Comparative study of temperature-dependent electroluminescence efficiency in blue and green (In,Ga)N multiple-quantum-well diodes

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Electroluminescence (EL) efficiency of blue light emitting diodes (LEDs) grown on a c-plane sapphire using (In,Ga)N quantum well (QW) heterostructures shows an anomalous behavior, that is, EL efficiency is strongly reduced at temperatures below 100 K, which is quite different from the usual characteristics of GaAs based QW diodes. The peculiar low temperature EL properties have been observed by several groups, and well documented previously [1-6]. As a matter of fact, the QW LED based on group III-nitride semiconductors with a ternary alloy active layer shows very bright emission characteristics in spite of the existence of high-density (~10^{10} /cm^2) misfit dislocations [7-10]. Thus, origins of the high quantum efficiency at room temperature and of the drastic reduction at low temperature have attracted much attention recently in order to pursue what determines the EL efficiency [11-13]. One of the anticipated genuine causes for the low temperature EL quenching may be ascribed to the deep Mg acceptor level of 170 meV in p-GaN, which can be deactivated at lower temperatures below 100 K. Therefore, holes are failed to be injected into the QW active region from the p-GaN layer, especially when the electron blocking p-type (Al,Ga)N barrier is introduced [4]. However, detailed physical pictures for the EL enhancement and quenching effects under the forward bias conditions are still controversial and deserve for further investigations.

In this paper, the temperature-dependent EL efficiency is comparatively investigated in blue and green (In,Ga)N multiple QW (MQW) LEDs as a function of current. The EL efficiency is found to be drastically changed with temperature and current for the blue LED, that is, the EL intensity collapses at lower temperatures below 100 K and at higher injection currents above 1 mA, while no low temperature EL quenching is observed for the green MQW-LED. We attribute these variations of temperature-dependent EL efficiency in the blue and green diodes to different carrier capture efficiencies between the two diodes, because localization potential fluctuations effectively collecting injected carriers into the radiative recombination sites are larger for the green diode due to the higher In contents in the well, especially under the higher forward bias conditions at low temperatures.

EL spectral properties of the blue and green (In,Ga)N MQW LED chip samples, fabricated by Nichia, have been studied as a function of lattice temperature with varying injection current from 0.01 mA to 10 mA. In the 5-periods...
(4-periods) blue (green) MQW diode the nominal (In,Ga)N well width is 2.0 nm (2.4 nm) and the claimed In concentration in the MQW layer is 0.3 (0.45). The (In,Ga)N MQW layer is confined by p-AlGaN and n-GaN barrier layers. A detailed experimental setup for EL measurements has been reported previously [1,5]. Current-voltage (I-V) characteristics of the blue and green MQW diodes were measured between 20 and 300 K. At 300 K, the logarithmic current below 0.1 mA is nearly proportional to the forward voltage in both cases. But, above 1 mA, the necessary forward voltage increases with increasing the current level, probably due to the low density of holes in the p-GaN and p-AlGaN layers. When decreasing temperature, this trend of I-V characteristics is even enhanced, and the forward bias significantly increases to obtain a necessary current level. The typical forward voltage at a forward current of 10 mA was 3.2 V at 300 K and 4.5 V at 20 K for the blue MQW diode. In all cases the forward voltage to get a certain current level is increased by about 1-1.5 V when the temperature is decreased from 300 K to 20 K.

Figure 1 shows EL spectra of (a) blue and (b) green MQW diodes as a function of temperature at an injection current of 1.0 mA. At 300 K, the blue MQW LED shows brighter emission characteristics than the green one, in agreement with the previously observed trend [1] due to the smaller piezo-field effect, since the lattice-mismatching between the active (In,Ga)N and GaN barrier layers is smaller for the blue diode with the smaller In mole fraction of 0.3. Temperature-dependent variation patterns of the EL intensity observed in Fig. 1 are very different between the two diodes. That is, the EL intensity for the green LED in Fig. 1(b) monotonously increases with decreasing temperature down to 20 K. However, when the temperature is decreased, the EL intensity for the blue LED initially increases, reaches the maximum around 160 K, and then quickly decreases at 20 K down to a value much lower than the one at room temperature, as shown in Fig. 1(a) in agreement with the general trend observed previously for the single QW LEDs [1].

