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Electrical measurement of internal quantum efficiency and extraction efficiency of III-N light-emitting diodes

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We propose a direct electrical measurement method for determining the extraction efficiency (EXE) and internal quantum efficiency (IQE) of III-Nitride light-emitting diodes (LEDs). The method is based on measuring the optical output power as a function of injection current at current densities near the external quantum efficiency (EQE) maximum and extracting IQE and EXE from the measurement data. In contrast to conventional methods, our method requires no low temperature measurements or prior knowledge of the device structure. The method is far more convenient than commonly used methods because it enables measuring the EXE and IQE of different LED structures at room temperature directly in a repeatable and consistent way. This enables convenient comparison of LED structures. We apply the method to determine the IQE and EXE of one commercial LED and selected self-grown planar LED chips to compare the effects of different LED structure designs. Our results are in line with published experimental results and also give more insight to our earlier findings regarding the effects of growth parameters on the quantum efficiency. In addition, our measurement method allows estimating the Shockley-Read-Hall and radiative recombination parameters if the Auger parameter is known. © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4736565]

The ability to measure the internal quantum efficiency (IQE) and the light extraction efficiency (EXE) of light-emitting diodes (LEDs) is an essential tool in characterization and optimization of III-N LEDs. Typically, however, it is only straightforward to measure the external quantum efficiency (EQE) of the device while determining the desired internal quantities is more challenging. These challenges are well seen, e.g., in the ongoing discussion on the efficiency droop of III-N LEDs, which is currently one of the largest challenges in the development of high power LEDs.[1]

Conventional methods to extract the IQE and EXE from EQE are based, e.g., on comparing the measured external photoluminescence (PL) or electroluminescence (EL) quantum efficiency at low temperature and room temperature,[2,3] simulating the optics of the device to estimate the EXE and deducing the IQE using the simulation results,[4,5] or on fitting a rate equation model to PL measurement data.[6] The first approach requires access to low temperature measurement setup and assumes IQE at low temperature to be unity. The use of the second approach is limited to very simple structures where the simulation data are reliable, and the last approach relies on a PL setup and requires data fitting and approximations in calculating the input power.

The use of IQE as a device characteristic is also complicated due to several different definitions used for it. The processes contributing to the efficiency are typically separated into (1) the radiative recombination in free space R_0, (2) the net radiative recombination rate R taking into account photon recycling, (3) the generation G of new electron-hole pairs through photon reabsorption, (4) the nonradiative recombination rate X, and (5) the photon output rate O, as depicted in Figs. 1(a) and 1(b). Accounting for these processes, the external quantum efficiency can be broken apart in several ways as represented in Fig. 1(c). In definition I, EXE is defined as the rate at which photons are extracted divided by the net radiative recombination rate. IQE is correspondingly defined as the net radiative recombination rate divided by the net recombination rate. In definition II, EXE is defined as the rate at which photons are extracted divided by the total radiative recombination rate and IQE is a material parameter with no dependence on cavity properties. In this definition, photon recycling and spontaneous emission suppression or enhancement are accounted for by a photon recycling factor (PRF) and the Purcell factor (PF). The injection efficiency has been omitted for simplicity but can be easily added in either definition as an additional factor $(R - G + X)q/I$, where I is the injection current.

In experimental works, definition I of Fig. 1(c) is typically preferred,[2,3,6] while in theoretical works one often encounters definitions that at least partly distinguish between direct light extraction, free space recombination typical of the emitting material, photon recycling effects, and modifications in the optical coupling strength due to the optical environment (i.e., the Purcell effect).[4,5,7] These definitions are closer to definition II of Fig. 1(c) or a modification with another combination of the efficiency factors.

We propose a measurement method where the EXE and IQE following definition I of Fig. 1(c) are calculated directly from the measurement of EQE of an LED. In the proposed method, the optical output power is measured as a function of injection current using a current source and a photodetector calibrated with an integrating sphere. The data are used

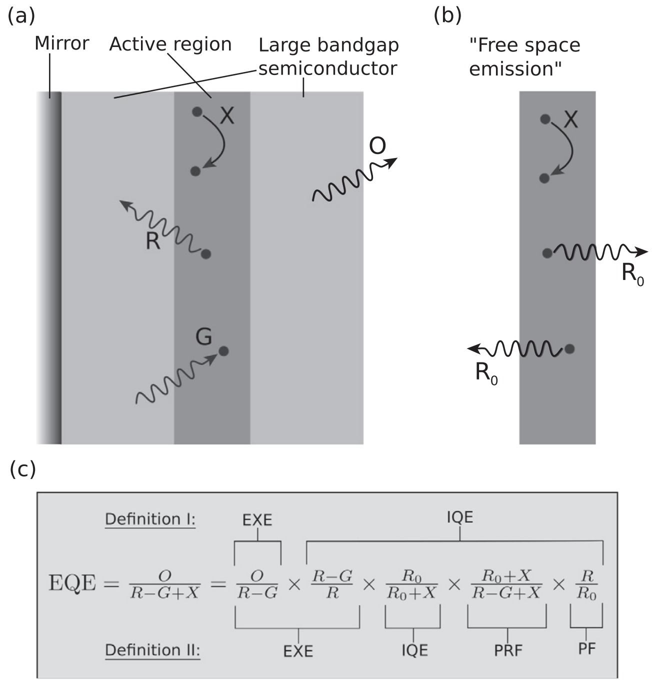

FIG. 1. (a) A schematic picture of the factors contributing to the external quantum efficiency in a simplistic LED cavity with the cavity walls formed by a mirror and a semiconductor-air interface. EQE generally depends on the photon output rate O, the net radiative recombination rate R, the generation rate G, and the nonradiative recombination rate X. (b) The radiative recombination rate R_0 in free space is generally different from R in the cavity, because the electromagnetic mode structure affects the spontaneous emission rate. (c) Two examples of separating EQE to form EXE and IQE.

to calculate the EQE as a function of optical output power and the maximum EQE, the corresponding optical output power, and the second derivative of the EQE curve are then used to determine the EXE and IQE. Essentially, the method is based on the fact that the current density and the optical output power do not have the same dependency on the carrier density. This difference determines the position of the maximum EQE typical of GaN LEDs (aka droop) and can be used to determine the internal efficiency parameters.

