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Electrical and Optical Properties of InGaN/AlGaN Double Heterostructure Blue Light-Emitting Diodes *

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Electrical and optical properties of InGaN/AlGaN double heterostructure blue light-emitting diodes were investigated. Measurement of the forward bias current–voltage behaviour of the device demonstrated a departure from the Shockley model of a p–n diode, and it was observed that the dominant mechanism of carrier transport across the junction is associated with carrier tunnelling. Electroluminescence experiments indicated that there was a main emission band around 2.80 eV and a relatively weaker peak at 3.2 eV. A significant blueshift of the optical emission band was observed, which was consistent with the tunnelling character of electrical characteristics. Furthermore, the degradation in $I-V$ characteristics and the low resistance ohmic short of the device were observed.

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Recently, the wide band gap semiconductors GaN, InN, AlN and their alloys have attracted considerable interest because of their great potential applications in electronics and optoelectronics.[1,2] They may be used in the fabrication of light-emitting diodes (LEDs) and lasers operating in the visible and ultraviolet (UV).[3,4] With the development of the materials and devices, an energy span ranging from the blue to near-UV wavelengths, which was inaccessible to semiconductor technology in the past, has been opened. Recently, group Ⅲ nitride-based electronic devices are being developed for various applications, most notably for blue laser diodes (LDs) and high-temperature electronics. In addition, the blue LEDs are the most mature amongst the nitride-based optoelectronic components, having been successfully commercialized since 1994. Several papers on high-brightness InGaN/AlGaN blue LEDs from the Nichia Chemical Industries Ltd have shown some behaviours of the emission spectra with various current injections.[5–7] Electrical and optical characterization of the devices can provide important information about the current transport through wide band gap p–n heterojunctions, layer materials and metal–semiconductor contacts.[8,9] So far, however, these aspects of nitride-based LEDs have received relatively little attention.

In this study, the electrical and optical properties of the InGaN/AlGaN double heterostructure blue LEDs made by Nichia Ltd were investigated at 77 and 300 K. It was found that the main transport mechanism was associated with carrier tunnelling, rather than thermal diffusion. Electroluminescence (EL) experiments indicated there was an emission band around 2.80 eV and a relatively weaker short-wavelength peak at 3.2 eV. Furthermore, the degradation in the $I-V$ characteristics and the low resistance ohmic short were observed.

The Nichia blue LEDs used in this study were of double heterostructures (DHs) with an n-type $In_{0.06}Ga_{0.94}N$ active layer co-doped with the donor Si and the acceptor Zn.[10,11] The epitaxial layers were grown by the two-flow metal organic chemical vapour deposition (MOCVD) method on (0001) oriented sapphire substrates. The 30 nm thick Si-doped GaN buffer layer was first grown at 510°C, and the 4 μm thick Si-doped GaN layer was grown at 1020°C. The Si-doped $Al_{0.15}Ga_{0.85}N$ layer for the carrier confinement was 0.15 μm in thickness. The 50 nm thick $In_{0.06}Ga_{0.94}N$ active layer co-doped with the donor Si and the acceptor Zn was grown at 780°C. The thin active layer and the $Al_{0.15}Ga_{0.85}N$ confinement layers ensure a region of uniform excitation and the EL in the active region results from efficient recombination of carriers via Zn-related deep levels. Therefore, the spontaneous emission spectra will be a replica of the minority carrier distribution.

Prior to measurements, the diodes were de-encapsulated to avoid the risk of epoxy-induced stress at the cryogenic temperatures. The direct current $I-V$ measurements were performed at 77 K and room temperature (300 K). For the measurements at 77 K, the diode was fixed on a cold finger in a vacuum chamber that was kept at the temperature of liquid nitrogen. In order to understand the possible relationship between the current components and light emission, optical experiments were performed using a monochromator, a chopper or signal generator, and a UV photomultiplier equipped with an EG&G 5210 lock-in amplifier.

The forward bias $I-V$ behaviours for a blue LED

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measured at 77 and 300 K are shown in Fig. 1. Contrary to the standard Shockley model of a p–n diode, the slope of $I-V$ characteristics in a semilogarithmic plot almost does not depend on temperature. The low current component from 5×10^{-6} to 5×10^{-4} A can be approximated by an exponential function $I = I_s^* \exp(nV)$, where I_s is a constant, and n the diode ideality factor being determined as large as 4.2. This indicates that the main transport mechanism in the device is associated with carrier tunnelling rather than thermal diffusion.[8] Furthermore, the observed external quantum efficiency of about 2.7% demonstrates that the non-diffusion current does inject the minority of carriers from the p-type AlGaN layer into the n-type InGaN active layer for the emission of light.

