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# Spectra of Superbright Blue and Green InGaN/AlGaN/GaN Light-Emitting diodes

V. E. Kudryashov,[a] A. N. Turkin,[a] A. E. Yunovich,[a] K. G. Zolina[a] and S. Nakamura[b]

[a]Moscow State Lomonosov University, Department of Physics, Moscow 119899, Russia
[b]Nichia Chemical Industries Ltd, PO Box 6, Anan, Tokushima-Ken 774, Japan

***Abstract***

*Electroluminescence spectra of blue and green light-emitting diodes (LEDs) based on $In_xGa_{1-x}N/Al_yGa_{1-y}N/GaN$ heterostructures with a thin quantum well active layers were studied at currents* $J = 0{\cdot}01–20$ *mA. Spectral maxima of blue LEDs are* $\hbar\omega_{max} = 2{\cdot}58–2{\cdot}75$ *eV, of green are* $\hbar\omega_{max} = 2{\cdot}3–2{\cdot}45$ *eV, depending on the In content in the active layer. The low and high energy tails of the spectra are exponential with the parameters* $E_0 = 42–50$ *meV and* $E_1 \approx 1–1{\cdot}3\,kT$*, respectively. The spectra can be described taking into account quantum-size effects, impurities and fluctuations in active layers. An interference structure in spectra was detected. Light intensity depended on J linearly in the interval 1–20 mA. Efficiency of blue LEDs dropped at* $J < 0{\cdot}7$ *mA as* $I \sim J^{4-5}$ *(300 K). The green LEDs had no such dependence. Tunnel radiation spectra with maxima moving with the voltage were detected at low J. © 1997 Elsevier Science Limited.*

## 1 Introduction

The developments of electroluminescent heterostructures based on GaN and III-N ternary compounds have been quite successful during the last three years. The papers on the problem were represented and discussed widely at the 1st International Symposium on GaN and related materials[1] (and references therein). The best achievements in light-emitting diodes (LEDs) for short wave-length side (violet, blue and bluish-green) of the visible spectrum were accomplished by MOVPE-grown multi-layered heterostructures InGaN/AlGaN/GaN with a thin (25–30 Å) $In_{1-x}Ga_xN$ active layer. External quantum efficiency of 4–9% range was achieved.[1,2]

The electroluminescence (EL) spectra of heterostructures InGaN/AlGaN/GaN were studied[2] and in the earlier publications of the same group.[3–5] In this paper, we report the spectra of the multi-layered structures InGaN/AlGaN/GaN with a thin active InGaN layer at currents $J = 0{\cdot}01–20$ mA at temperatures $T = 200–300$ K.

A model of the radiative recombination in 2D-structures taking into account potential fluctuations[6] was previously applied to describe photoluminescence spectra of multiple quantum wells GaAs/AlGaAs,[7] and is used to analyse spectra of new nitride 2D-structures. Optical interference can occur in multi-layered structures, and we have detected the influence of interference on the spectra of the LEDs. The spectra of tunnel radiation were detected for the first time in GaN-based structures.

## 2 Experimental

We have studied LEDs made from structures described in Ref. 2. A GaN buffer layer ($\approx 300$ Å) was grown on the sapphire substrate, followed by an *n*-GaN:Si ($t \approx 5\,\mu m$) base and electrone emitter (barrier for holes). The thin active layer $In_xGa_{1-x}N$ was $\approx 25–30$ Å. The In-content ($x = 0{\cdot}2–0{\cdot}43$) and thickness of this layer were varied to move the spectra from violet-blue to green. A *p*-type $Al_{0{\cdot}1}Ga_{0{\cdot}9}N$:Mg ($\approx 100$ nm), was grown onto the active layer as a hole emitter (barrier for electrons) and the structure was completed by a top-GaN:Mg ($\approx 0{\cdot}5\,\mu m$) cap. The ohmic contact metallizations were Ni–Au (*p*-type) and Ti–Al (*n*-type). The device had a mesa structure with an active area $S = 350 \times 350\,\mu m^2$.

EL spectra were recorded on a spectral complex connected to an x486 PC.

