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Defect-related tunneling mechanism of efficiency droop in III-nitride light-emitting diodes

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The quantum efficiency of GaN-based light-emitting diodes (LEDs) is investigated at temperatures 77–300 K. It is found that the efficiency droop is due to a decrease in the internal quantum efficiency (IQE) in the low-energy part of the emission spectrum. The efficiency starts to decrease at a temperature independent forward voltage of $U_{max} \approx 2.9$ V. At this voltage tunneling current through the LED-structure begins to dominate. It is suggested that the external quantum efficiency droop is related to reduction of the IQE due to tunneling leakage of carriers from the quantum well (QW) to defect states in barriers, and to reduction of the injection efficiency by excess tunneling current under QW through deep defect states in barriers. © *2010 American Institute of Physics*. [doi:10.1063/1.3367897]

The key problem of high-power light-emitting diodes (LEDs) is the efficiency droop upon an increase in the current density to above $j = 0.4-4$ A/cm^2.[1] Several mechanisms have been suggested to explain this effect, including electron transport along the quantum well (QW) from indium-rich regions to dislocations,[2] electron overflow above the QW,[3–5] current leakage via structural defects,[5,6] Auger recombination,[7] and the effect of built-in piezoelectric fields in a QW.[8] However, the significance of the contribution of each of the suggested mechanisms to the efficiency droop still remains unclear.[9,10]

In this paper we present experimental data concerning a mechanism of efficiency droop. (i) The efficiency droop is caused by the decrease in the internal quantum efficiency (IQE) in the low-energy part of the emission spectrum. (ii) The efficiency measured over a wide temperature range 77–300 K starts to decrease at a temperature independent diode forward voltage of $U_{max} \approx 2.9$ V. (iii) At $U > U_{max} \approx 2.9$ V ideality factor increases to $n > 2$ indicating that tunneling dominates in the current through the LED structure at high voltages.[11,12] These findings allow us to suggest a defect-related tunneling current model for the external quantum efficiency (EQE) droop.

For the present study we have chosen a single quantum well (SQW) LEDs to simplify interpretation of the results. The devices under study are Nichia Chemical Industries planar 5 mm LEDs on a sapphire substrate (model NSPB-500S). The active region forms a SQW structure consisting of a 30 Å thick $In_{0.2}Ga_{0.8}N$ active layer sandwiched by 4 μm thick *n*-type GaN and 100 nm thick *p*-type $Al_{0.2}Ga_{0.8}N$ barrier layers.[13] The chip size of LEDs was 350×350 μm^2. The structures are described in detail in Ref. 13. The peak EQE of a conventionally processed SQW LEDs under study is 26% at 77 K and 15% at 300 K and decreases to 11% at operating current of 20 mA. Assuming the light extraction efficiency $\eta_{ext} \approx 25\%$, the IQE can be estimated to be about unity at 77 K. Then the room temperature (RT) peak value of the product of IQE and the injection efficiency (IE) can be estimated to be about 60% and decreases to 40% at operating current, which is comparable to those reported for typical state-of-art MQW LEDs.[14]

For low temperature measurements (77–300 K) LEDs encapsulated within an epoxy lens are mounted on a cold finger of cryostat chamber. The forward current J and the electroluminescence (EL) intensity under continues-wave operation are measured simultaneously as functions of dc diode forward voltage U using a current/voltage source (Keithley 238) and a calibrated Si photodiode.

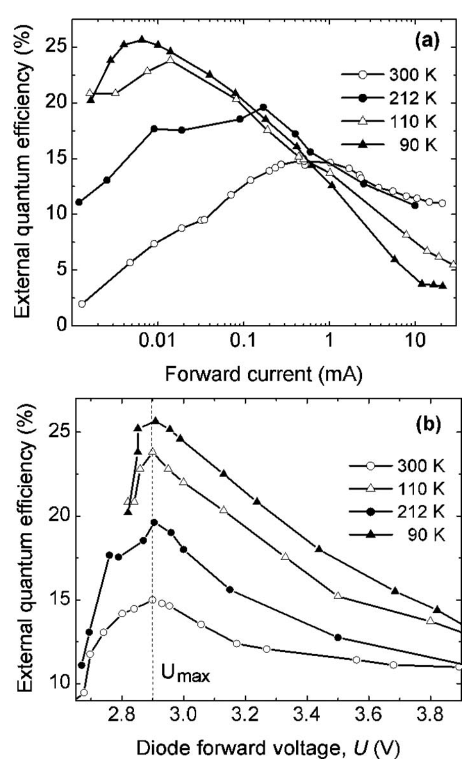

FIG. 1. EQE as a function of forward current (a) and diode forward voltage (b) in the temperature range from 90 to 300 K.

