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Is Auger recombination responsible for the efficiency rollover in III-nitride light-emitting diodes?

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Practically all III-nitride light emitting diodes (LEDs) suffer from the efficiency rollover that occurs at high electric currents in the devices and limits their performance. At the moment, the mechanisms responsible for the rollover are not yet confidently identified despite the crucial importance of this problem for the LED production. On the basis of simulation, we suggest that the Auger recombination is a likely mechanism, producing the efficiency reduction at high currents. Using an empirically estimated Auger recombination coefficient, we argue for significance of this mechanism under practical operation conditions.

1 Introduction Already in the beginning of research and development of high-brightness III-nitride LEDs it had been recognized that the external quantum efficiency (EQE) rollover was the major factor limiting the device performance at high currents. The rollover was commonly observed in blue, green, violet, and ultraviolet LEDs at the current densities of ~1-30 A/cm^2, resulting in the EQE decrease by a factor of ~1.5-2.5 at 300-500 A/cm^2 [1-5] (Fig.1a). Since EQE is controlled by both the light extraction efficiency weakly dependent on current and the internal quantum efficiency (IQE), η_{int} , the EQE reduction was entirely attributed to the IQE behavior. More recent studies identified the LED self-heating as a mechanism producing the efficiency decrease with current [6]. However, observation of the EQE rollover in the flip-chip LEDs [1,2,5] having a lower thermal resistance and under pulsed operation [1,5] (see also Fig.1a) suggested that the self-heating was not the only reason for the efficiency reduction at high current densities. Comparison of EQEs of the LED structures obtained on sapphire substrates with and without lateral epitaxial overgrowth had demonstrated the efficiency rollover to be independent of threading dislocation density [7].

To explain the non-thermal IQE reduction at high currents, very popular is the model invoking the localized electronic states formed in the InGaN active layers due to composition fluctuations [8]. The basic idea of the model is that electrons and holes captured in the localized states do not contribute much to the non-radiative carrier recombination at threading dislocations, in contrast to delocalized electrons and holes that are quite mobile and, hence, may easily approach the dislocations to recombine there. At a low current density, i.e. at a low non-equilibrium carrier concentration, almost all electrons/holes are captured by the localized states, providing a high IQE of an LED. Increasing current density gives ever growing rise to the concentration of delocalized carriers in the conduction and valence bands, thus resulting in the IQE reduction. Then the IQE maximum is expected to be reached at the current density nearly corresponding to complete filling of the localized states with non-equilibrium carriers.

In our opinion, the above model cannot interpret correctly the efficiency dependence on the current density in a wide range of its variation. Indeed, the rate of the non-radiative carrier recombination at point defects and threading dislocations $R_{\text{nr}}=N/\tau_{\text{nr}}$, where N is the non-equilibrium carrier concentration in the LED active region and τ_{nr} is the effective carrier life time. In turn, the radiative recombination rate $R_{\text{rad}}=BN^2$, where B is the bimolecular recombination rate constant. Since $\eta_{\text{int}}=R_{\text{rad}}/(R_{\text{nr}}+R_{\text{rad}})$, the IQE should tend to unity at high N , i.e. at high current densities irrespective of the τ_{nr} variation caused by filling up the localized states. Even if the carriers in the active region are degenerate and the recombination rate constant B becomes proportional to N^{-1}, the IQE should saturate at high N rather than gradually decrease, as it is observed.

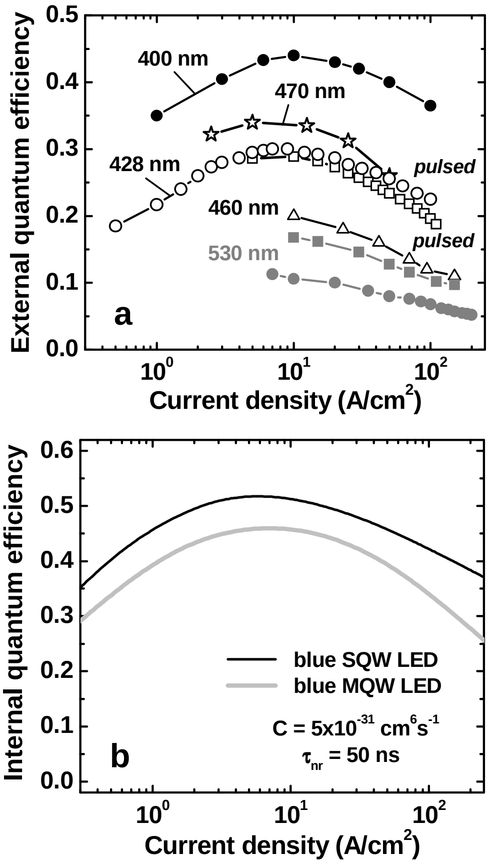

Figure 1 Measured EQEs of various LEDs *versus* current density (a) and IQEs of blue SQW and MQW LEDs simulated with account of Auger recombination in the InGaN active regions (b).