## 3 Experimental Results

### 3.1 Spectra at room temperture

The luminecence spectra of some LEDs at the room temperature (RT) and $J = 10\,\mathrm{mA}$ are given in Fig. 1. The violet-blue and blue LEDs have spectral maxima $\hbar\omega_{max} = 2{\cdot}58$–$2{\cdot}75\,\mathrm{eV}$, and the green LEDs in the $\hbar\omega_{max} = 2{\cdot}38$–$2{\cdot}45\,\mathrm{eV}$ range dependent on the active layer In content ($x = 0{\cdot}20$–$0{\cdot}25$ for the blue and $0{\cdot}42$–$0{\cdot}44$ for the green LEDs). The LEDs span the entire visible short wavelength spectrum.[1,2] The spectra of a blue diode at various currents are shown in Fig. 2. The exponential decay on both sides of the peak are unchanged over the range of currents plotted ($J = 0{\cdot}3$–$20\,\mathrm{mA}$). The long wavelength side is described by an exponent:

$$I(\hbar\omega) \sim \exp(\hbar\omega/E_0) \qquad (1)$$

The parameter $E_0$ varied for different diodes between $E_0 = 42$–$50\,\mathrm{meV} > kT$, and was independent of temperature. The short wavelength side of the peak is described to first approximation by the formula:

$$I(\hbar\omega) \sim \exp(-\hbar\omega/E_1) \qquad (2)$$

with a temperature-dependent parameter equal to $E_1 = 31$–$34\,\mathrm{meV}$ at RT.

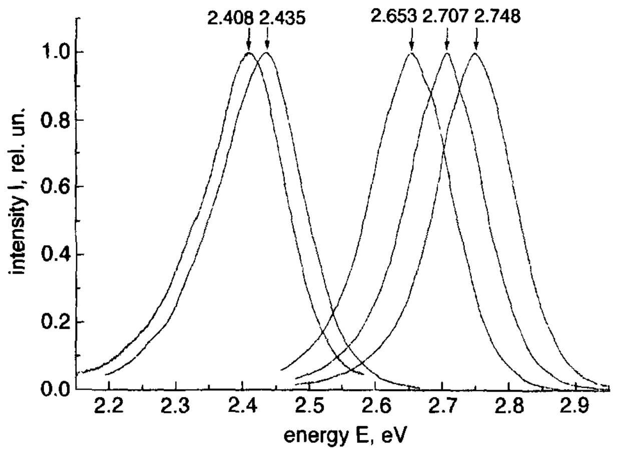


**Fig. 1.** Luminescence spectra of blue and green InGaN/AlGaN/GaN LEDs. $J = 10\,\mathrm{mA}$, room temperature. Arrows show $\hbar\omega_{max}$, eV.

### 3.2 Temperature dependence of spectra

The temperature dependence of spectra at $T = 200$–$300\,\mathrm{K}$ for one of the blue diodes is shown in Fig. 3. The temperature, measured by a thermocouple attached to the plastic cap of the LED, was current-dependent above 1 mA as a result of Joule heating. Therefore, measurements were taken at $J = 1\,\mathrm{mA}$, where such heating was negligible. The high energy side of the spectra is changing according to eqn (2), the parameter $E_1$ being approximately proportional to $T$.

### 3.3 Interference structure

A distinct structure on the spectra could be detected when measurements were taken at a spectral resolution better than 1 meV. This structure is better resolved when a Gaussian or hyperbolic fitting function is substracted from experimental curves, or if the derivatives of spectra were analysed (Fig. 4). The structure is nearly periodical. This can be understood if the light interference is taken into account. The period of the spectral structure is of the order of several nm. If the interference is localized in a layer having thickness $t$ and a refractive index $n$, then

$$2tn(1 + (\lambda/n)(dn/d\lambda)) = \lambda(1 + \lambda/\Delta\lambda) \qquad (3)$$

The $n$-GaN layer of the structure is $t = 5{\cdot}0 \pm 0{\cdot}5\,\mu\mathrm{m}$. The values of the refractive index $n$ and its dispertion $(1 + (\lambda/n)(dn/d\lambda)$ calculated