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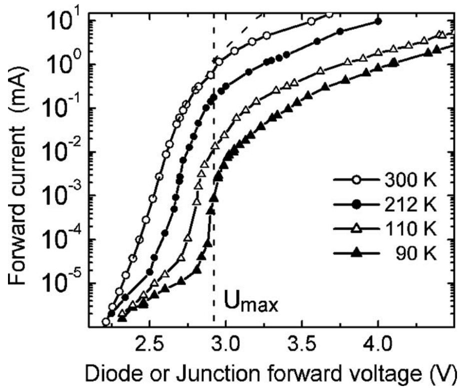

FIG. 2. Forward current vs diode forward voltage in the temperature range from 90 to 300 K (solid lines) and vs junction forward voltage at $T=300$ K (dashed line).

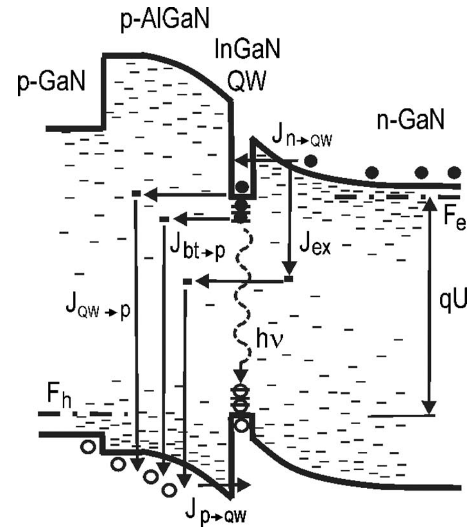

FIG. 3. Proposed defect-related tunneling model for a *p-n* structure with an AlGaN/InGaN/GaN QW.

Figures 1(a) and 1(b) show dependences of the EQE on forward current $\eta(J)$ and diode forward voltage $\eta(U)$ over the temperature range 90–300 K. As can be seen from Fig. 1(a), the EQE maximum is reached at lower currents with decreasing temperature, and the EQE maximum value increases. The peak current decreases from $J_{\max}=0.47$ mA ($j=0.78$ A/cm^2) at 300 K to $J_{\max}=7$ μA at $T=90$ K. This efficiency decrease at low currents can hardly be attributed to Auger recombination. Moreover, according to our data, the efficiency droop is controlled by the forward voltage rather than by the forward current magnitude because the onset of the reduction in EQE occurs at the same voltage $U_{\max} \approx 2.9$ V over the investigated temperature range from 77 to 300 K [Fig. 1(b)].

It is important to stress that at this voltage the difference between the electron and hole quasi-Fermi levels $\Delta F \equiv F_e - F_h$ is equal to $\Delta F = qU_{\max} \approx 2.9$ eV and is close to the effective band gap ($E_{g,\mathrm{InGaN}}$) or mobility edge ($E_{\mathrm{me}} \equiv E_{\mathrm{g,InGaN}}$) in the $In_{0.2}Ga_{0.8}N$ active layer, which is $E_{g,\mathrm{InGaN}} = 2.89$ eV.[12,15] Therefore, the efficiency begins to decrease with forward voltage when the electron and hole quasi-Fermi levels in barriers reach the bottom of the conduction band and the top of the valence band in QW, respectively.

Also, in the vicinity of the voltage $U_{\max} \approx 2.9$ V, a decrease in the slope of the $\log J-U$ curves is observed (Fig. 2, solid curves). RT current is also plotted versus junction voltage $U_j = U - JR_s$ (dashed curve) being corrected for the voltage drop at series resistance of $R_s = 40$ Ω, estimated by extrapolating the dU/dJ versus $1/J$ characteristic to $1/J \to 0$. Hence, at RT and $U_j > U_{\max}$, the ideality factor increases from $n=1.4-2$, typical for a thermally activated current, to $n=4.4$, typical for tunneling current.

We suggest a qualitative model of defect-related tunneling transport, that can consistently describe the features of $\log J(U)$ and $\eta(U)$ dependences. The model takes into account that according to data on photoconductivity,[17] optical absorption,[18] and photoluminescence[19] there is a deep defect-related density-of-states distribution in energy gaps of *p*-GaN and *n*-GaN.[17] Figure 3 schematically illustrates tunneling transport via defect-related states in the depleted *p*-region.