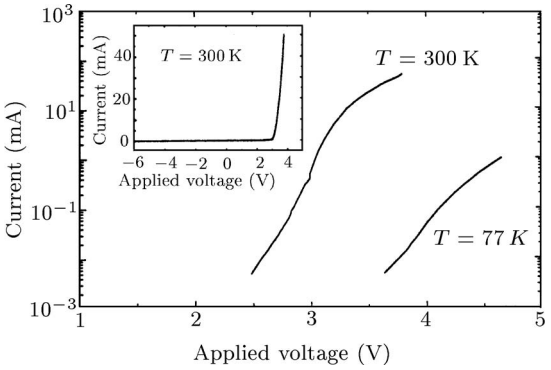


Fig. 1. Forward bias $I-V$ characteristics of a Nichia blue LED at 77 and 300 K. Two different current components were observed, including a low voltage (0–3.1 V) component and a medium voltage (3.1–3.8 V) one.

Similar to Ref. 12, two different current components of the device were observed, including a low voltage ($0-3.1$ V) component and a medium voltage ($3.1-3.8$ V) one. A change in the $I-V$ curve slope indicates a change in the predominant mechanism of the current transport through the junction. As the sample temperature is decreased, carrier concentration initially decreases and then saturates at levels usually about two orders of magnitude lower than those at room temperature. It was shown in Ref. 13 that a significant fraction of electron transport took place by hopping in the compensation centers leading to low mobility as compared to normal band carriers. This process becomes dominant at low mobility as compared to normal band carriers. It becomes dominant at low temperatures. In addition, low series resistance of the device is probably caused by a high density of threading dislocations.[12] These defects can provide a parallel path for current flowing across the highly resistive p-type layers, which is consistent with the degradation mechanism under high electrical-stress conditions as discussed below.

Figure 2 shows the EL spectra obtained for the injection current ranging from $0.5-10$ mA (Fig. 2 (a)) and $20-75$ mA (Fig. 2(b)). The large emission bandwidth around 2.8 eV is related to the strong lattice coupling of the Zn states in both GaN and InGaN. When the current is higher than 4.0 mA, a considerable blueshift of the sharp short-wavelength edge of the emission band is observed with the increase of the current. Meanwhile, a separate short-wavelength peak at 3.2 eV appears at room temperature when the current is higher than 3.0 mA, as shown by the arrows in Figs. 2(a) and 2(b). This peak is associated with the band-edge transition in InGaN.

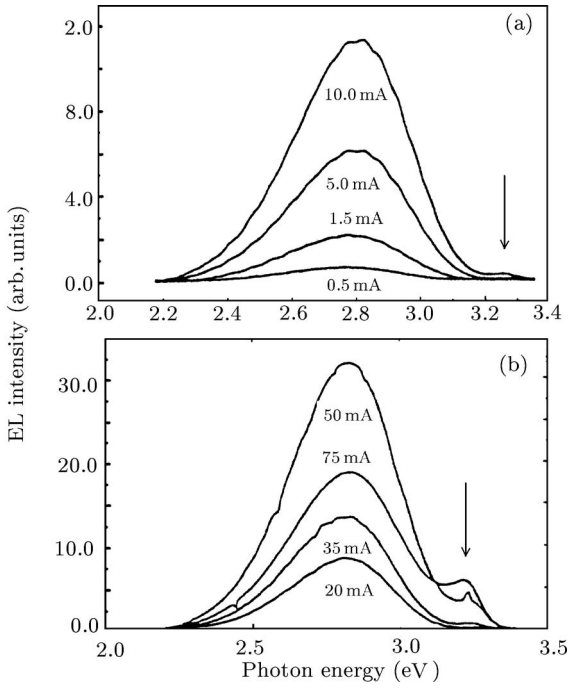


Fig. 2. EL emission spectra as a function of junction current at room temperature in the cases: (a) injection current between $0.5-10$ mA, and (b) injection current between $20-75$ mA.

