

# Candela-class high-brightness InGaN/AlGaN double-heterostructure blue-light-emitting diodes

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Candela-class high-brightness InGaN/AlGaN double-heterostructure (DH) blue-light-emitting diodes (LEDs) with the luminous intensity over 1 cd were fabricated. As an active layer, a Zn-doped InGaN layer was used for the DH LEDs. The typical output power was 1500  $\mu\text{W}$  and the external quantum efficiency was as high as 2.7% at a forward current of 20 mA at room temperature. The peak wavelength and the full width at half-maximum of the electroluminescence were 450 and 70 nm, respectively. This value of luminous intensity was the highest ever reported for blue LEDs.

Recently, there has been much progress in wide-band-gap II-VI compound semiconductor research, in which the first blue-green<sup>1</sup> and blue injection laser diodes (LDs)<sup>2</sup> as well as high-efficiency blue-light-emitting diodes (LEDs)<sup>3</sup> have been demonstrated. For the application to blue light-emitting devices, there are promising materials, such as wide-band-gap nitride semiconductors, which have great physical hardness, extremely large heterojunction offsets, high thermal conductivity, and high melting temperature.<sup>4</sup> In this area, there has recently been great progress in the crystal quality, *p*-type control, and growth method of GaN films.<sup>5,6</sup> For practical applications to short-wavelength optical devices, such as LDs, a double heterostructure is indispensable for III-V nitrides. The ternary III-V semiconductor compound, InGaN, is one candidate as the active layer for the blue emission because its band gap varies from 1.95 to 3.40 eV, depending on the indium mole fraction. Up to now, not much research has been performed on InGaN growth.<sup>7-9</sup> Recently, relatively high-quality InGaN films were obtained by Yoshimoto *et al.*,<sup>9</sup> at a high growth temperature (800 °C) and a high indium source flow rate ratio. The present authors discovered that the crystal quality of InGaN films grown on GaN films was greatly improved in comparison with that on a sapphire substrate, and the band-edge (BE) emission of InGaN became much stronger in photoluminescence (PL) measurements.<sup>10</sup> Thus, the first successful InGaN/GaN DH blue LEDs were fabricated using the above-mentioned InGaN films.<sup>11</sup> On the other hand, Zn doping into GaN has been intensively investigated to obtain blue emission centers for the application to blue LEDs by many researchers because strong blue emissions have been obtained by Zn doping into GaN.<sup>12-15</sup> However, there are no reports on Zn doping into InGaN. In this letter, the InGaN/AlGaN DH blue LED which has a Zn-doped InGaN layer as an active layer is described for the first time.

InGaN films were grown by the two-flow metalorganic chemical vapor deposition (MOCVD) method. Details of the two-flow MOCVD are described in other articles.<sup>16,17</sup> The growth was conducted at atmospheric pressure. Sapphire with (0001) orientation (*C* face), two inches in diameter, was used as a substrate. Trimethylgallium (TMG), trimethylaluminum (TMA), trimethylindium (TMI), monosilane (SiH<sub>4</sub>),

