High-power InGaN/GaN double-heterostructure violet light emitting diodes

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(Received 2 November 1992; accepted for publication 15 February 1993)

InGaN/GaN double-heterostructure light-emitting diodes were fabricated. The output power was 90 μW and the external quantum efficiency was as high as 0.15% at a forward current of 20 mA at room temperature. The peak wavelengths of the electroluminescence (EL) varied between 411 and 420 nm with changes in the growth temperatures of an InGaN active layer between 820 and 800 °C. The full widths at half maximum of EL were between 22 and 25 nm.

Recently, there has been much progress in wide-band-gap II-VI compound semiconductor research, in which the first blue-green[1] and blue injection laser diodes (LDs)[2] as well as high-efficiency blue-light emitting diodes (LEDs)[3] have been demonstrated. On the other hand, in another wide-band-gap semiconductor, GaN, there has recently been great progress in the crystal quality, *p*-type control, and growth method of GaN films.[4–9] For high-performance optical devices, a double heterostructure (DH) is indispensible. The ternary III-V semiconductor compound, InGaN, is one candidate as the active layer of DH LEDs and LDs for the blue emission because its band gap varies from 1.9 to 3.4 eV depending on the indium mole fraction. To date, only a small amount of research has been performed on InGaN growth.[10–12] Recently, relatively high-quality InGaN films were obtained on a (0001) sapphire substrate by Yoshimoto *et al.*[12] using a high growth temperature (800 °C) and a high indium mole fraction flow rate. The present authors discovered that the crystal quality of InGaN films grown on GaN films was much improved in comparison with those on a sapphire substrate, and the band-edge (BE) emission of InGaN became much stronger in photoluminescence (PL) measurements.[13,14] In this letter, we describe the *p*-GaN/*n*-InGaN/*n*-GaN DH violet LEDs.

InGaN films were grown by the two-flow metalorganic chemical vapor deposition (MOCVD) method. Details of the two-flow MOCVD are described in other papers.[15,16] Sapphire with (0001) orientation (C face) was used as a substrate. Trimethylgallium (TMG), trimethylindium (TMI), monosilane (SiH_4), bis-cyclopentadienyl magnesium (Cp_2Mg) and ammonia (NH_3) were used as Ga, In, Si, Mg, and N sources, respectively. First, the substrate was heated to 1050 °C in a stream of hydrogen. Then, the substrate temperature was lowered to 510 °C to grow the GaN buffer layer. The thickness of the GaN buffer layer was approximately 250 Å. Next, the substrate temperature was elevated to 1020 °C to grow GaN films. During the deposition, the flow rates of NH_3, TMG, and SiH_4 (10 ppm SiH_4 in H_2) in the main flow were maintained at 4.0 ℓ/min, 50 μmol/min, and 10 nmol/min, respectively. The flow rates of H_2 and N_2 in the subflow were both maintained at 10 ℓ/min. The Si-doped GaN films were grown for 60 min. The thickness of Si-doped GaN film was approximately 4 μm. After GaN growth, the temperature was decreased to 800 °C, and the Si-doped InGaN film was grown for 8 min. During Si-doped InGaN deposition, the flow rates of NH_3, TMI, TMG, and SiH_4 in the main flow were maintained at 4.0 ℓ/min, 24 μm/min, 1 μmol/min, and 1 nmol/min, respectively. The thickness of the Si-doped InGaN layer was approximately 100 Å. After the Si-doped InGaN growth, the temperature was increased to 1020 °C to grow Mg-doped *p*-type GaN film. Mg-doped *p*-type GaN film was grown for 15 min by introducing Cp_2Mg gas at the flow rate of 3.6 μmol/min. After the growth, electron-beam irradiation was performed to obtain a highly *p*-type GaN layer under the condition that the accelerating voltage of incident electrons was kept at 15 kV. Fabrication of LED chips was accomplished as follows: the surface of the *p*-type GaN layer was partially etched until the *n*-type layer was exposed. Next, an Au/Ni contact was evaporated onto the *p*-type GaN layer and an Al contact onto the *n*-type GaN layer. The wafer was cut into a square shape (0.9 mm×0.9 mm). These chips were set on the lead frame, and then were molded. The characteristics of LEDs were measured under direct current (dc) biased conditions at room temperature.