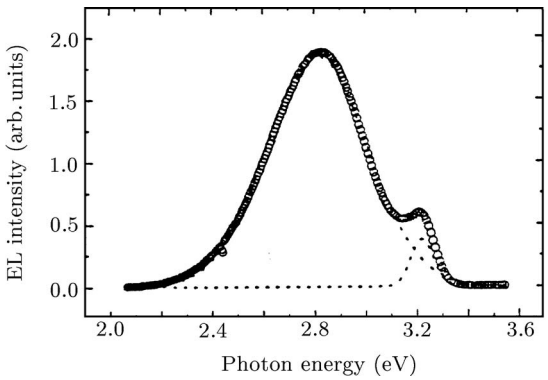


Fig. 3. EL emission peaks exhibit Gaussian broadening. The open circles are the experimental data, which are fitted by two Gaussian curves (dashed lines).

EL with shifting peak spectra has been observed and studied for the GaAs p–n junctions.[14] In GaAs, the two mechanisms that may be responsible for the shifting peak spectra are the photon-assisted tunnelling and the band filling. Contrary to the behaviour of photo-assisted tunnelling, the emission spectra

shown in Fig. 2 are consistent with the band filling mechanism. The shifting peak spectra are due to the injection of holes via tunnelling into an empty acceptor impurity band and vacant valence band tails.[7] As shown in Fig. 3, the emission peaks exhibit Gaussian broadening.

The output spectra under pulsed conditions with amplitudes ranging from 0.5 to 75 mA were obtained. The band-edge emission at 3.2 eV increases with a faster rate than the impurity-related emission band around 2.8 eV, and becomes dominant at very large current densities, while the impurity-related emission appears to saturate. As a result of the high pulsed current measurements, several LEDs show a degradation in $I-V$ characteristics and some show a low resistance ohmic short ($\sim 100\,\Omega$) as shown in Fig. 4. It is interesting that the shorts can be removed by applying a modest (-5 V) reverse bias and will recreate by applying a pulsed forward current. When the LED is in the shorted state, light output under continuous wave (cw) condition is impossible. The shorted LED will still, however, emit light under pulsed condition. After a reverse bias is applied to remove the short, cw operation is once again possible. The effects of the stress are not completely removable, i.e. the LED can be placed in a shorted state or in a degraded state, and will not return back into its original, unstressed state.

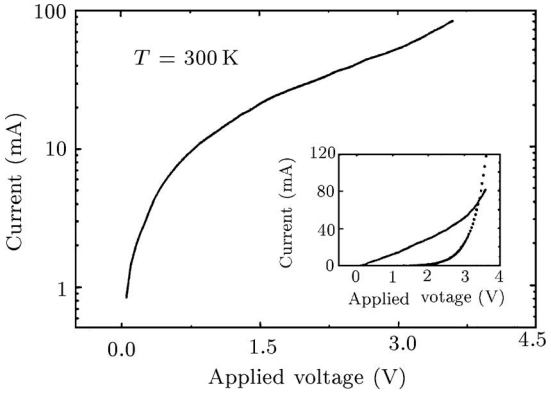


Fig. 4. Typical $I-V$ behaviour of a stressed LED. As a result of the high pulsed current measurements, some LEDs showed a degradation in $I-V$ characteristics and a low resistance ohmic short.

Osinski *et al.*[15] studied the performance of the commercial AlGaN/InGaN/GaN blue LEDs under high current pulse conditions. They analysed the results of measurements of the deep level transient spectroscopy, the thermally stimulated capacitance spectroscopy and the admittance spectroscopy in the stressed state of the devices. The experimental data suggested that the stress did not cause a significant change in any impurity levels, especially deep impurity levels. The image of the electron beam induced current (EBIC) showed that the high forward current applied to these blue LEDs had caused metal from the p contact to migrate across the junction along the threading dislocations. A dislocation density as high as $10^9 - 10^{10}\,\mathrm{cm}^{-2}$ has been determined from the transmission electron microscopy analysis.[16] Therefore, it is possible that the metal migration along the defect tubes is the main process responsible for degradation of the Nichia blue LEDs under high electrical stress conditions.

In conclusion, the electrical and optical characteristics of the InGaN/AlGaN double heterostructure blue LEDs with an $In_{0.06}Ga_{0.94}N$ active layer were investigated. The temperature-independent slopes of the $I-V$ curves in the semilogarithmic plot and the significant blueshifts of the optical emission band indicate that the main transport mechanism of the device is associated with carrier tunnelling, rather than thermal diffusion. EL experiments demonstrate there is an emission band around 2.80 eV and a relatively weaker short-wavelength peak at 3.2 eV. Furthermore, the degradation in the $I-V$ characteristics and the low resistance ohmic short were observed.

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