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Influence of ion beam bombardment on characteristic of InGaN/GaN single quantum well grown by metal–organic chemical vapor deposition

Seung-Kyu Choi · Jae-Min Jang · Sung-Hak Yi · Jung-A Kim · Woo-Gwang Jung

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Abstract The influence of ion beam bombardment on sapphire substrate was investigated on the electrical and optical characteristics of Indium–Gallium–Nitride/Gallium–Nitride (InGaN/GaN) single quantum well (SQW) structure. Ion bombardment of N^+, He^+, H^+ ions were made on single crystal substrate of sapphire with dose of $1 \times 10^{14-17}$ ions/cm^2. The InGaN/GaN SQW was fabricated on the ion beam bombarded sapphire substrate in two-flow Metal Organic Chemical Vapor Deposition (MOCVD) equipment. The thickness of InGaN/GaN SQW was about 20 nm and the composition of InGaN/GaN SQW was found to be $In_{0.1}Ga_{0.9}N$. In PL spectra, it is found that InGaN/GaN SQW was emitted from 441.1 to 446.6 nm (2.8–2.7 eV). The highest mobility value of 118 cm^2/V–S and the lowest carrier concentration of 3.41×10^{17}/cm^2 was found for N of 10^{16} ions/cm^2 ion beam bombarded sample. The optimal condition for InGaN/GaN SQW on sapphire substrate of ion beam bombardment was deduced to be N^+ ion dose of 10^{16} ions/cm^2.

Keywords GaN · InGaN · Ion beam bombardment · Single quantum well · N^+ · He^+ · H^+

1 Introduction

In recent years, the group-III nitrides are promising material for its direct and wide band gap energy of 0.7–6.2 eV (InN–AlN) and have been recognized as the very important materials for optoelectronic devices operating in the blue/UV region as well as for high temperature/high power electronic devices. The group-III nitrides, the binary compound GaN and its alloys with Indium Nitride (InN) or Aluminum Nitride (AlN) have received an amazing amount of attention over the past few years [1–3]. The group-III nitrides have been applied for the realization of blue and green light emitting diodes (LEDs) and laser diodes (LDs), all of which use Indium–Gallium–Nitride (InGaN) alloy in active regions [4–8]. Reduction of the threshold current density is possible in III-nitride quantum structure material laser due to high transparency current density originating from a large selective mass in comparison with GaAs based devices.

In this study, we fabricated InGaN/GaN single quantum well (SQW) structure on the sapphire substrate with and without ion beam bombardment of N^+, He^+ and H^+ ions by two flow horizontal low pressure metal organic chemical vapor deposition (MOCVD). The atomic force microscopy (AFM) was utilized to study the surface morphology of InGaN/GaN SQW with/without ion beam bombardment substrate. The comparison of optical and electrical properties of InGaN/GaN SQW was grown on substrates with and without ion beam bombardment.

2 Experimental

Ion beam of nitrogen, helium or hydrogen ion was bombarded on single crystal substrate of (0001) sapphire with dose ranging from 1×10^{14} to 1×10^{17} ions/cm^2 at room temperature (RT). Ion bombardment was made with various current densities and with energy of 120, 42 and 29 keV into sapphire substrate, which was tilted by 7°.

S.-K. Choi · J.-M. Jang · S.-H. Yi · J.-A. Kim · W.-G. Jung (✉)
Kookmin University,
Seoul, South Korea
e-mail: wgjung@kookmin.ac.kr

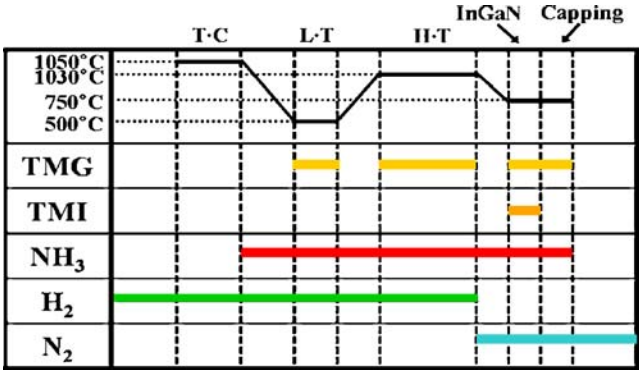

Fig. 1 A profile of temperature and supply of sources and carrier gases in MOCVD growth process for InGaN/GaN single quantum well structure

The InGaN/GaN SQW was grown in two-flow Metal Organic Chemical Vapor Deposition (MOCVD) equipment. The horizontal quartz reactor was maintained at the pressure of 200 torr. The sapphire (0001) substrate was cleaned using several organic solvents and was then etched in a solution of H_2SO_4:H_3PO_4=3:1 at 140–160 °C. Then the oxide layer on sapphire substrate was removed by dipping in solution of 10% HF. After the surface was cleaned, the sapphire substrate was loaded in the reactor of MOCVD equipment. Trimethylgallium (TMG), Trimethylindium (TMI) and high purity ammonia gas were used as precursors, and the carrier gas was a high purity hydrogen or nitrogen.