Figure 1 shows the electroluminescence (EL) of the InGaN/GaN DH LEDs at forward currents of 10 and 20 mA. The peak wavelength was 420 nm and the full width at half maximum (FWHM) of the peak emission was 25 nm at each current (these LEDs are named 420-LEDs), as shown in Fig. 1(a). The peak wavelength and the FWHM did not vary under these dc biased conditions. Other peaks were not observed at all. We can control the indium mole fraction (X) of InGaN active layer by changing the growth temperature or indium source flow rate during InGaN growth.[13,14] Thus, the peak wavelength of the EL emission of DH LEDs can be changed. This is shown in Fig. 1(b). These DH LEDs were grown under the same conditions as those of the above-mentioned 420-LEDs except for the Si-doped InGaN growth temperature, which was changed to 820 °C. These LEDs show that the peak wavelength is 411 nm and the FWHM of the peak emission is 22 nm at each current (these LEDs are named 411-LEDs). Next, Si-doped InGaN films were grown on GaN films under the same conditions as those of the above-mentioned LEDs except for the InGaN growth time, which was changed to 60 min. After the Si-doped InGaN growth, PL measurement was performed. Figure 2 shows the results of PL measurements at room temperature. The excitation source was a 10 mW He-Cd laser. Curve a shows

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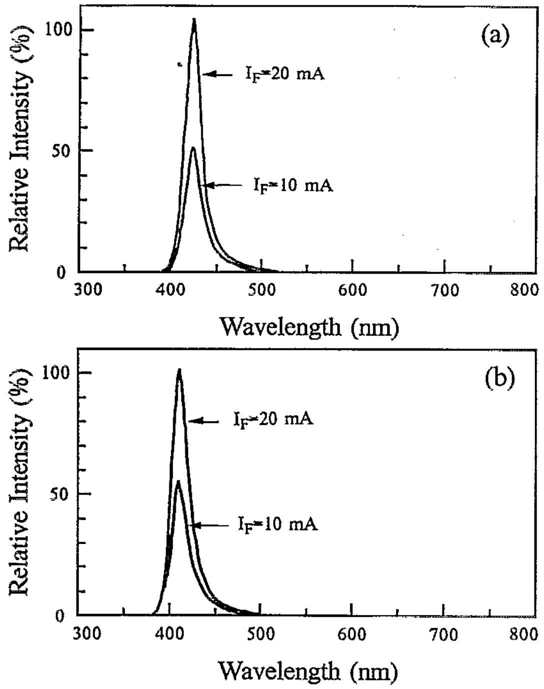

FIG. 1. Electroluminescence spectra of the p-GaN/n-InGaN/n-GaN double-heterostructure blue LEDs which were grown under the same conditions except for the growth temperature of an InGaN active layer. The growth temperatures of InGaN were (a) 800 °C and (b) 820 °C.