The *I-V*-characteristics of the investigated LED structures consist of three regions (Fig. 2).

The low voltage region corresponds to voltages below the threshold voltage of EL detection U_{th}. In this region, $U < U_{\mathrm{th}}$, the excess tunneling current $J_{\mathrm{ex}}(U)$ via defect states within energy band gaps of *n*-GaN and *p*-AlGaN layers dominates[16] (current J_{ex} as shown in Fig. 3).

The intermediate voltage region is observed at $U_{\max} > U > U_{\mathrm{th}}$. In this region, electron and hole currents into QW are determined by thermal diffusion from neutral regions followed by thermionic-field emission through the band gap discontinuity spikes ΔE_c and ΔE_v (currents $J_{n\to \mathrm{QW}}$ and $J_{p\to \mathrm{QW}}$ in Fig. 3). At $U_j < U_{\max}$ the injection currents through these spikes are limited by the densities of major carriers in front of the spikes. These densities increase exponentially with junction voltage and the injection current into QW rises with U_j as $J_{n\to \mathrm{QW}} \propto \exp(qU_j/kT)$. This results in the high slope of $\log J-U$ curves (Fig. 2).

The high voltage region is observed at $U > U_{\max}$. In this case the injection current in QW, $J_{n\to \mathrm{QW}}$, is controlled by the thermionic-field current through the spike, ΔE_c. According to thermionic-field emission theory,[20] the current at $U_j > U_{\max}$ is proportional to $J_{n\to \mathrm{QW}} \propto \exp[qU_j/E_{00} \coth(E_{00}/kT)]$ at $E_{00} \geq kT$, where $E_{00} = (\hbar/2)\sqrt{(N/\varepsilon m^*)}$ and m^* is the effective mass, ε is the dielectric constant, $\hbar$ is the Plank constant, k is the Boltzmann constant, and N is the concentration of ionized impurities. Hence, the current $J_{n\to \mathrm{QW}}$ at $U_j > U_{\max}$ increases more slowly with increasing voltage than at $U_j < U_{\max}$ (Fig. 2).

The EQE is proportional to the product of the IQE and IE. The EQE maximum is observed at a temperature independent diode voltage $U_{\max} \approx 2.9$ eV [Fig. 1(b)]. Thus, we can divide diode forward voltages in two regions.

At low and intermediate voltages $U < U_{\max}$, the currents $J_{n\to \mathrm{QW}}$ and $J_{p\to \mathrm{QW}}$ (Fig. 3) increase with voltage faster than the excess tunneling current J_{ex}, and the IE into the QW rapidly grows with voltage as $\eta_{\mathrm{inj}}(U) = J_{n\to \mathrm{QW}}/J = (1 + J_{\mathrm{ex}}/J_{n\to \mathrm{QW}})^{-1}$ (total current $J \equiv J_{n\to \mathrm{QW}} + J_{\mathrm{ex}}$). The decrease in the $J_{\mathrm{ex}}(U)$ at lower temperatures leads to an increase in the IE and corresponding increase in EQE at low voltages and currents (Fig. 1)

At high voltages $U > U_{\max}$ the growth of $\eta_{\mathrm{inj}}(U)$ into the QW slows down due to slower increase in thermionic-field current $J_{n\to \mathrm{QW}}$ and faster increase in current J_{ex} with forward voltage resulting from exponential increase in defect density of states between quasi-Fermi levels. Deep exponential tail

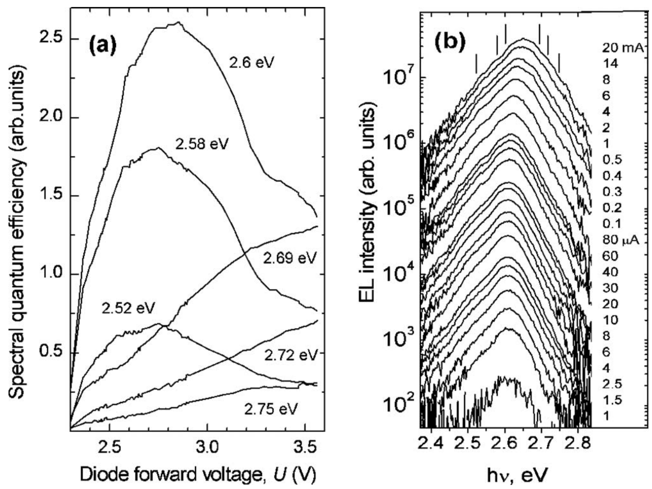

FIG. 4. (a) Spectral efficiency of EL vs diode forward voltage for different spectral regions. (b) RT EL spectra at driving currents from 1 μA to 20 mA; the energies of emitted photons for the $\eta_{h\nu}(U)$ curves are shown.

of defect states in p-AlGaN barrier results also in the IQE decrease with increasing voltage due to the increase in density-of-states energetically aligned with occupied states in the QW.

