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On the ideality factor of the radiative recombination current in semiconductor light-emitting diodes

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While there have been many discussions on the standard Si *pn*-diodes, little attention has been paid and confusion still arises on the ideality factor of the radiative recombination current in semiconductor light-emitting diodes (LEDs). In this letter, we theoretically demonstrate and experimentally confirm by using blue and infrared semiconductor LEDs that the ideality factor of the radiative recombination current is unity especially for low-current-density ranges. We utilize the data of internal quantum efficiency measured by the temperature-dependent electroluminescence to separate the radiative current component from the total current. *Published by AIP Publishing.*
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The ideality factor of a *pn* diode is a parameter that denotes the dominance of different recombination mechanisms when it is operated under forward bias. Typical *pn* diodes based on Si, which are the topics of many semiconductor textbooks, are known to have mainly two current components when forward-biased, namely, the diffusion current and the recombination current.[1] According to the Shockley diode theory, the diffusion current has an ideality factor of 1.[2] The recombination current in the context of the Si diode flows via defect levels in the bandgap. It is called "recombination current" because the electrons and holes entering the depletion region recombines before they become minority carriers in the opposite regions and diffuse there to form the diffusion current. From the theory by Shockley, Read, and Hall, the recombination current via midgap defect levels has an ideality factor of 2.[1,3] Note in this case of the Shockley-Read-Hall (SRH) recombination, no light is emitted, i.e., the SRH recombination is *nonradiative*.

When the current starts to flow in the Si *pn* diode as the forward bias is increased from zero, the current initially flows through defects ("recombination current" with an ideality factor of 2) and then the diffusion current increases rapidly, having the higher slope with the ideality factor of 1.[1] When the current range is intermediate so that both the diffusion and recombination currents play roles, the ideality factor lies between 1 and 2. In Si *pn* diodes, the value of the ideality factor is sometimes considered as an index for the crystal quality as the ideality factor close to 2 indicates the dominance of recombination current through defect levels at the particular current level.

In the case of semiconductor light-emitting diodes (LEDs), which is the topic of interest in this letter, the recombination mechanisms are different from the Si *pn* diodes.[4] First, the nonradiative recombination mechanisms considered under forward bias are more various: not just the SRH recombination via defect levels, such processes as the tunneling leakage possibly assisted by defects are also considered to play significant roles in nonradiative recombinations in LEDs.[5–9] While there have been many investigations on the nonradiative recombination processes and associated ideality factors, especially for the GaN-based LEDs that exhibit ideality factors greater than 2,[10,11] a systematic discussion on the ideality factor of the *radiative* recombination, which is the dominant and desired component in LEDs, is rarely found in the literature. For example, in Refs. 12 and 13, there exist brief descriptions on the radiative recombination current with the ideality factor of 1 but no systematic justification is given. Still in many cases in the literature or within the community, discussions on the radiative recombination current in the semiconductor LEDs are made implicitly based on the Si diode theory. Sometimes, the "recombination current" in Si diodes, which is actually by the SRH *nonradiative* recombination, is confused with the one by the radiative recombination in LEDs.

In this letter, we want to address this issue, namely, the lack of discussion and the persistent confusion concerning the radiative recombination current and its ideality factor. After discussing the radiative recombination current and its ideality factor in the LEDs, we experimentally demonstrate by using both blue and infrared (IR) semiconductor LEDs that the ideality factor of the radiative recombination current equals unity. We utilize the commercial blue and IR LED samples based on InGaN/GaN and GaAs/AlGaAs with peak emission wavelengths of ∼450 and ∼860 nm, respectively. As two samples have different chip sizes (blue LED: 640 × 960 μm^2, IR LED: 300 × 900 μm^2), the current density is frequently used instead of current when presenting the experimental data. We employ the standard method of temperature-dependent electroluminescence (TDEL) to obtain the data of internal quantum efficiency (IQE)[14] and, using this data, separate the radiative recombination current from the total current.