Another mechanism that may lead to the IQE reduction with current is the electron leakage from the active layer of an LED. Our simulations of typical LEDs have shown that the leakage becomes noticeable, starting from the current densities as high as ~3-5 kA/cm^2. This means that this mechanism is also incapable of explaining the efficiency rollover normally observed at much lower current densities.

Here, we consider an alternative mechanism, Auger recombination, to explain the efficiency rollover at high currents, occurring in III-nitride LEDs. As the Auger recombination rate $R_{\rm Aug} \propto N^3$, the account of this non-radiative recombination channel may provide a physical basis for understanding the IQE reduction in high-brightness LEDs.

2 Model and parameter estimation The Auger recombination rate in a bulk semiconductor is generally defined as $R_{\rm Aug} = C_n n^2 p + C_p n p^2$, where n and p are the electron and hole concentrations and C_n and C_p are the Auger coefficients, related to the microscopic processes involving two electrons and a hole or two holes and an electron, respectively. The coefficients C_n and C_n are not reliably known for III-nitride materials. In the earlier study [9], the value of $C = C_n + C_p = 1.4\times10^{-31}$ cm^{6}s^{-1} has been extrapolated for GaN from the data on the Auger coefficients reported for various semiconductor materials as a function of their electron effective masses. Such a rather high value of C was obtained largely due to including silicon into the data considered, the material with an indirect bandgap, along with the direct-bandgap III-V compounds. After [9], the Auger recombination was included in simulations of III-nitride lased diodes, using the coefficients $C = 2\times10^{-31}$ cm^{6}s^{-1} in [10] and 1.5×10^{-30} cm^{6}s^{-1} in [11].

To understand better the effect of the band type on the Auger coefficients, we have included into consideration additional materials, plotting in Fig. 2 the values of C versus bandgap E_G for a number of direct and indirect semiconductors. One can see that the Auger coefficients of indirect semiconductors are nearly independent of E_G , while those of direct semiconductors decrease exponentially with the bandgap at $E_G <$ ~1 eV. At higher E_G , the coefficients tends to the values typical of indirect semiconductors.

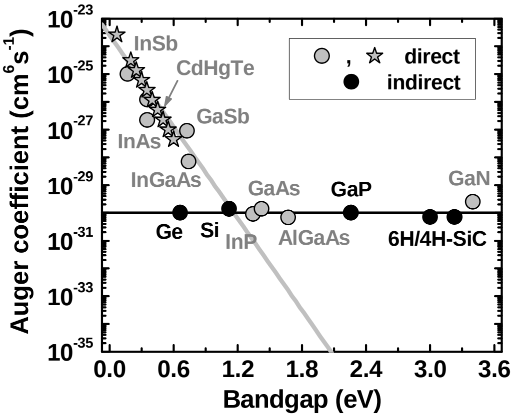

Figure 2 Auger recombination coefficients C of direct- and indirect-bandgap semiconductors *versus* their bandgap. Lines are shown for eyes to indicate the trends in the behaviour of C.

The time-resolved study of carrier dynamics in GaN under high-excitation conditions has been reported in [12]. From the analysis of the non-equilibrium carrier life time as a function of the carrier concentration it was found that the Auger coefficient of GaN may be as high as ~5×10^{-30} cm^{6}s^{-1}. Our revisiting the data [12] with account of additional defect-mediated non-radiative recombination channel provided a slightly lower value $C = 2.5\times10^{-30}$ cm^{6}s^{-1}. This estimate agrees well with the values of the Auger coefficients of other wide-bandgap materials having indirect bandgap (Fig. 2), despite the fact that GaN is a direct-bandgap semiconductor.