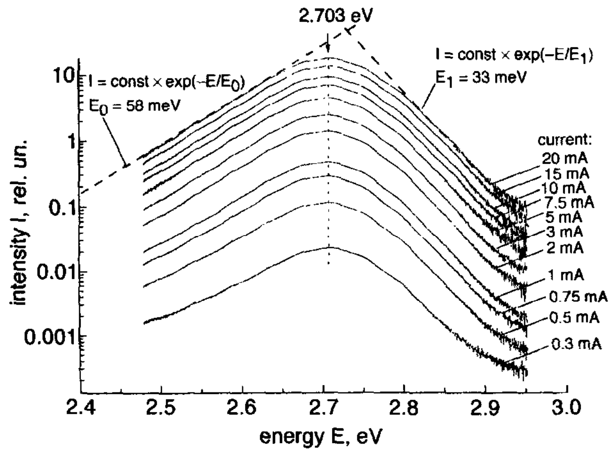


**Fig. 2.** Spectra of blue InGaN/AlGaN/GaN LED N 3; room temperature, $J = 0{\cdot}3$–$20\,\mathrm{mA}$.

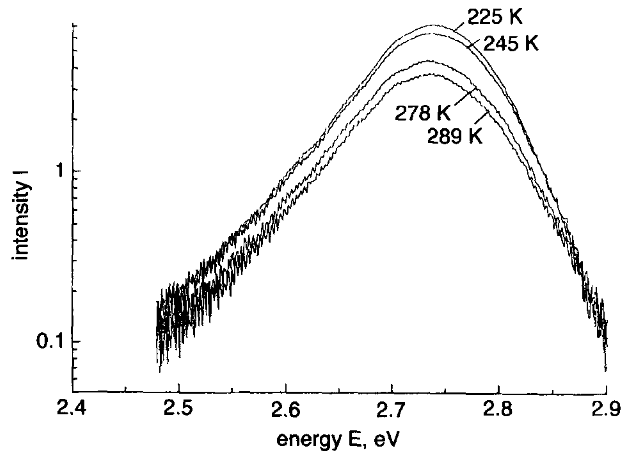


**Fig. 3.** Temperature dependence of spectra. Blue LED N 2, $J = 1\,\mathrm{mA}$.

from eqn (3) for different blue LEDSs were 2·48, 2·73 and 3·03. These values correspond to the known refractive index of GaN $n = 2{\cdot}5$ to within the limits of the above analysis.

### 3.4 Dependence of intensity versus current

The integated radiation intensity of the spectrum was proportional to the intensity at the peak $I_{max}$ and the full width at half-maximum $\Delta(\hbar\omega)_{1/2}$. The $\Delta(\hbar\omega)_{1/2}$ values for the blue ($\Delta(\hbar\omega)_{1/2} = 0{\cdot}12$–$0{\cdot}13$ eV) and green ($\Delta(\hbar\omega)_{1/2} = 0{\cdot}15$–$0{\cdot}16$ eV) LEDs were current-independent. We, therefore, were able to determine the current-dependence of integrated intensity by merely measuring $I_{max}$.

The current-dependence $I_{max}(J)$ was different for blue and green LEDs (Figs 5 and 6). The linear dependence $I_{max}(J) \sim J$ is seen in the current range $1\,\mathrm{mA} < J < 10\,\mathrm{mA}$. For $J > 10\,\mathrm{mA}$, Joule heating over-rides the dependence. The intensity drops dramatically at currents below 1 mA in the blue diodes, following a $I_{max}(J) \sim J^{4.5}$ dependence at RT (Fig. 2). At lower temperature, the transition between the two regimes occurs at lower current levels ($J < 0{\cdot}1$ mA). The green diodes had no such temperature dependence (Fig. 6(a)).

The difference in efficiency corresponds to the different $J$–$V$ characteristics of blue and green diodes (Figs 5 and 6). The low temperature $J(V)$ of the blue diodes was exponential:

$$J(V) \sim \exp(eV/E_J) \tag{4}$$

with $E_J = 130$–$140$ meV independent of temperature. This can be caused by a tunnel in the space charge region. At higher currents the curve flattens and can be described by a temperature-dependent exponent. In this regime, series resistance $R_s$ is limiting the current: $V = U + JR_s$, where $U$ is the $p$–$n$-junction potential. The green diodes have higher series resistance and $J(V)$ curve had no tunnel component.

