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Invited

InGaN/AlGaN Double-Heterostructure Light-Emitting Diodes

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High-brightness InGaN/AlGaN double-heterostructure (DH) blue-green-light-emitting diodes (LEDs) with a luminous intensity of 2 cd were fabricated by increasing an indium mole fraction of the InGaN active layer. The external quantum efficiency was as high as 2.4 % at a forward current of 20 mA. The peak wavelength and the full width at half-maximum (FWHM) of the electroluminescence (EL) were 500 nm and 80 nm, respectively. Also, high-power InGaN/AlGaN DH violet LEDs were fabricated. The output power was as high as 1.5 mW. The peak wavelength and the FWHM of the EL were 385 nm and 10 nm, respectively.

1. Introduction

Much research has been done on high-brightness blue-light-emitting diodes (LEDs) for use in full-color displays, full-color indicators and light sources for lamps with the characteristics of high efficiency, high reliability and high speed. For these purposes, II-VI materials such as ZnSe,[1] SiC[2] and III-V nitride semiconductors such as GaN[3] have been investigated intensively for a long time. However, it was impossible to obtain high-brightness blue LEDs with brightness over 1 cd. Recently, the present authors succeeded in producing for the first time 1-cd-brightness blue InGaN/AlGaN LEDs suitable for commercial applications.[4,5] The characteristics of those LEDs were peak wavelength of 450 nm, forward voltage of 3.6 V and output power of 1.2 mW at 20 mA. From the standpoint of application to traffic lights, the color of blue InGaN/AlGaN LEDs is too bluish and inadequate. Also, the color of commercially available GaP green LEDs with a peak wavelength of 560 nm is too greenish and the brightness of the GaP LEDs is too low (about 100 mcd) for application to outdoor traffic lights. Therefore, there are no available blue-green LEDs with the peak wavelength between 450 nm and 550 nm.

Recent research on III-V nitrides has paved the way for realization of high-quality crystals of AlGaN and InGaN, and p-type conduction in AlGaN.[6-12] Also, the hole-compensation mechanism of p-type AlGaN has been elucidated.[13,14] High-brightness blue LEDs with a luminous intensity of 1 cd have been achieved by using these techniques and are now commercially available.[4,5] In order to obtain blue emission centers in these InGaN/AlGaN double-heterostructure (DH) LEDs, Zn doping into the InGaN active layer was performed. This impurity-assisted recombination mechanism has not been elucidated. In this paper, co-doping with both Zn and Si into the InGaN active layer in InGaN/AlGaN DH LEDs in order to increase the output power of LEDs is described. Also, in order to achieve longer-wavelength (500nm) emission for the application of traffic lights, indium mole fraction of the InGaN active layer was increased.

2. Experimental

InGaN films were grown by the two-flow MOCVD method. Details of the two-flow MOCVD are described in other papers.[15,16] The growth was conducted at atmospheric pressure. Sapphire with (0001) orientation (C face), which had a two-inch diameter, was used as a substrate. The structure and growth conditions of LEDs are described in detail in other papers.[4,5] Only growth conditions of the InGaN active layer were changed from previous reports. The temperature of the InGaN active layer was decreased to 780°C to increase the indium mole fraction of InGaN to 0.23. During InGaN growth, both Si and Zn were co-doped with a flow of monosilane (SiH_4) and diethylzinc (DEZ). Fabrication of LED chips was accomplished as mentioned in previous reports.[4,5] The characteristics of LEDs were measured under DC-biased conditions at room temperature.

3. Results and Discussions

Figure 1 shows the electroluminescence (EL) spectra of the InGaN/AlGaN DH LEDs at forward currents of 0.5 mA, 1 mA and 20 mA. The carrier concentration of the InGaN active layer in this LED was $2x10^{19}$ cm^{-3}. A typical peak wavelength and full width at half-maximum (FWHM) of the EL were 500 nm and 80 nm, respectively, at 20 mA. The peak wavelength varies to a shorter wavelength with increasing forward current. The peak wavelength is 537 nm at 0.5 mA, 525 nm at 1 mA and 500 nm at 20mA. Figure 2 shows the peak wavelength of the EL spectra as a function of the forward current. When the forward current increases, the peak wavelength becomes shorter. This blue shift of EL spectra with increasing forward current suggests that the luminescence mechanism is the DA pair recombination in the InGaN active layer co-doped with both Si and Zn. At 20 mA, a more narrow, high-energy peak emerges around 425 nm in Fig. 1. This peak is due to band-to-band recombination in the InGaN active layer. This peak becomes resolved at injection levels where the impurity-related recombination is saturated.

The output power of the InGaN/AlGaN DH LEDs is 0.6 mW at 10 mA, 1.2 mW at 20 mA and 2.2 mW at 40 mA. The external quantum efficiency is 2.4 % at 20 mA. The typical on-axis luminous intensity of InGaN/AlGaN LEDs with 15° cone viewing angle is 2 cd at 20 mA. This luminous intensity is the highest value ever reported for blue-green LEDs. Also, this luminous intensity is so bright that these blue-green InGaN/AlGaN LEDs can be used for outdoor applications, such as traffic lights and displays requiring high brightness. The forward voltage was 3.5 V at 20 mA.

Figure 3 shows a chromaticity diagram where blue InGaN/AlGaN LEDs and blue-green InGaN/AlGaN LEDs are shown. Also, the commercially available green GaP LEDs and red GaAlAs LEDs are shown. From this figure, only blue-green InGaN/AlGaN LEDs are within the regions of roadway signals and railway signals. Therefore, InGaN/AlGaN LEDs are suitable for those applications from the viewpoint of color.