bis-cyclopentadienyl magnesium (Cp<sub>2</sub>Mg), diethylzinc (DEZ), and ammonia (NH<sub>3</sub>) were used as Ga, Al, In, Si, Mg, Zn, 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 about 300 Å. Next, the substrate temperature was elevated to 1020 °C to grow GaN films. During the deposition, the flow rates of NH<sub>3</sub>, TMG, and SiH<sub>4</sub> (10 ppm SiH<sub>4</sub> in H<sub>2</sub>) in the main flow were maintained at 4.0 ℓ/min, 30  $\mu\text{mol}/\text{min}$ , and 4 nmol/min, respectively. The flow rates of H<sub>2</sub> and N<sub>2</sub> in the subflow were both maintained at 10 ℓ/min. The Si-doped GaN films were grown for 60 min. The thickness of the Si-doped GaN film was approximately 4  $\mu\text{m}$ . After GaN growth, a Si-doped Al<sub>0.15</sub>Ga<sub>0.85</sub>N layer was grown to the thickness of 0.15  $\mu\text{m}$  by flowing TMA and TMG. After Si-doped Al<sub>0.15</sub>Ga<sub>0.85</sub>N growth, the temperature was decreased to 800 °C, and the Zn-doped In<sub>0.06</sub>Ga<sub>0.94</sub>N layer was grown for 15 min. During the In<sub>0.06</sub>Ga<sub>0.94</sub>N deposition, the flow rates of TMI, TEG, and NH<sub>3</sub> in the main flow were maintained at 17  $\mu\text{m}/\text{min}$ , 1.0  $\mu\text{mol}/\text{min}$ , and 4.0 ℓ/min, respectively. The Zn-doped InGaN films were grown by introducing DEZ at the flow rate of 10 nmol/min. The thickness of the Zn-doped InGaN layer was about 500 Å. After the Zn-doped InGaN growth, the temperature was increased to 1020 °C to grow Mg-doped *p*-type Al<sub>0.15</sub>Ga<sub>0.85</sub>N and GaN layers by introducing TMA, TMG, and Cp<sub>2</sub>Mg gases. The thicknesses of the Mg-doped *p*-type Al<sub>0.15</sub>Ga<sub>0.85</sub>N and GaN layers were 0.15 and 0.5  $\mu\text{m}$ , respectively. A *p*-type GaN layer was grown as the contact layer of a *p*-type electrode in order to improve Ohmic contact. After the growth, N<sub>2</sub> ambient thermal annealing was performed to obtain a highly *p*-type GaN layer at a temperature of 700 °C.<sup>18</sup> With this thermal annealing technique, the entire area of the as-grown *p*-type GaN layer uniformly becomes a highly *p*-type GaN layer.<sup>18</sup> Fabrication of LED chips was accomplished as follows. The surface of the *p*-type GaN layer was partially etched until the *n*-type GaN layer was exposed. Next, a Ni/Au contact was evaporated onto the *p*-type GaN layer and a Ti/Al contact onto the *n*-type GaN layer. The wafer was cut into a rectangular shape. These chips were set on the lead frame, and were then molded. The characteristics of LEDs

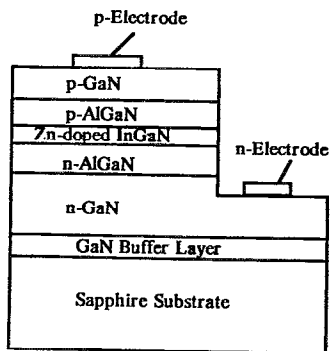


FIG. 1. The structure of the InGaN/AlGaIn double-heterostructure blue LED.

were measured under dc-biased conditions at room temperature. Figure 1 shows the structure of the InGaN/AlGaIn DH LEDs.

Figure 2 shows the electroluminescence (EL) spectra of the InGaN/AlGaIn DH LEDs at forward currents of 10, 20, 30, and 40 mA. The peak wavelength is 450 nm and the full width at half-maximum (FWHM) of the peak emission is 70 nm at each current. The peak wavelength and the FWHM are almost constant under these dc-biased conditions. In the PL measurements, Zn-related emission energy obtained with Zn doping into InGaIn was about 0.5 eV lower than the BE emission energy of InGaIn depending on the indium mole fraction. Therefore, the energy level of Zn in InGaIn is almost the same as that of Cd in InGaIn, and the peak position of EL of DH LEDs depends on the indium mole fraction of InGaIn.<sup>19</sup> Zn doping into InGaIn films will be described in other articles in detail. The output power is shown as a function of the forward current in Fig. 3. The output power increases sublinearly up to 40 mA as a function of the forward current. The output powers of the InGaN/AlGaIn DH LEDs are 800  $\mu$ W at 10 mA, 1500  $\mu$ W at 20 mA, and 2500  $\mu$ W at 40 mA. The external quantum efficiency is 2.7% at 20 mA. A typical on-axis luminous intensity of DH LEDs with 15°