After loading into the reactor, the sapphire substrates of with/without ion beam bombardment were thermally cleaned at 1050 °C for 10 min in the steam of hydrogen. A low-temperature GaN nucleation layer was deposited at 500 °C for 6 min (thickness 25–30 nm), and then 2 μm GaN buffer layer was deposited at 1030 °C on GaN nucleation layer for 30 min. During the growth of GaN buffer layer, the flow rate of TMG was 89 μmol/min and NH_3 was used as group V source with a flow rate of 1.8 slm. Hydrogen was used as a dilution and carrier gas for the TMG. After GaN buffer layer was grown, the temperature was lowered to 750 °C to grow the InGaN/GaN SQW. For the InGaN SQW growth, the flow rates were 17.7 μm/min for TMG and 27.0 μm/min for TMIn and 3.6 slm for NH_3, respectively. The growth time was 60 sec. The final GaN capping layer was grown on the InGaN SQW, and the thickness was 50 nm. During the growth of InGaN/GaN SQW, carrier gas in the growth of InGaN epilayer and GaN capping layer was nitrogen gas.

Surface roughness of GaN capping layer was investigated using AFM with non-contact mode. Structural properties of InGaN/GaN SQW were characterized by field emission scanning electron microscopic (FE-SEM) with compositional mode. The composition of InGaN/GaN SQW was confirmed using Auger Electron Spectroscopy (AES) analysis. The optical properties of the SQW structure were investigated by photoluminescence (PL) measurement at room temperature using Nd-YAG laser operating at 266 nm as the excitation source and electrical properties were analyzed by Hall measurement.

Figure 1 shows a profile of temperature and supply of sources and carrier gases in the growth of InGaN/GaN single quantum well structure by MOCVD.

3 Results and discussion

Figure 2(a) shows the compositional mode image of FE-SEM of InGaN/GaN SQW. The thickness of InGaN layer was approximately 20 nm for 1 min growth, and GaN capping layer, 150 nm for 3 min (growth rate of GaN capping layer: 50 nm/min). Figure 2(b) shows the AES analysis. From the AES analysis, the composition in InGaN interlayer was found to be $In_{0.1}Ga_{0.9}N$ (Gallium:Indium= 58.4:6.5). Results have shown that the $In_{0.1}Ga_{0.9}N$/GaN SQW was fabricated successfully by MOCVD equipment in the present work.

Figure 3 shows the atomic force microscopy (AFM) images and root mean square (RMS) for GaN buffer layer fabricated on the N ion beam bombardment substrates. The RMS for samples of N ion beam bombardment was increased than that for GaN buffer layer without ion beam bombardment. The RMS in InGaN/GaN SQW was high for in samples of 10^{14}–10^{16} ions/cm^2, and the RMS for sample of 10^{17} ions/cm^2 was low.

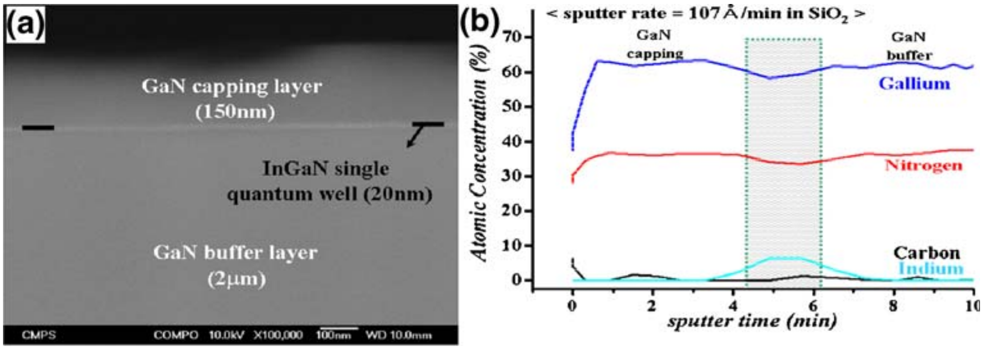

Fig. 2 (**a**) The compositional mode image of FE-SEM for InGaN/GaN single quantum well (**b**) atomic concentration of InGaN/GaN single quantum well by Auger electron spectroscopy

