as the detector and the excitation source, respectively.

3 Results and discussion

Figures 1(a)-(f) show the RHEED patterns and SEM images of the MQW structures grown at 470-510 °C. As shown in Fig. 1, the surface morphology is strongly dependent on the growth temperature. The streak pattern was observed for MQW grown at 470 and 490 °C, indicating that the surface is very smooth at the atomic level. On the other hand, the spotty streak pattern was observed at 510 °C. From the SEM observation, the MQW structures grown have grain boundaries, which may be due to the domain boundaries of 3C–SiC, but the surface was very smooth. In particular, the surface of the MQW structures grown at 490 °C was the smoothest in this study. Thus, we have fixed the growth temperature at 490 °C for growing the MQWs with various well widths.

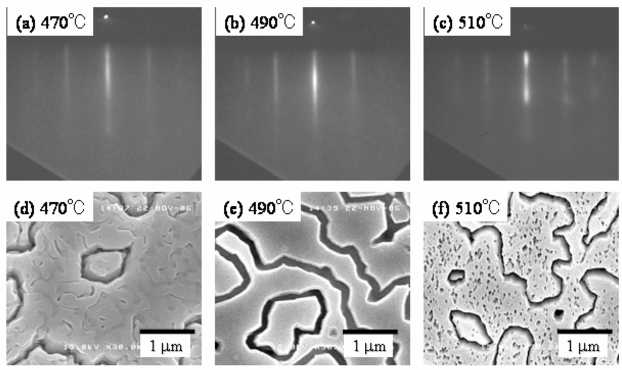

Figure 1 RHEED patterns and SEM images of the MQW structures grown at (a), (d) 470 °C, (b), (e) 490 °C, and (c), (f) 510 °C.

Figure 2 shows the XRD θ–2θ scan profile for the MQW structures grown at 490 °C. The peaks observed at 31.36° and 31.89° correspond to InN (0002) and $In_{0.82}Ga_{0.18}N$ (0002), respectively, unequivocally indicating that h-InN and InGaN layers grow with hexagonal (0001) ‖ 3C-SiC (001). XRD satellite peaks due to the periodic structure were clearly observed. Simulated curves are well fitted to the experimental curves, as shown in this figure. From the simulation, the thicknesses of well and barrier layers were evaluated to be 4.5 and 12.5 nm, respectively.

Figure 3 shows the PL spectra of the MQW structures with various well widths measured at 14 K. PL peaks related to quantum wells were observed at the energy range of 0.75-0.9 eV. With decreasing well width, the PL peak is found to shift to higher energies due to quantum confinement effect. PL peaks observed at around 0.67 and 1.03 eV are assigned as the emission from InN underlayer and InGaN caplayer, respectively.

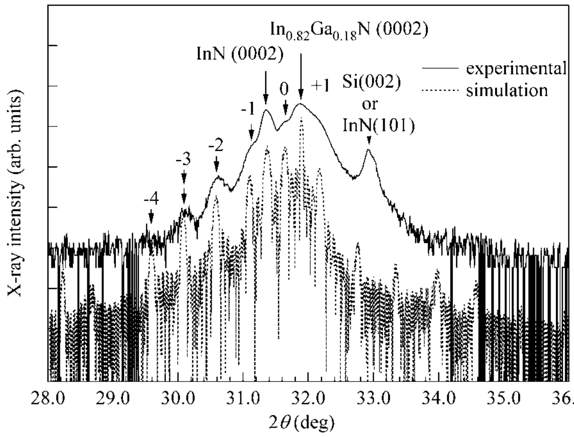

Figure 2 XRD θ–2θ scan profile for InN/InGaN MQW structures grown at 490 °C.

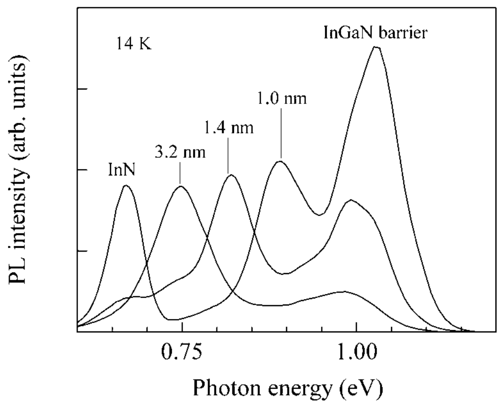

Figure 3 PL spectra of MQW structures with various well widths measured at 14 K.

Several reports have pointed out the quantum confined Stark effect due to large built-in electric fields in InN/InGaN MQWs [6, 7]. In order to examine the effect of the built-in electric fields, therefore, we measured the excitation power density dependence of the PL peak energy. With increasing excitation power density from 0.07 to 4 W/cm^2, the PL peak related to quantum well was found to shift to higher energies. For example, the energy shift was 17 meV for the MQW structure with well width of 3.2 nm, while the PL peak from the InN underlayer did not shift at all. The energy shift observed in the InN/InGaN MQWs is probably due to the screen effect of photo-excited carriers on the built-in electric fields which lead to the quantum confined Stark effect.

For the purpose of further improving the sample quality, we have increased the thickness of the InGaN underlayer from 300 to 900 nm. In Fig. 4, solid and dashed curves show 300-K PL spectra observed from InN/InGaN MQW structures grown with 900-nm and 300-nm InGaN underlayers, respectively. The well width was 1.4 nm for the both samples. The PL peak related to quantum well was observed at 0.8 eV, i.e. the wavelength of 1.55 µm. The PL peak observed at 1.0 eV can be assigned as the emission from the InGaN cap layer. The PL peak intensity at 0.8 eV for the sample with a 900-nm InGaN underlayer is approximately 8 times stronger than that for the sample with a 300-nm InGaN underlayer. This clearly shows that the sample quality can be significantly improved by increasing the thickness of the InGaN underlayer.

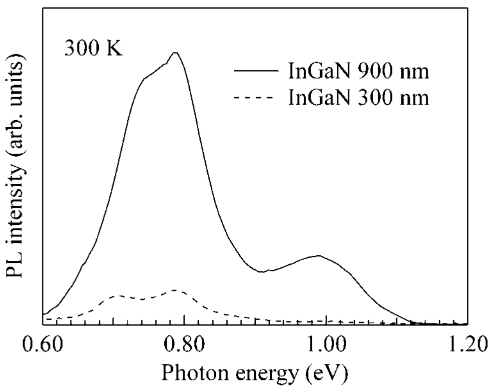

Figure 4 Solid and dashed curves show 300-K PL spectra observed from InN/InGaN MQW structures grown with 900-nm and 300-nm InGaN underlayers, respectively.

4 Conclusion

We studied the photoluminescence from hexagonal InN/InGaN MQW structures grown on 3C-SiC (001) substrates with an InGaN underlayer by RF-MBE. We have observed photoluminescence spectra of InN/InGaN MQWs with various well widths. The PL peak related to quantum wells was observed to shift to higher energies with decreasing well width due to the quantum confinement effect. With increasing excitation power density, the PL peak shifted to higher energies, indicating that photo-excited carriers screened the built-in electric fields in the MQW structures. We have successfully observed a strong 0.8-eV PL peak at room temperature by increasing the thickness of the InGaN underlayer.

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