Comprehensive studies of light emission from GaN/InGaN/AlGaN single-quantum-well structures

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Abstract
Results of our comprehensive studies of Nichia blue and green SQW LEDs are presented. These include measurements of the emission spectra over a wide range of currents, temperatures, and pressures. The observed anomalous blue shift with temperature and rapid current-induced blue shift at low excitation levels can be explained using a simple model of recombination between Gaussian band-tail states. © 1998 Published by Elsevier Science B.V. All rights reserved.

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1. Introduction

Studies of light emission from GaN/InGaN/AlGaN quantum wells are of critical importance, since these structures are used as active regions in high-performance light-emitting diodes (LEDs) has not been accompanied by a similar effort to explore the physical properties of group-III nitride quantum wells. This resulted in a fairly unusual situation, when SQW LEDs were introduced commercially by Nichia Chemical Industries towards the end of 1995, in spite of a rather incomplete knowledge of radiative recombination in GaN/InGaN/AlGaN quantum wells. It was, however, observed that the peak wavelength of emitted light was much longer than expected for band-edge emission of InGaN [1]. Since then, several groups have reported various additional peculiarities of light emission from GaN/InGaN/AlGaN quantum wells, such as large shift of emission spectra with current [2] or anomalous blue shift with increasing temperature [3]. Most of these observations, however, have not been accompanied by any quantitative description of the emission spectra.

While in the case of LEDs knowledge of the true nature of radiative transitions was not apparently necessary to develop high-performance devices, quite a different situation may exist in the case of...
lasers. Optimization of laser design inherently requires a better understanding of the true nature of radiative and nonradiative recombination channels.

In this paper, we present results of our comprehensive studies of Nichia blue and green SQW LEDs. These include measurements of the emission spectra over a wide range of currents, temperatures, and hydrostatic pressures. Our experiments indicate that the observed anomalous blue shift with temperature and rapid blue shift with increasing current at low excitation levels can be explained in terms of a simple model of radiative recombination between Gaussian band tails of the conduction and valence bands.

2. Current-induced shift of the electroluminescence spectra

Fig. 1 shows typical electroluminescence (EL) spectra of Nichia NSPG-500 green SQW LEDs recorded over a wide range of driving currents. The spectra are basically of Gaussian shape with typical linewidth close to 160 meV at low currents, broadening to \( \sim 260 \) meV at high currents. At low currents, the position of the luminescence peak lies significantly below the bandgap energy of the \( \text{In}_{0.45}\text{Ga}_{0.55}\text{N} \) active material, \( E_g = 2.505 \) eV. At high currents, however, the emission peak energy is consistent with interband transitions between confined energy states in the quantum well. In addition, as shown in the inset in Fig. 1, the EL peak position moves quickly to higher energies once the pumping current exceeds 0.1 mA. This shift is about two orders of magnitude faster than what is expected from the filling of conduction band states, thus a much lower density of states is required to account for the magnitude of the observed effect.

Originally, the discrepancy between the emission wavelength and the bandgap was assigned to a combination of excitonic effects and tensile strain caused by the difference in thermal expansion coefficients between the well and barrier materials [1]. The 2 A spectrum in Fig. 1 implies that no significant change in the bandgap energy occurs compared to unstrained material, but states located below the band edge may dominate the emission spectra at low currents. As discussed in Section 5, we interpret the observed low-current spectral features in terms of band-tail states which may be associated with defects or with local fluctuations of alloy composition.

3. Temperature dependence of electro- and photoluminescence spectra

We have measured the EL spectra of green and blue Nichia SQW LEDs in function of both temperature and current. The results are plotted in Figs. 2 and 3 for the green and blue LEDs, respectively. Above \( \sim 50 \) K, at any fixed current lower than 0.1 mA (i.e. before the band-tail filling effect begins to be important) the EL undergoes blue shift with increasing temperature. Between 15 and 300 K, this shift can be as large as 70 meV for the lowest applied currents and it is of the opposite sign than the shrinkage of the InGaN bandgap. Thus, even if we take into account the uncertainty in determination of the actual composition of the active region material, the nature of the radiative
transitions at low currents is different from the usual interband transitions in undoped quantum wells.

We have also observed a similar blue shift with temperature using photoluminescence (PL). This indicates that the anomalous blue shift is not caused by the tunneling processes, commonly observed in GaN-based LEDs [3].

4. Pressure dependence of electro- and photoluminescence spectra

In order to shed more light on the nature of radiative recombination in InGaN quantum wells, high hydrostatic pressure measurements of the PL and EL emission in Nichia green and blue SQW LEDs have been performed [4]. The linear pressure coefficients obtained from these experiments
Fig. 4. Peak position of the PL as a function of pressure for both NSPG-500 green (triangles) and NSPB-500 blue (squares) SQW LEDs. Solid lines show the pressure-induced shift of the bandgaps in bulk GaN and InN.

are unusually low, 12 and 16 meV/GPa for PL from the green and blue LEDs, respectively (see Fig. 4). The pressure coefficient of the EL peak position in green SQW LEDs was also very low, close to 16 meV/GPa. These results are much smaller than the available values for the pressure coefficients of the bandgaps of GaN (40 meV/GPa) and InN (33 meV/GPa), and indicate strong localization of states involved in radiative transitions. Deep electronic states extending into the forbidden gap are known to have pressure coefficients determined by an average over the whole Brillouin zone. The average coefficients are usually much lower than that of the $\Gamma$-point direct bandgap.

5. Band-tail recombination model

As illustrated by the solid curve in Fig. 3, a good quantitative agreement with measured spectral shifts can be achieved in the range of applicability of non-degenerate occupation of band-tail states. More details of the Gaussian band-tail model are given in Ref. [5].

Also, relative insensitivity of EL and PL emission wavelengths to high hydrostatic pressure is consistent with defect-related band tails. Small pressure coefficients are expected for transitions involving localized excitons as well as when the recombination takes place between uncorrelated electrons and holes trapped in band-tail states that may arise from In content fluctuations and/or from defect states [4].

6. Discussion and conclusions

The anomalous temperature behavior of light emission in Nichia SQW LEDs cannot be easily explained by other models of the emission mechanism proposed earlier. The localized exciton model [2] may explain the fact that the emission energy is well below the bandgap. When combined with quantum-confined Stark effect, it can also explain the blue shift of the emission wavelength with increasing current. The magnitude of the effect, however, cannot be explained by the Stark shift alone, and would require additional consideration of band filling and screening of the piezoelectric effect (associated with strain induced by lattice mismatch). So far, no attempt has been made to explain the anomalous temperature shift using these effects.

Another model frequently invoked to explain emission from GaN/InGaN/AlGaN quantum wells is recombination within quantum dots [2,6]. If we assume that the electronic levels inside quantum dots are sufficiently unmixed by disorder so that they behave like normal band-edge states, we cannot account for the small magnitude of the measured pressure coefficients for any possible fixed value of local In composition. Hence, a distribution of quantum dot compositions and sizes would have to be invoked, and this would give rise to a significant density of localized band-tail states. In conclusion, the band-tail model offers a simple explanation of the observed temperature, current, and pressure dependence of the EL and PL spectra in Nichia green and blue SQWs.

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References