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The radiative recombination rate R_r is given as follows:

$$R_r = Bnp, \tag{1}$$

where B is the bimolecular radiative recombination coefficient and n (p) is the electron (hole) concentration. In Eq. (1), only the direct band-to-band recombination is considered, excluding any exciton effect. It is typically known that the exciton effect can be neglected in the semiconductor LEDs under normal operation (with high forward current and at room temperature) as collisions with phonons or other carriers easily break the excitons with relatively small binding energies (~10 meV). Furthermore, in the wide-bandgap GaN-based LEDs grown on *c*-plane sapphire substrates, where the exciton binding energy is higher than that of the lower-bandgap GaAs-based LEDs, there exists an internal electric field caused by the piezoelectric polarization, reducing the possibility of exciton formation.

In modern semiconductor LEDs, multiple quantum wells (MQWs) are commonly utilized to enhance the carrier concentrations, thus increasing the overall radiative recombination rate. In this case, one can extend Eq. (1) to

$$R_r = \sum_l B_l n_l p_l, , \tag{2}$$

where the index l represents each parameter for the l-th quantum well (QW). Then the current density due to the radiative recombination, J_r, is obtained as

$$J_r = q d_{\mathrm{QW}} \sum_l B_l (n_l p_l - n_i^2). \tag{3}$$

Here, q is the elementary charge, d_{QW} is the thickness of each QW and n_i is the intrinsic carrier concentration. The term n_i^2 is subtracted as no current flows at thermal equilibrium.

If the carrier concentration in each QW is the same, i.e., $n_l = n$ and $p_l = p$, then

$$J_r = q d_t B (np - n_i^2). \tag{4}$$

Here, d_t is the total QW thickness, i.e., $d_t = N d_{\mathrm{QW}}$, where N is the number of QWs. In actual situations, the carrier concentrations in each QW may not be the same. However, we can introduce the *effective* active thickness d_{eff} as follows:

$$J_r = q d_{\mathrm{eff}} B (np - n_i^2), \tag{5}$$

where n and p in Eq. (5) should be considered as *average* electron and hole concentrations and B is the corresponding radiative recombination coefficient. The effective active thickness d_{eff} defined in Eq. (5) may be smaller than the nominal active QW thickness d_t, owing to the nonuniformity of carrier concentrations in QWs.

The carrier concentrations n and p should depend on the quasi-Fermi levels in the following manner:

$$n = n_i e^{(E_{Fn} - E_{Fi})/kT}; \tag{6}$$

$$p = n_i e^{(E_{Fi} - E_{Fp})/kT}, \tag{7}$$

where E_{Fi} represents the intrinsic Fermi level, E_{Fn} (E_{Fp}) the quasi-Fermi level for electrons (holes), k the Boltzmann constant, and T the absolute temperature. Putting Eqs. (6) and (7) into Eq. (5), one obtains

$$\begin{aligned} J_r &= q d_{\mathrm{eff}} B n_i^2 [e^{(E_{Fn} - E_{Fp})/kT} - 1] \\ &= q d_{\mathrm{eff}} B n_i^2 (e^{qV_j/kT} - 1), \end{aligned} \tag{8}$$

as the potential drop at the junction V_j determines the separation of the quasi-Fermi levels. From Eq. (8), we see that the ideality factor, n_{ideal}, which is typically inserted in the exponent as $qV_j/n_{\mathrm{ideal}}kT$, should be 1 for the radiative recombination current.

The current density-voltage (J-V) characteristics of the two LED samples are shown in Fig. 1. Reflecting the difference in emission wavelength, the forward voltages at 1 A/cm^2 for IR and blue LED samples are ~1.2 and ~2.6 V, respectively. The current densities shown here contain both the radiative and nonradiative recombination currents, i.e., $J = J_r + J_{nr}$, where J_r (J_{nr}) is the radiative (nonradiative) current density.

Figure 2 shows the results of TDEL measurements for the blue LED sample. A helium closed-cycle cryostat by Advanced Research Systems has been used to cool the devices to cryogenic temperatures. As the temperature is lowered from 300 to 50 K, the electroluminescence (EL) efficiency, defined as the ratio of the light output power to the input current, which is proportional to the external quantum efficiency (EQE), gradually increases and eventually saturates as the defects freeze out. The IQE at room temperature (300 K) is obtained by normalizing the efficiency by the maximum EL efficiency value in the TDEL data.[14] Fig. 2 shows the results of this normalization. The method assumes that at the lowest temperature of 50 K, there is no nonradiative recombination in the maximum EL efficiency and that the extraction efficiency is independent of the current level. The peak IQE value at room temperature obtained in this way is ~92%. The peak IQE for the IR LED sample at room temperature, obtained in a similar way, is ~88% in the current range used in the experiment.

