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Radiative Recombination of Hot Electrons in InGaN Single Quantum Well Blue LEDs

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1. Introduction

Considerable progress has been emerged to elucidate the fundamental optical and electrical properties of InGaN-based quantum well structures because of commercial realization of high-brightness blue and green LEDs.[1,2] However, little has been known concerning the electrical transport properties of injected carriers in these InGaN/GaN quantum-well structured diodes as well as the origin of the recombination centers. Carriers in the high-brightness LEDs are confined to a thin active layer by high bandgap of GaN and AlGaN, so that the injected electrons and holes are strongly heated by electric fields. The carrier distribution and the heating effect of carriers in the active layer under high electric fields are very important, because radiative recombination spectrum reflects transport properties of injected carriers. We have recently found that the distribution function of injected carriers has a significant effect on the efficiency of the radiative recombination.

We are concerned in this paper with the first experimental results on the radiative recombination of hot carriers injected in the Nichia InGaN/GaN single quantum well (SQW) diodes.

2. Experimental Results and Discussion

Forward-biased injection electroluminescence (EL) spectra were measured at 77 K by the pulse voltages from 0 to 30 V with a duration of 100 nsec. The rise of lattice temperature was insignificant because of the low-duty pulse voltage (10 Hz).

Figure 1 shows the EL spectra obtained at 77 K as a function of forward-biased pulse current. It has been well-known that the higher energy portion of the spectrum comes from the recombination of hot electrons injected in the InGaN active layer, and the spectrum of the recombination reflects directly the electron distribution function. The recombination radiation intensity is generally expressed for electron-hole (e, h) transition [3],

$$I(h\upsilon) \cong N(E)\, f_e(E)\, f_h(E)\, |M(e,h)|^2$$

where $f_e(E)$ and $f_h(E)$ are the distribution function of electrons and holes, respectively. $|M(e,h)|^2$ is the transition matrix element. Usually, the Maxwell distribution functions are used to determine the carrier temperature of the photo-excited carriers by fitting the radiative recombination spectrum. However, in this figure, it should be noted that the peak position is found to slightly move toward higher photon energy with increasing injection current. The important evidence is that the carrier distribution function is displaced from the Maxwell distribution function. Therefore, in order to evaluate the transport properties of hot electrons under high electric fields, the following displaced Maxwell distribution function $f(E_d, T_e)$ is adopted,

$$f(E_d, T_e) = (\pi k T_e)^{(-\frac{1}{2})} E_d^{(-\frac{1}{2})} \exp\left[-\frac{(E-E_G)+E_d}{kT_e}\right] \sinh\left[2\frac{\{(E-E_G)E_d\}^{\frac{1}{2}}}{kT_e}\right]$$

where E_d is a displacement energy of hot electrons and T_e a temperature of hot electrons.

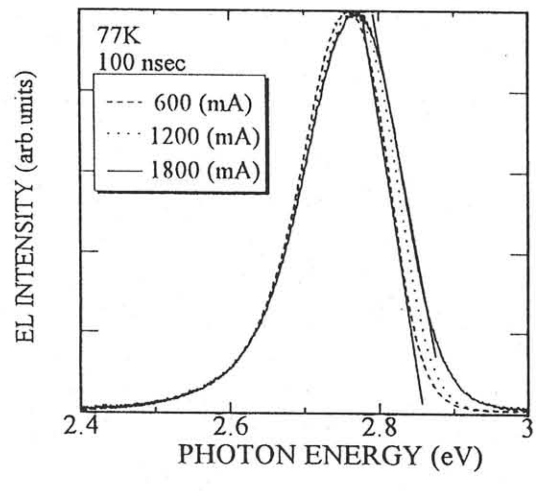

Fig. 1. Forward-biased EL spectra obtained at 600, 1200 and 1800 mA at 77 K.

Figure 2 illustrates the calculated results (□) of the emission intensities as a function of photon energy under a forward bias of 1.8 A, assuming that the displacement energy (E_d) is 1.65 meV (same as that of GaAs) and an electron temperature (T_e) is about 400 K. The experimental spectrum agrees well with the calculated curve.

Figure 3 shows the calculated electron temperatures as a function of forward-biased current in the SQW blue LED at

77 K. With increasing forward bias current, electron temperatures become increased and approach about 400 K. In high-brightness LEDs, when carriers with high densities up to approximately $10^{18}cm^{-3}$ are injected into the active region, inter-carrier scattering [4] becomes dominant. As a result, the electron temperature of the injected hot electrons may be saturated. It is therefore demonstrated that a high carrier temperature up to 400 K can be obtained under the forward bias currents of about 4.5×10^{3} A/cm^{2}.

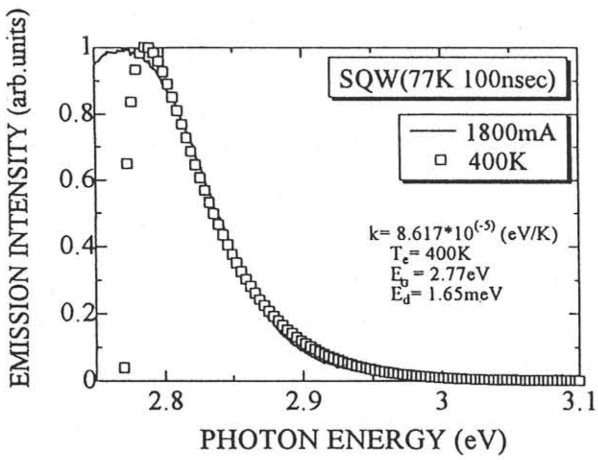

Fig. 2. Calculated emission spectrum obtained at a current of 1800 mA using the displaced Maxwell distribution function : T_e=400 K and E_d=1.65 meV.

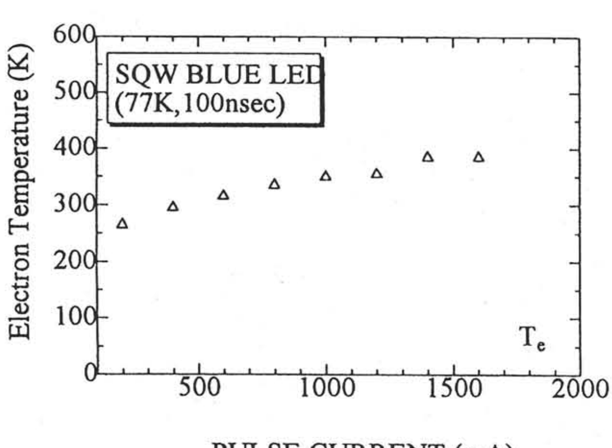

Fig. 3. Temperatures of injected hot electrons as a function of forward-bias current at 77 K.

3. Conclusions

It is suggested that a high electron temperature up to 400K can be obtained under the forward-bias current of about 4.5×10^{3} A/cm^{2}. Such high temperature of electrons has never been observed in III-V semiconductors. The present result shows a superior characteristic of hot electrons in the InGaN based diodes. The origin of the recombination center involving in the InGaN mixed alloy may be discussed on the basis of the detailed analysis of the blue radiative recombination of hot electrons.

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References

1) Z. C. Huang, J. C. Chen, Y. Zheng and D. B. Mott, Mat. Res. Soc. Symp. Proc. **395** (1996) 789.
2) S. Chichibu, T. Azuhata, T. Sota and S. Nakamura, Appl. Phys. Lett., **69** (1996) 4188.
3) "Semiconductors and semimetals" vol.8 eds. R. K. Willardson and A. C. Beer (Academic Press,1972) Chap.4
4) B. K. Ridley, Quantum process in semiconductors (Oxford,1998).