The lifetimes of carriers τ_{QW} in QW at $U>U_{\max}\equiv E_{me}/q$ can be written as follows:

$$\tau_{\mathrm{QW}}(U)=\left[\frac{1}{\tau_r}+\frac{1}{\tau_{n-r,\mathrm{QW}}}+\frac{1}{\tau_{\mathrm{QW}\to p}}\right]^{-1}, \tag{1}$$

where τ_r, $\tau_{n-r,\mathrm{QW}}$, and $\tau_{\mathrm{QW}\to p}$ represent carrier lifetimes associated with radiative recombination, nonradiative recombination, and tunneling from QW to defect-related states in p-barrier. The lifetime related to tunneling is given by $\tau_{\mathrm{QW}\to p}=qn_{\mathrm{QW}}d/j_{\mathrm{QW}\to p}$, where $j_{\mathrm{QW}\to p}$ is the density of the tunneling leakage current from QW, n_{QW} is the density of carriers localized in QW, and d is the QW width. IQE of LED is equal to $\tau_{\mathrm{QW}}/\tau_r$ and decreases with decreasing $\tau_{\mathrm{QW}\to p}$ with forward voltage.

Thus, the behavior of EQE at $U>U_{\max}$ depends on behavior of product $\eta\propto\eta_{\mathrm{inj}}(U)\eta_{\mathrm{int}}(U)$. As a result, EQE of LED structure decreases with voltage in the whole temperature range 77–300 K [Fig. 1(b)].

To verify this qualitative picture we made measurements of partial quantum efficiencies for different spectral regions. Figure 4(a) illustrates the behavior of the emission efficiency of photons with energy $h\nu$ with increasing diode forward voltage. Here, $\eta_{h\nu}(U)\equiv I_{h\nu}(U)/J(U)$ can be defined as the spectral efficiency equal to the number of emitted photons with energy $h\nu$ per electron flowing in the external circuit ($I_{h\nu}$ is the emission intensity). The dependences $\eta_{h\nu}(U)$ were derived from a series of EL spectra measured at various drive currents in the range 0.001–20 mA, some spectra are shown in Fig. 4(b).

As can be seen in Fig. 4(a), the efficiency of emission at $h\nu<h\nu_{\max}=2.65$ eV as a function of the forward voltage has a maximum shifted to higher voltages as the energy of the emitted photon increases. At the same time, the efficiency of emission at $h\nu>h\nu_{\max}$ increases only nonmonotonically with the voltage. Thus, the efficiency droop results from a decrease in the low energy emission efficiency. Also, at $U>U_{\max}\approx 2.9$ V (at corresponding current of 0.47 mA), a blueshift of the spectral peak and line broadening predominantly into the high energy region are observed.

The high IQE of InGaN/GaN QWs has been ascribed to the carrier localization caused by compositional fluctuations of the energy gap of InGaN. The nonradiative lifetime of carriers localized in the band tails in the QW decreases as their localization energy approaches the mobility edge E_{me}.[21] The tunneling of localized carriers to defect-related states in the barriers (current $J_{bt\to p}$ in Fig. 3) leads to a decrease in the lifetime of localized carriers. Deeply localized carries have the longest nonradiative lifetime in the QW. Therefore, the tunneling of electrons to deep states in the p-AlGaN barrier has the strongest effect on their lifetime, which leads to a decrease in the low energy emission efficiency, blueshift of the spectrum, and broadening of the high energy side of the spectrum with increasing voltage. For shallowly localized carriers $\eta_{h\nu}(U)$ is controlled by limitation of IE with voltage.

In conclusion, defect-related tunneling leakage currents from the QW to deep states in the barriers and excess tunneling current under the QW can be responsible for the droop of IQE and IE, respectively, in the investigated SQW LEDs at current densities up to 40 A/cm^2.

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