Figure 4 shows luminous intensity as a function of the peak wavelength of various commercially available LEDs. Judging from this figure, there are no LED materials except for InGaN that have strong luminous intensity over 1 cd below the peak wavelength of 550 nm. Therefore, InGaN is one of the most promising materials for LEDs and laser diodes (LDs) of peak wavelengths between 550 nm and 360 nm.

Figure 5 shows the EL spectrum of the InGaN/AlGaN DH violet LEDs at a forward current of 20 mA. These violet LEDs were grown under the same conditions as blue-green LEDs, except for the InGaN active layer. During InGaN growth, only Si was doped with a flow of SiH_4. The typical output power was 1.5 mW and the external quantum efficiency was as high as 2.3 % at a forward current of 20 mA at room temperature. The peak wavelength and the FWHM of the EL were 385 nm and 10 nm, respectively. Therefore, we can also fabricate high-power violet LEDs using III-V nitride materials.

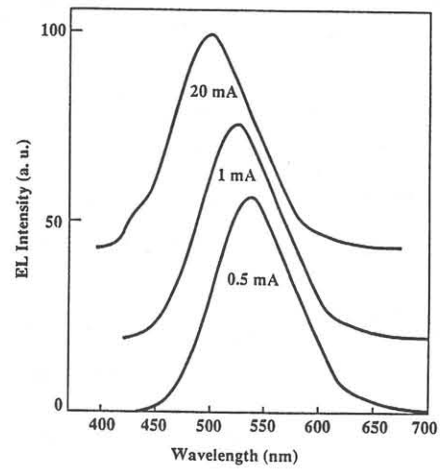

Fig. 1. EL spectra of the InGaN/AlGaN DH blue-green LEDs under different forward currents.

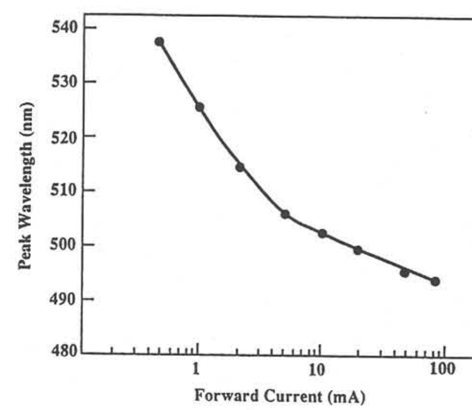

Fig. 2. The peak wavelength of the EL spectra of the InGaN/AlGaN DH blue-green LEDs as a function of the forward current.

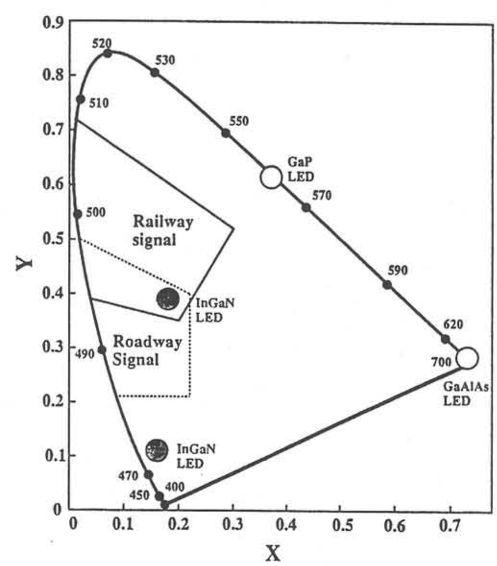

Fig. 3. Chromaticity diagram in which blue InGaN/AlGaN LEDs, blue-green InGaN/AlGaN LEDs, green GaP LEDs and red GaAlAs LEDs are shown.

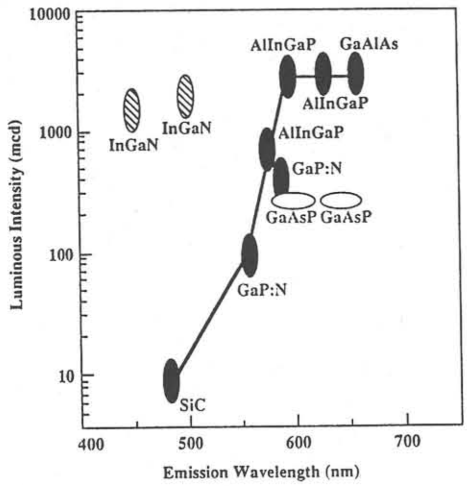

Fig. 4. Luminous intensity as a function of the peak wavelength of various commercially available LEDs.

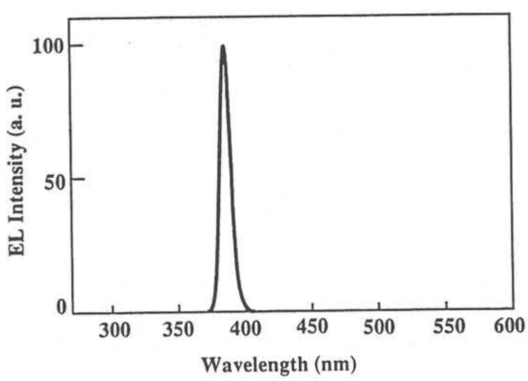

Fig. 5. EL spectrum of the InGaN/AlGaN DH violet LEDs under a forward current of 20 mA.

4. Summary

In summary, 2-cd high-brightness InGaN/AlGaN DH blue-green LEDs were fabricated for the first time. The output power was 1.2 mW and the external quantum efficiency was as high as 2.4 % at a forward current of 20 mA at room temperature. The peak wavelength and the FWHM of the EL were 500 nm and 80 nm, respectively. Traffic lights may prove to be a fertile application for the blue-green LEDs.

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