the InGaN films which were grown at 800 °C in the same conditions as those of the 420-LEDs and curve b shows the InGaN films which were grown at 820 °C in the same conditions as those of the 411-LEDs. Curve a shows a strong sharp peak at 425 nm and curve b at 408 nm. These emissions of PL are considered to be the BE emissions of Si-doped InGaN films because they have a very narrow FWHM (about 20 nm for curve a and 18 nm for curve b). In the comparison of the peak wavelength and the FWHM of the band-edge emission of PL measurements with those of EL of the above-mentioned LEDs, the values of peak wavelength and the FWHM are almost the same. In view of these results, these violet emissions of InGaN/GaN DH LEDs can be assumed to take place through recombination between the electrons injected into the conduction band and holes injected into the valence band of the InGaN active layer. The typical output power of 420-LEDs is shown as a function of the forward current in Fig. 3. Below 3 mA, the output power increases gradually possibly because nonradiative recombination currents are dominant. Above 3 mA, the output power increases sharply and almost linearly up to 25 mA as a function of the forward current. The output power of the InGaN/GaN DH LEDs is 40 μW at 10 mA and 90 μW at 20 mA. The external quantum efficiency is 0.15% at 20 mA. Recently, there has been much progress in wide-band-gap II-VI compound semiconductor research. In particular, Zn(S,Se)-based LEDs showed that the output power was 60 μW at a forward current of 20 mA, the external quantum efficiency was as high as 0.1% and the peak wavelength was 494 nm in room-temperature operations.[3] Therefore, the output power and external quantum efficiency of the InGaN/GaN DH LEDs are much higher than those of Zn(S,Se)-based LEDs at the same forward current, and the peak wavelength (420 and 411 nm) is much shorter than that of Zn(S,Se)-based LEDs (494 nm). A typical example of the I-V characteristics of InGaN/GaN DH LEDs (420-LEDs) is shown in the inset. The forward voltage is about 12 V at 20 mA. This forward voltage is too large in comparison with that of homostructure GaN LEDs (4 V).[9] This may be caused by the high resistivity of the p-type GaN layer of InGaN/GaN DH structure because the broad deep-level (DL) emissions around 750 nm could still be observed after the electron-beam irradiation treatment. We already reported that these DL emissions are related to the hole compensation mechanism.[17] In summary, high-power InGaN/GaN DH violet LEDs were fabricated. The output power was 90 μW at a forward current of 20 mA and the external quantum efficiency was as high as 0.15% under the room-temperature and dc-biased operations. The peak wave-

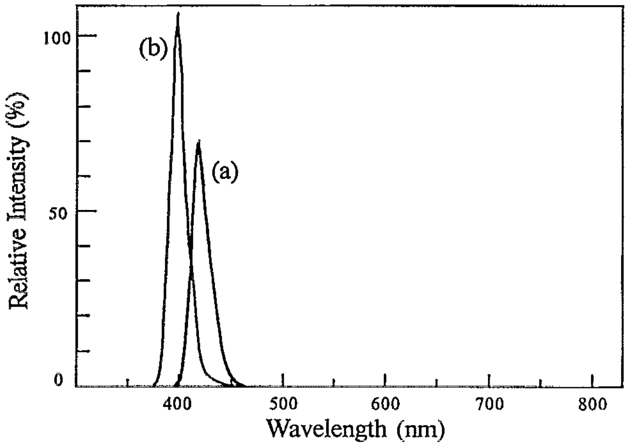

FIG. 2. Room-temperature PL spectra of Si-doped InGaN films grown on GaN films under the same growth conditions except for the Si-doped InGaN growth temperature. The growth temperatures of Si-doped InGaN were (a) 800 °C and (b) 820 °C.

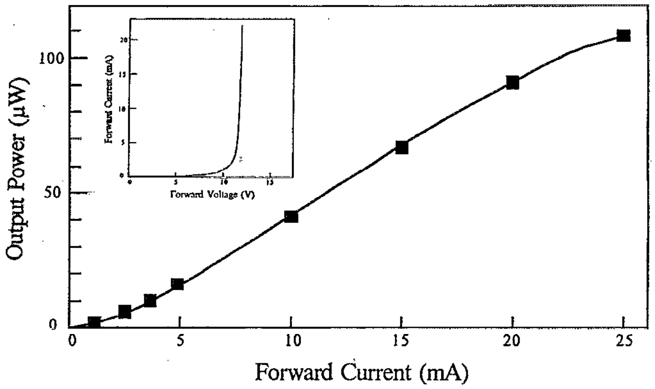

FIG. 3. The output power of the p-GaN/n-InGaN/n-GaN double-heterostructure blue LED as a function of the forward current. The inset shows the typical I-V characteristics of the p-GaN/n-InGaN/n-GaN double-heterostructure blue LED.

length and the FWHM of peak emission were 420 and 25 nm, respectively.

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