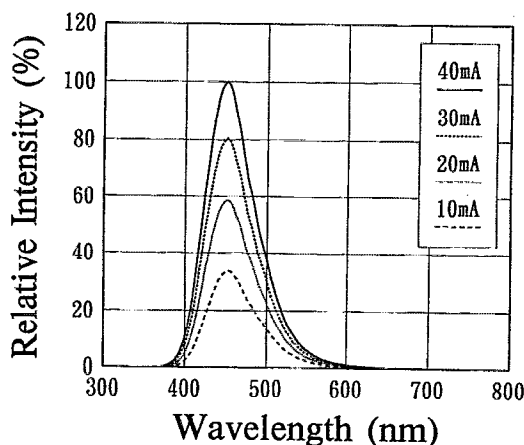


FIG. 2. Electroluminescence spectra of the InGaN/AlGaIn double-heterostructure blue LED under different dc currents.

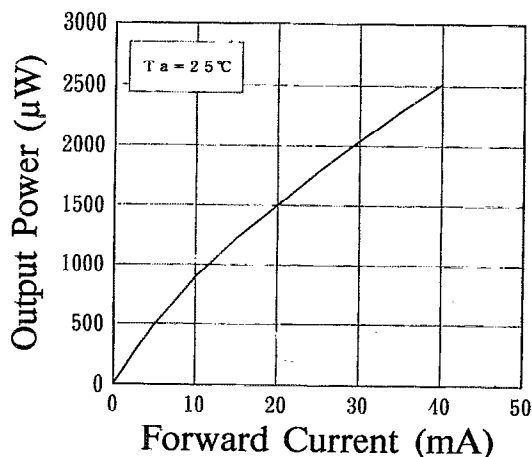


FIG. 3. The output power of the InGaN/AlGaIn double-heterostructure blue LED as a function of the forward current.

cone viewing angle is 1.2 cd at 20 mA. This luminous intensity is the highest value ever reported for blue LEDs. A typical example of the current-voltage ( $I$ - $V$ ) characteristics of InGaN/AlGaIn DH LEDs is shown in Fig. 4. It is shown that the forward voltage is 3.6 V at 20 mA. This forward voltage is the lowest value ever reported for III-V nitride LEDs. In previous reports on InGaIn/GaN DH LEDs, the forward voltage was as high as about 10 V and the output power was not so high (about 125  $\mu$ W).<sup>11</sup> In the previous study, electron beam irradiation instead of thermal annealing was performed for as-grown InGaIn/GaN epilayers in order to obtain a highly  $p$ -type GaIn layer. It is considered that the forward voltage was as high as 10 V and the output power was not so high because the entire area of the  $p$  layer was not uniformly changed into a highly  $p$ -type GaIn layer by electron beam irradiation. By thermal annealing, the entire area of as-grown high-resistivity  $p$ -type GaIn layer can be uniformly changed into a low-resistivity  $p$ -type GaIn layer.<sup>18</sup>

In summary, candela-class high-brightness InGaIn/AlGaIn DH blue LEDs with the luminous intensity over 1 cd were fabricated for the first time. The output power was 1500  $\mu$ W and the external quantum efficiency was as high as 2.7% at a forward current of 20 mA at room temperature. The peak wavelength and the FWHM of the EL were 450 and 70 nm, respectively. This value of luminous intensity was the high-

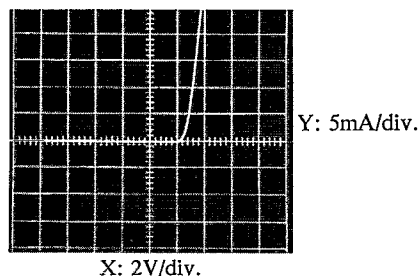


FIG. 4. Typical  $I$ - $V$  characteristic of the InGaIn/AlGaIn double-heterostructure blue LED.

est ever reported for blue LEDs. Using these high-brightness blue LEDs, high-brightness full-color indicators and flat panel displays will be developed in the near future.

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