The IQEs of both samples are summarized against the current density in Fig. 3. The IQE data of the blue LED sample (circles) show a peak value at a low current density <5 A/cm^2 and gradually decrease to <80%, showing the typical droop behavior of the GaN-based blue LEDs. On the

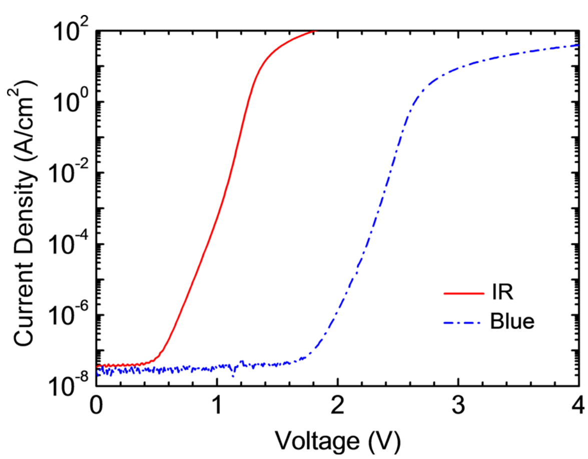

FIG. 1. *J*-*V* characteristics of blue and IR LED samples under investigation.

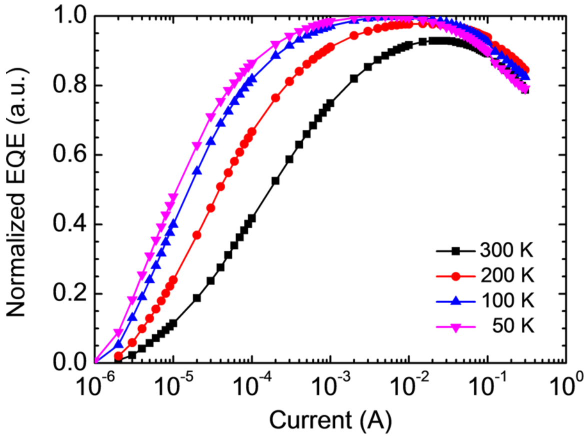

FIG. 2. TDEL measurement results for the blue LED sample.

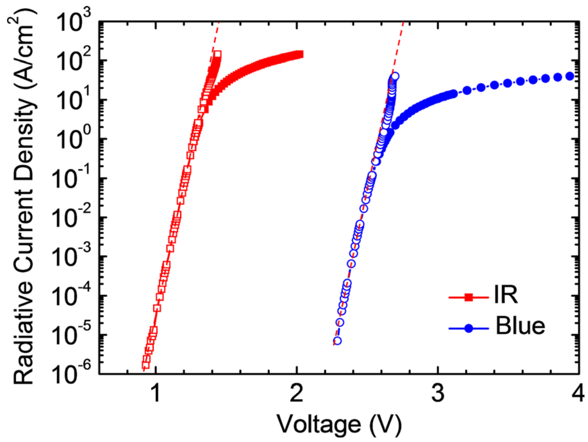

FIG. 4. J_r-V obtained from the J-V and IQE characteristics (filled symbols). J_r-V_j are also shown (open symbols).

other hand, the data of the IR sample (squares) do not show any droop and keep increasing. The difference in droop behavior between blue and IR samples is considered to originate from the drastic difference in effective active volume: Typical GaN-based blue LEDs grown on *c*-plane sapphire substrates tend to have much smaller effective active volumes than the nominal ones owing to factors such as the potential fluctuation, strong internal piezoelectric field, and inefficient hole transport through QWs.[15] On the other hand, IR LEDs grown homo-epitaxially on native GaAs substrates have much larger nominal active volumes than the blue counterparts without any detrimental effects caused by defects and internal fields.[16] Since a smaller active volume induces a higher carrier concentration, leading to earlier saturation of the radiative recombination rate, the onset of the efficiency droop in blue LEDs occurs at a much lower current density than in the IR LEDs.[17]