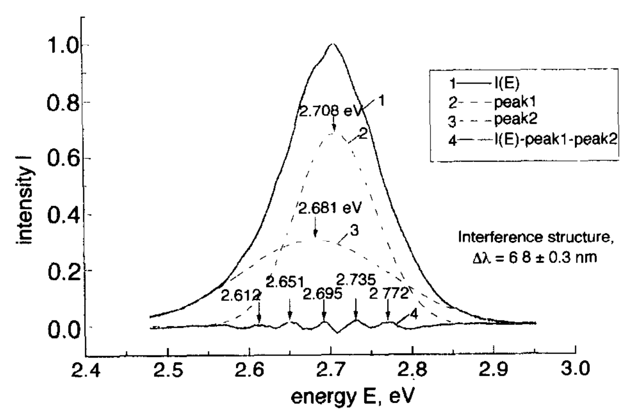


**Fig. 4.** Approximation of a blue LED spectra by two Gaussians; diode N 3, room $T$, $J = 10$ mA. Lower curve is the difference between experimental data and the approximation–interference spectrum.

### 3.5 Tunnel radiative recombination

Tunneling effects in blue LEDs were detected also in the low current EL spectra (Fig. 7). A wide spectral band is seen on the low energy side of the specta with its maximum moving nearly equal to the voltage $\hbar\omega_{max} \approx V \approx U$. Analogous spectra were studied in highly doped GaAs, InP and GaSb narrow $p$–$n$-junctions.[8,9] It was shown that optical transitions between the tails in the density of states at the band gap edges are caused both by the high electric field at the junction and the fluctuating fields of charge impurities. Now we can conclude that such a situation occurs in GaN-based structures characterized by narrow space charge region and a thin 2D-layer.

## 4 Discussion

### 4.1 Energy diagram

Let us analyze the energy diagram of a multilayered structure at forward bias (Fig. 8). There are three main current components in the space charge regions: tunneling, injection and recombination, and only injection and recombination currents in the 2D active layer. The tunneling component can dominate at low currents in high dope junctions with thin space charge regions. The larger part of the space charge corresponds to the $p$-$Al_{0.1}Ga_{0.9}N$:Mg (~100 nm) layer. The space charge width is lower for blue diodes as determined by preliminary capacitance measurements which give values of 25 nm for blue and 40 nm for green LEDs. We conclude that the difference between the two LED groups is differing concentrations of charge impurities in the $p$-regions. Tunneling dominates at low currents in blue LEDs. The main part of this component is non-radiative recombination, but another part is the tunnel radiative recombination. Injection and recombination in space charge $p$-region dominate in green LEDs at low currents.

Effective radiative recombination is achieved when both carrier types are injected to the active QW layer. At high currents, some of the voltage will drop across the adjacent layers, and some recombination will occur there. This produces the maximum of the quantum efficiency at a given current density. It means that the charge distribution in InGaN/AlGaN/GaN heterostructures is very important for optimizing the efficiency.

### 4.2 A model approximation of the main spectral band

The effective energy gap of a doped QW can be estimated by taking into account the dependence