When the injection current is varied, these variation patterns of the temperature-dependent EL intensity are changed drastically. Temperature-dependent results of the blue and green integrated EL intensities as a function of current are plotted in Figs. 2(a) and 2(b), respectively, in a logarithmic-logarithmic plot between 0.01 and 10 mA. We note here that there exists a strong contrast of the EL intensity variation patterns between blue and green MQW diodes. For the blue MQW diode the EL intensity is significantly decreased with decreasing temperature below 160 K, especially at the highest injection of 10 mA, that is, the EL intensity is strongly dependent on temperature. We also note a clear trend that the EL intensity variation in Fig. 2(a) is stronger with increasing injection current, indicating the current-dependent EL anomalies at low temperatures. In contrast to the blue MQW diode (shown in Fig. 2(a)) the EL intensity evolution for the green MQW diode

![Figure 1](image1)

**Figure 1** Temperature dependence of EL spectra for (a) blue and (b) green (In,Ga)N MQW diodes at 1.0 mA injection.

![Figure 2](image2)

**Figure 2** Integrated EL intensity versus current in a logarithmic-logarithmic plot at various temperatures between 20 and 300 K for (a) blue and (b) green MQW diodes.
is moderate, as seen in Fig. 2(b). At the lowest injection current of 0.01 mA in Fig. 2(b), the EL intensity is highest at 20 K, and it monotonously decreases with increasing temperature, while it is not so sensitive to temperature at the highest injection of 10 mA. From these observations it is clear that the EL efficiency is not solely determined by temperature, but strongly depends on the In content in the MQW layer as well as the current levels. This finding rules out interpretation of low temperature EL collapse for the blue LED in terms of hole freeze-out, since the green MQW diode with the same p-type layers does not show such anomalous EL quenching.

In order to show variations of the EL efficiency as a function of injection current, the integrated EL intensity divided by current, which is proportional to the EL external quantum efficiency $\eta_{ex}$, is plotted in Fig. 3 for the blue (circles and squares) and green (stars and triangles) diodes as a function of current at 20 and 300 K. As noted before, with decreasing temperature the external quantum efficiency for the green diode always increases irrespective of the current level (0.01-10 mA) due to reduced non-radiative recombination processes, showing the maximum value at 20 K. This means that electrically injected carriers (electrons and holes) are efficiently captured into the active region of the green MQW diode. On the other hand, the external quantum efficiency for the blue diode is much more sensitively varied with temperature and current. When the current is fixed at 0.01 mA and the temperature is slightly decreased, the $\eta_{ex}$ value is significantly increased and shows the maximum value around 160 K. The $\eta_{ex}$ value is then decreased with further decreasing the temperature, and reaches the minimum at 20 K. When the current is highest at 10 mA, the external quantum efficiency is surprisingly low (almost zero) at 20 K in strong contrast to the case of 0.01 mA injection. Therefore, $\eta_{ex}$ variations are in fact very large for the blue diode and show dramatic dependence on the current level. We attribute the strong $\eta_{ex}$ reduction at higher injection currents, observed for the blue MQW diode, to the carrier escape out of the wells due to increased forward bias voltages (external field effects). Because the QW potential depth is shallower for the blue diode, overflow of the injected carriers is significant and thus carriers are not effectively captured by the active radiative recombination centers within the well, especially when the temperature is low enough below 100 K and the current is high above 1 mA.

In summary, the external electroluminescence efficiency of blue and green (In,Ga)N MQW diodes has been comparatively investigated as a function of temperature and current. The EL efficiency of the two types of diodes shows very different variation patterns with temperature and current. We attribute these variations in EL efficiency to different carrier escape/capture efficiencies by the wells due to the different In contents. Thus, the injection current dependence of the $\eta_{ex}$ variations shows a striking difference between low and high In content wells, since the QW potential depth for localized carriers escape is shallow and deep, respectively, under the forward bias conditions.

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References


Figure 3 EL external quantum efficiency $\eta_{ex}$ defined by EL intensity divided by current, for blue (circles and squares) and green (stars and triangles) diodes as a function of injection current at 20 and 300 K.