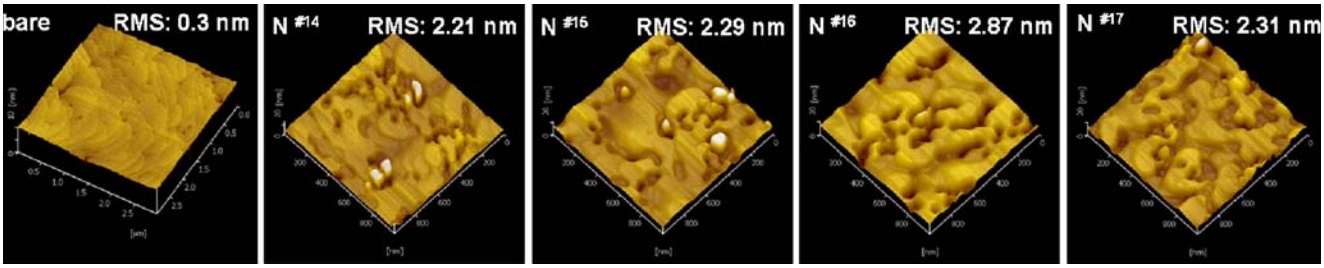

Fig. 3 1×1 μm^2 AFM images of GaN buffer layer and InGan/GaN single quantum well fabricated on the N$^+$ ion beam bombardment; GaN buffer layer, N$^{\#14}$, N$^{\#15}$, N $^{\#16}$, N$^{\#17}$

Figure 4 shows the atomic force microscopy (AFM) images with root mean square (RMS) for InGaN/GaN SQW fabricated on the substrates with He$^+$ or H$^+$ ion beam bombardment. The RMS of InGaN/GaN SQW was decreased for the samples of 10^{14}–10^{16} ions/cm^2 and RMS for the samples of 10^{17} ions/cm^2 was increased. Especially, the RMS for sample of 10^{17} ions/cm^2 H ion beam bombardment was increased remarkably than those for other InGaN/GaN SQW of low dose amount.

The InGaN/GaN SQW was grown on sapphire substrate of various ion beam bombardment, and their optical properties were analysed by photoluminescence (PL) measurement, which was made using Nd-YAG laser with wavelength of 266 nm at room temperature. Figure 5 shows the room temperature PL spectra of InGaN/GaN SQWs which are grown on sapphire substrates with/without ion beam bombardment. PL spectra of GaN buffer layer have an emission peak at 362.2 nm (3.41 eV) and InGaN/GaN SQWs have an emission peak from 441.1 to 446.6 nm (2.8–2.7 eV). The emission peak in PL measurement for $In_xGa_{1-x}N$ was known in the previous reports [9, 10]. According to the previous reports, 446.6 nm PL peak was appeared in the composition of $In_{0.1}Ga_{0.9}N$. Hence, the composition estimated from the PL spectra was in good agreement with that from the AES analysis. For the samples of N ion bombardment, the PL intensity of InGaN/GaN SQW was increased for the samples with 10^{14}–10^{16} ions/cm^2 of N ion dose than that for the samples of InGaN/GaN SQW grown on sapphire of non ion beam bombardment, and then PL intensity for 10^{17} ions/cm^2 N ion dose was decreased. The PL spectra peak of InGaN SQW showed the blue shift as the dose amount of N ion was increased. The PL intensity from He^{14}, He^{17} ions/cm^2 InGaN/GaN SQW was similar with that for the InGaN/GaN SQW grown on sapphire without ion beam bombardment. As for the samples with H$^+$ ion bombardment, the PL intensity of InGaN/GaN SQW was increased for H^{14}–H^{16} ions/cm^2 than that for the samples without ion beam bombardment, and it was estimated that the InGaN/GaN SQW for H^{17} ions/cm^2 ion beam bombardment was not fabricated normally.