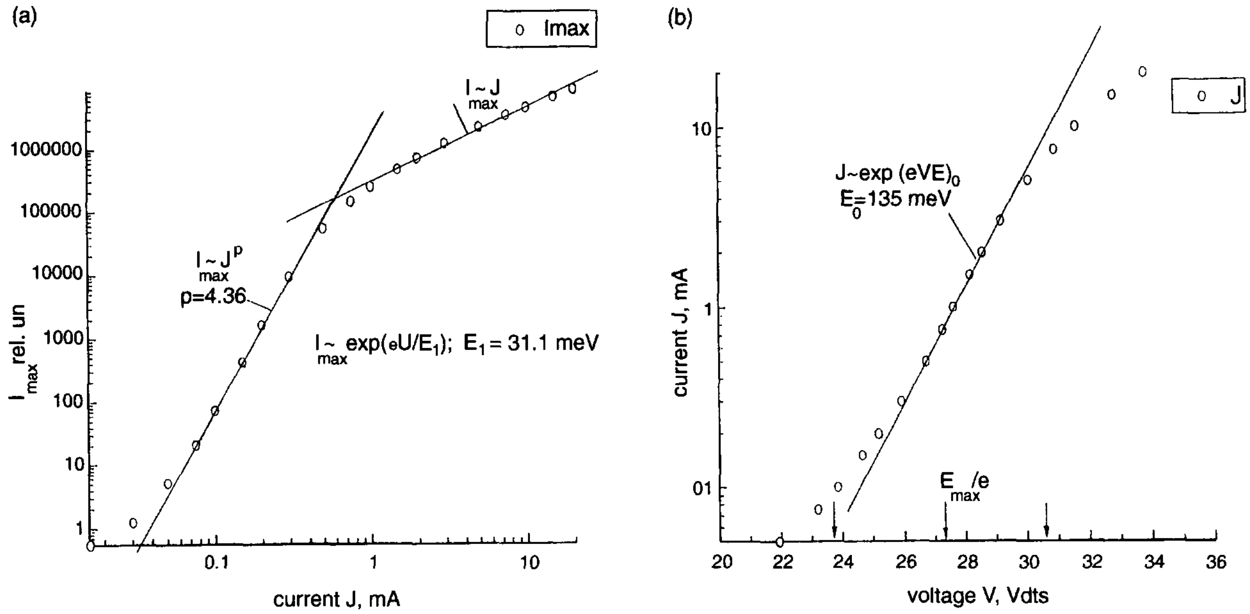


**Fig. 5.** (a) Dependence of intensity on the current, room $T$, blue LED N 5. (b) Current–voltage characteristic, room $T$, blue LED N 5.

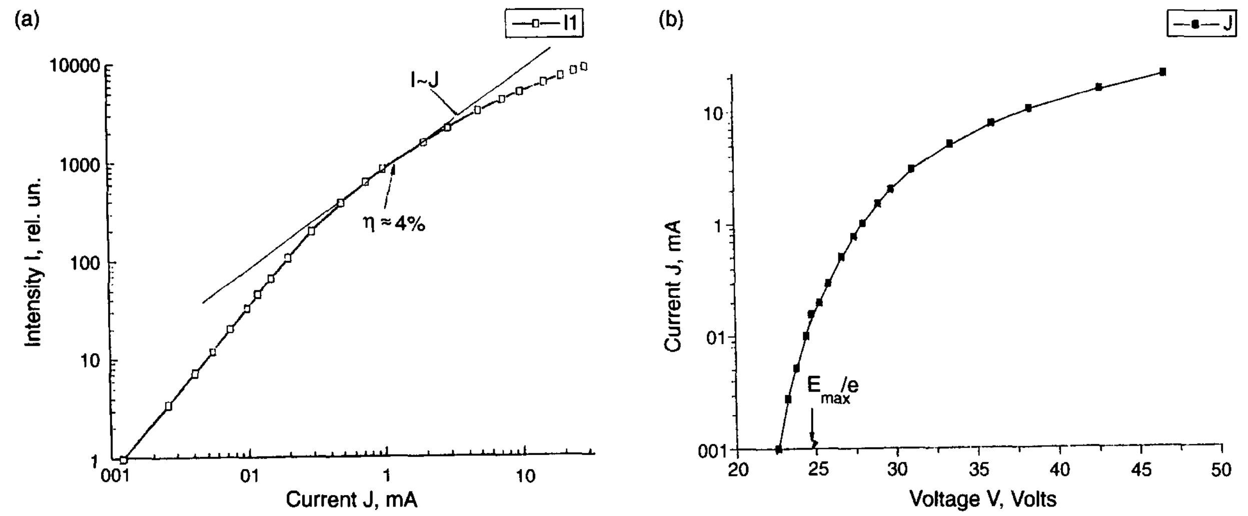


**Fig. 6.** (a) Dependence of intensity on the current, room $T$, green LED N 3. (b) Current–voltage characteristic, room $T$, green LED N 3.

of $E_g(x,T)$ for InGaN, shifts of QW levels for electrones and holes ($\Delta E_{1c}, \Delta E_{1v}$), shifts due to deformations $\Delta E_p$, and due to impurity band tails $\Delta E_{A,D}$:

$$E_g^{\text{eff}} = E_g(x, T) + \Delta E_{1c} + \Delta E_{1v} + \Delta E_p - \Delta E_{A,D} \quad (5)$$