To examine the Auger recombination effect on IQE of blue III-nitride LEDs, we have employed the SiLENSe 3.0 simulator to consider both single-quantum well (SQW) and multiple-quantum well (MQW) heterostructures. The representative SQW structure consisted of a thick n-GaN

([Si] = 3×10^{18} cm^{-3}) contact layer, an unintentionally doped 3.5 nm $In_{0.2}Ga_{0.8}N$ ($n = 1\times10^{17}$ cm^{-3}) SQW, a 50 nm p-$Al_{0.2}Ga_{0.8}N$ ([Mg] = 1.5×10^{19} cm^{-3}) stopper layer followed by a p-GaN ([Mg] = 2×10^{19} cm^{-3}) contact layer. In turn, the MQW structure contained a thick n-GaN ([Si] = 3×10^{18} cm^{-3}) contact layer, four 3 nm $In_{0.2}Ga_{0.8}N$ ($n = 1\times10^{17}$ cm^{-3}) quantum wells separated by 12 nm n-GaN ([Si] = 3×10^{18} cm^{-3}) barriers, a 50 nm p-$Al_{0.15}Ga_{0.85}N$ ([Mg] = 1.5×10^{19} cm^{-3}) stopper layer, and a p-GaN ([Mg] = 2×10^{19} cm^{-3}) contact layer. The threading dislocation density of 10^9 cm^{-2} was assumed in both structures everywhere except for the quantum wells, where it was set an order of magnitude lower to account for suppression of the non-radiative recombination at threading dislocations due to indium composition fluctuations in the InGaN alloys [13]. The Auger recombination was assumed to occur only in the SQW or MQW active region, and the Auger coefficients were assumed to be $C_p = C_n = 5\times10^{-31}$ cm^6s^{-1}. These values correspond to the total Auger coefficient C being 2.5 times lower than the value derived from the data of [12].

3 Results and discussion

Computed IQEs of blue SQW and MQW LEDs as a function of current density are plotted in Fig.1b. One can see that the IQEs peak at the current density of ~5-10 A/cm^2 and behave very similarly to the measured EQEs shown in Fig.1a. In particular, an IQE reduction about 1.2-1.8 times is predicted, if the current density rises from 10 to 200 A/cm^2, which closely correlates with the measured decrease of an EQE.

The maximum IQE obtained by the simulation is ~45-50%. This value is, however, dependent on the assumed materials quality. At a lower non-radiative recombination at threading dislocations and point defects, e.g. at that providing the non-radiative life time τ_{nr} ~100 ns and on, the maximum IQE may well exceed 70% but its peak shifts to the current densities lower than 1 A/cm^2. In turn, the predicted IQE approaches the values of 55% and 35% for 20 and 400 A/cm^2, respectively.

The similarity in the variation of the predicted IQE and measured EQE with the current density (Fig.1) suggests that the Auger recombination may be considered as the universal mechanism responsible for the efficiency roll-over in III-nitride LEDs. Nevertheless, there is a number of still open questions. First, it is seen from Fig.2 that direct semiconductors exhibit nearly exponential decrease of the Auger coefficients with the bandgap. In contrast, those of the indirect materials are nearly independent of the bandgap. It is unclear at the moment, what is the actual tendency for III-nitride compounds. The data of [12] suggest GaN to obey the trend of the indirect semiconductors. This fact requires, however, additional experimental confirmation and, apparently, theoretical justification.

Second, it is very important to understand the role of various microscopic mechanisms of the Auger recombination (CHCC process involving two electrons and a heavy hole and CHHS process involving two heavy holes and an electron with the transition of one of the holes to the split-off valence subband) and the quantum-well effect on the recombination rate. It has been recently shown that threshoÂldless Auger processes may dominate in sufficiently narrow quantum wells [14], which is typical of InGaN LEDs. Clarifying of this issue would allow better understanding of the Auger coefficient dependence on the InGaN composition in the wells and, hence, prediction of the IQE variation with the emission wavelength.

One more open question concerns the temperature dependence of the Auger recombination rate. As the current increase in an LED is frequently accompanied by its self-heating, the variation of the Auger recombination rate with temperature may additionally affect the IQE. Besides, the temperature dependence of the bulk and quantum-well Auger processes may be different [14].

Answers to the above questions are expected to form a basis for the heterostructure optimization aimed at suppression of the Auger recombination and thus increasing the light emission efficiency of high-brightness LEDs.

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