Figure 6 shows the Hall measurement results for InGaN/GaN SQWs which were grown on sapphire substrate with/without ion beam bombardment. It was found that mobility of InGaN/GaN SQW was increased and carrier concentra-

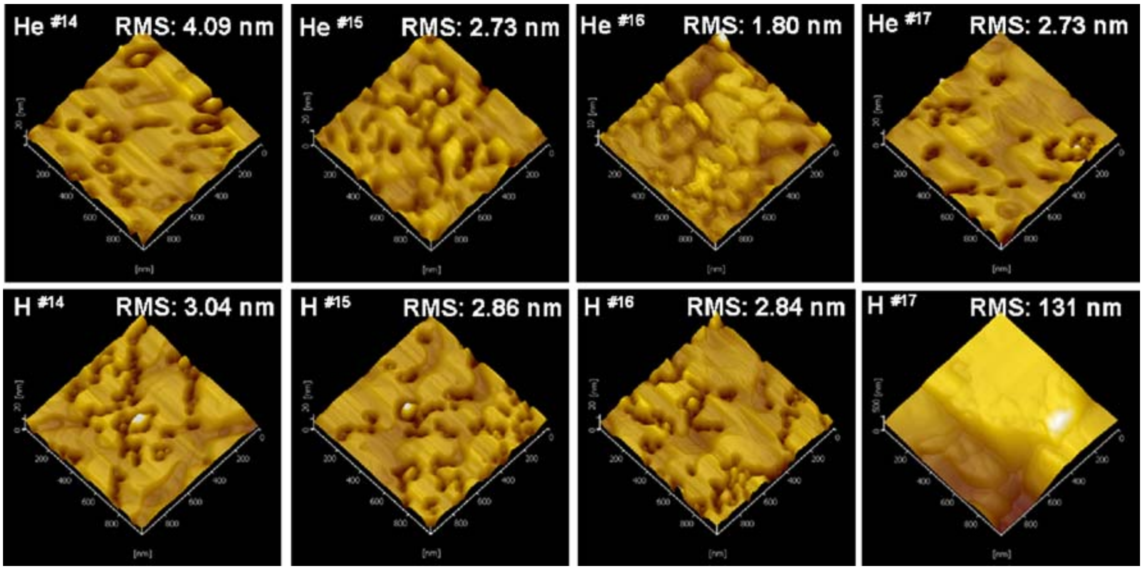

Fig. 4 1×1 μm^2 AFM images of InGan/GaN single quantum well of He$^+$ or H$^+$ ion beam bombardment; He$^{\#14}$, He$^{\#15}$, He$^{\#16}$, He$^{\#17}$, H $^{\#14}$, H$^{\#15}$, H$^{\#16}$, H$^{\#17}$

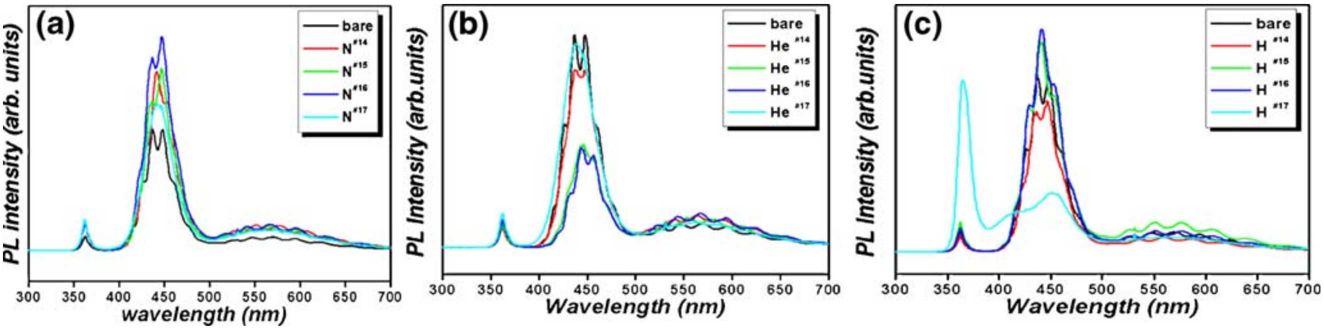

Fig. 5 The room temperature photoluminescence of InGaN/GaN single quantum well of with/without ion bombardment on sapphire substrate; (**a**) nitrogen ion (**b**) helium ion (**c**) hydrogen ion

tion was decreased for samples of $N^{\#14}$–$N^{\#16}$. The highest mobility value of 118 cm^2/V–S and the lowest carrier concentration of 3.41×10^{17} /cm^2 was found for N of 10^{16} ions/cm^2 ion beam bombarded sample. The highest mobility of 108 cm^2/V–S was observed for the sample of $He^{\#14}$ ion beam bombardment, and the mobility was decreased. InGaN/GaN SQW mobility was increased with dose of H^+ ion up to 10^{16} ions/cm^2 dose, and then the mobility was decreased at H^+ 10^{17} ions/cm^2.