With the IQE data, the radiative current density can be separated from the total current J by the relation $J_r = \eta_{\rm int}(J) \cdot J$, where $\eta_{\rm int}(J)$ is the IQE as a function of current density. The separated radiative current densities as a function of applied voltage (filled symbols) are shown in Fig. 4 on semi-log scales. Also shown are the radiative current densities as a function of junction voltage $V_j = V - R_s J_r A$ (open symbols), where R_s is the series resistance and A is the device area. The R_s values used for IR and blue LED samples are 1.5 and 5.0 Ω, respectively. Before the bending occurs, the J_r–V data for both samples show perfectly linear increases (dotted lines are added to guide the eyes). Fitting has been performed to obtain the slope of the linear portion of the J_r–V data. Using this slope, denoted as m, an ideality factor $n_{\rm ideal}$ can be obtained from $n_{\rm ideal} = (q/mkT)\log e$. The ideality factors thus obtained for IR and blue LEDs are 1.00 and 1.08, respectively, confirming the analysis summarized in Eq. (8). While slight deviations are observed in J_r–V_j data from the ideal behavior represented by the dotted lines, the degree of deviation (<0.03 V) indicates that the bending can be considered to occur mostly due to the voltage drop by R_s outside the *pn* junction. The exact reason for the deviation is not clear at the moment and requires more rigorous analysis.

In conclusion, we have analyzed the radiative recombination current both theoretically and experimentally, using blue and IR LEDs. By introducing the effective active thickness for the MQW LEDs as well, the radiative recombination current can be shown to have the ideality factor of 1 as observed in experiments especially for the low-current-density ranges where the bending does not occur. Other GaN-based devices with low IQEs or high droops, where threading dislocations or transport issues in the MQWs play more significant roles, may need further study. The present work draws attention to the often neglected ideality factor of the radiative recombination current in semiconductor LEDs and can form the basis of analyzing various optoelectronic characteristics of LEDs.

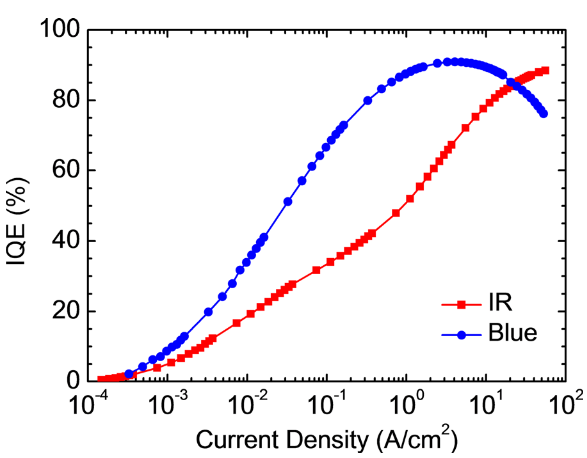

FIG. 3. The IQE as a function of current density for blue and IR LED samples under investigation.

We acknowledge the anonymous reviewer for pointing out that the ideality factor of the SRH recombination current can be dependent on the injection level.

[1]See, for example, D. A. Neamen, *An Introduction to Semiconductor Devices* (McGraw Hill, New York, 2005).
[2]Under high-injection condition, where the concentration of the injected minority carriers is comparable to that of the majority carriers, both the drift and diffusion currents play roles in the forward-biased *pn* diode. It is known in this case that the ideality factor is equal to ∼2. See S. M. Sze and K. K. Ng, *Physics of Semiconductor Devices*, 3rd ed. (Wiley-Interscience, New Jersey, 2007), pp. 99–100.

[3]It is pointed out that if the lifetime of the SRH recombination decreases with the injection level, the ideality factor of the corresponding recombination current approaches 1. See S. M. Sze and K. K. Ng, *Physics of Semiconductor Devices*, 3rd ed. (Wiley-Interscience, New Jersey, 2007), pp. 40–44 for more discussion.

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