An esitmation of $E_g(x,T)$ was made by taking data from a review.[10] The parameters $\Delta E_{1c} + \Delta E_{1v}$ were approximated using standard formulae for levels in rectangular quantum wells[11] and approximate effective masses in InGaN. A model of joint 2D-density of states suggested in Ref. 6 and used in Ref. 7 to analyze spectra of GaAs/AlGaAs MQWs can be applied to fit the spectral band by the equations:

$$I(\hbar\omega) \sim N^{2D}(\hbar\omega, E_g^{\text{eff}}) f_c(\hbar\omega, kT, F_n) \times (1 - f_v(\hbar\omega, kT, F_p)) \quad (6)$$

$$N^{2D}(\hbar\omega, E_g^{\text{eff}}) = (1 + \exp(-(\hbar\omega - E_g^{\text{eff}})/E_0))^{-1} \quad (7)$$

with $f_c(\hbar\omega,kT,F_n)$ and $(1 - f_v(\hbar\omega,kT,F_p))$ representing the Fermi functions for states near the effective band edges. One of the fits is shown in Fig. 3. The fit is quite successful and the number of parameters is not so high. The parameter $E_0$ depends on the roughness of interfaces, strains, alloy inhomogeneities and Coulombic impurity fields. The exponential decay on the high energy side in the case of direct interband transitions is described by the exponents:

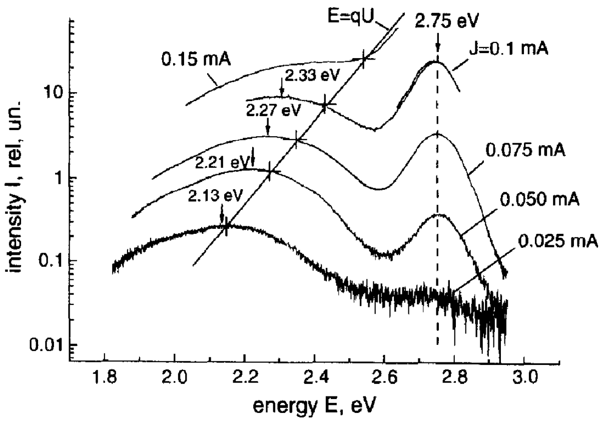


**Fig. 7.** Luminescence spectra at low currents, tunnel radiative recombination; blue LED N 2, room T.

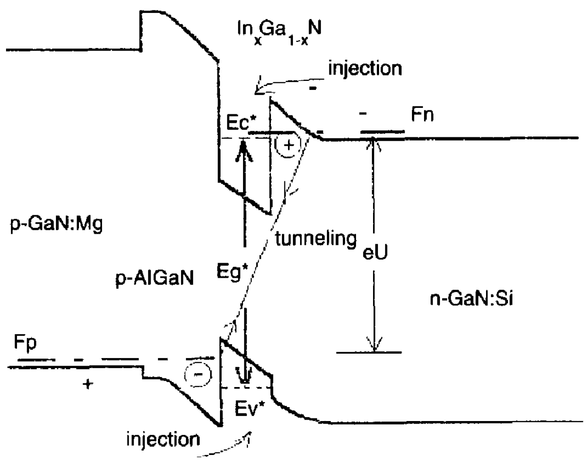


**Fig. 8.** Enery diagram of InGaN/AlGaN/GaN heterostructure at forward bias.

$$((m_c^*(\hbar\omega - E_g^{\text{eff}})/(m_c^* + m_v^*)kT)$$

and

$$(m_v^*(\hbar\omega - E_g^{\text{eff}})/(m_c^* + m_v^*)kT)$$

We would like to discuss the parameters of the fit in the future.

## 5 Conclusions

The luminescent spectra of InGaN/InGaN/GaN heterostructures have maxima and exponential decays in the blue and green spectral regions which can be described by taking into account the impurity band tails in the 2D-active layer. A model approximation for the spectra is suggested.

The periodical structure was detected in the spectra which can be described by interference effects in the GaN base layer.

The dependence of intensity versus current differs for blue and green LEDs. The fall-off of blue LED efficiency at low currents is caused by a non-radiative tunnel component of the current.

The tunnel radiative recombination spectra with the maxima moving with the voltage have been detected for the first time in GaN-based heterostructures.

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