4 Summary

The influence of ion beam bombardment on sapphire substrate was investigated on the electrical and optical characteristics of InGaN/GaN SQW structure. InGaN/GaN single quantum well structure was fabricated in the low pressure MOCVD. The composition of InGaN SQW was found to be $In_{0.1}Ga_{0.9}N$. In PL spectra, it was found that InGaN/GaN SQW was emitted from 441.1 to 446.6 nm (2.8–2.7 eV). The PL intensity of InGaN/GaN SQW was increased for samples of ion dose of 10^{14}–10^{16} ions/cm^2 of N^+, H^+ ion than those for InGaN/GaN SQW grown on sapphire without ion beam bombardment. The mobility in InGaN/GaN SQW was increased and the carrier concentration was decreased for the samples with 10^{14}–10^{16} ions/cm^2 of N^+, H^+ ion dose. The optimal condition for InGaN/GaN SQW on sapphire substrate of ion beam bombardment was deduced to be N^+ ion dose of 10^{16} ions/cm^2. It was obvious that the N^+, H^+ ion beam bombardment of sapphire substrate has the potential to improve the optical and electrical properties of InGaN/GaN SQW.

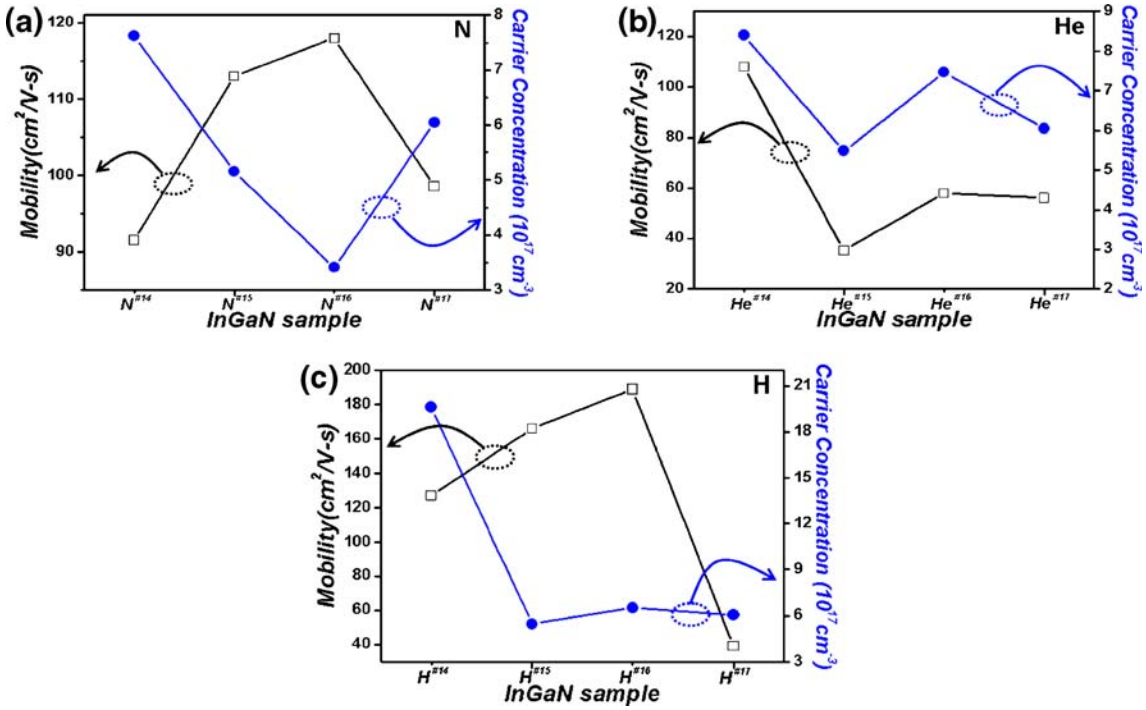

Fig. 6 Mobility and carrier concentration of InGaN/GaN single quantum well of ion bombardment on sapphire substrate; (**a**) nitrogen ion (**b**) helium ion (**c**) hydrogen ion

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