Our measurement method does not require detailed information of the structure and it can be applied to any III-N LED structure. In addition to providing IQE and EXE, our method can be used to estimate the radiative and Shockley-Read-Hall (SRH) recombination parameters once the Auger parameter is known. As a demonstration, we present measurement results for 7 blue-emitting III-N LEDs. We compare our results to those obtained using the previous methods and also discuss the approximations made in deriving the method.

The current density J through a diode can be expressed as a third order Taylor series of the excess carrier density n in the active region as

$$J = qd(An + Bn^2 + Cn^3), \tag{1}$$

where q is the elementary charge, d is the thickness of the active region, and A, B, and C are first to third order Taylor coefficients. In most LED structures where leakage current is moderate these coefficients approximate the SRH, radiative, and Auger recombination coefficients.[8]

As our measurement focuses on the regime where n is relatively small, we assume that the radiative recombination is proportional to n^2.[9] Then the component of the injected current density responsible for emitting the extracted photons can be written as

$$P = \chi qdBn^2, \tag{2}$$

where χ is the number of extracted photons divided by the total number of emitted photons (or more accurately the fraction of net bimolecular recombination events resulting in a detected photon). In the following, we refer to P as photocurrent density. Solving n from Eq. (2) and substituting it into Eq. (1) gives (see Ref. 10 for details)

$$J = \frac{P}{\chi} + \frac{\sqrt{P}}{\sqrt{qd\chi^3B^3}}(CP + Aqd\chi B), \tag{3}$$

and the EQE is correspondingly given by

$$\eta(P) = \frac{P}{J(P)}. \tag{4}$$

The χ coefficient can be solved from Eq. (4), after differentiating twice with respect to P, as

$$\chi = \frac{\eta_m^2}{\eta_m + 4P_m^2 D_2}, \tag{5}$$

where η_m is the maximum EQE, P_m is the corresponding photocurrent density, and D_2 is the second derivative of $\eta(P)$ at P_m. Measuring $\eta(P)$ in the vicinity of its maximum allows calculating all the quantities in Eq. (5), so that an estimate for χ is simple to obtain. If leakage current is not excessively large, which is generally the case for relatively small currents,[11,12] it directly follows that χ corresponds to the EXE in the sense of definition I of Fig. 1(c) and $\eta_{IQE} = \eta/\chi$.

Using Eqs. (1)–(4) as a starting point, one can also use the $P(J)$ measurement to estimate two of the three Taylor coefficients of Eq. (1). This is not required to estimate IQE and EXE but can be used to obtain more information on the relations between the different recombination and loss mechanisms in the LED. Solving, e.g., A and B as a function of C gives

$$A = \left(\frac{(1 - \eta_m/\chi)P_m}{qd\eta_m}\right)^{2/3} \sqrt[3]{\frac{C}{4}} \tag{6}$$

and

$$B = \left(\frac{2\eta_m C}{1 - \eta_m/\chi}\right)^{2/3} \sqrt[3]{\frac{P_m}{qd} \cdot \frac{1}{\chi}}. \tag{7}$$

In contrast with χ and IQE, calculating the values of A and B requires some prior knowledge of the structure, since they depend on the effective active region thickness d and the coefficient C, which can, under certain circumstances, be assumed equal to the Auger recombination coefficient. Similar equations can also be written for B and C if coefficient A is determined, e.g., using small signal measurements as in Ref. 9.

We measured the optical power emitted by 7 blue and near-UV LEDs at room temperature as a function of the injection current. The LEDs were labeled with letters A-G, where LED A was a commercially packaged blue LED and LEDs B-G were unpackaged near-UV LED chips mounted on a TO header. LED chips were grown by metal organic vapor phase epitaxy on c-plane sapphire substrates and processed into $440 \times 440\,\mu\text{m}^2$ chips. The chips were bonded on a silver coated TO header. The active region consisted of ten 2.5 nm thick InGaN quantum wells separated by GaN barriers. The growth process is described in more detail in Ref. 13. To test how additional scattering affects the estimates of the EXE, LED chips B-D were grown with a SiN interlayer within the n-GaN layer. This has been reported to enhance light extraction in near-UV LEDs.[14] LED chips E-G were grown without an interlayer.

The LEDs were measured using pulsed current to avoid heating of the LED chip. The measurements were done with a relatively low current density eliminating high injection level effects on radiative recombination. We also tested the setup with continuous injection and found the discrepancies between pulsed and continuous results modest for the high efficiency LEDs. The measurements were performed with a current source and a photodetector calibrated using an integrating sphere collecting all the extracted light. The EQE was calculated from the measured optical power and electrical current. The surface area of the commercial LED was estimated with an optical microscope.

The measured EQE values as a function of P on a logarithmic scale and parabolas fitted to the data are shown for three of the LEDs in Fig. 2(a). The values have been normalized by their peak values to make the parabolicity of the curves better visible. Equation (4) exhibits a parabolic shape near its maximum when plotted on a logarithmic photocurrent scale, and the experimental EQE curves of Fig. 2(a) indeed have a parabolic shape, verifying that the assumption leading to Eq. (2) is correct.

The second derivative D_2 needed in Eq. (5) can be easily calculated from the second derivative of the EQE vs. $\log_{10}(P)$

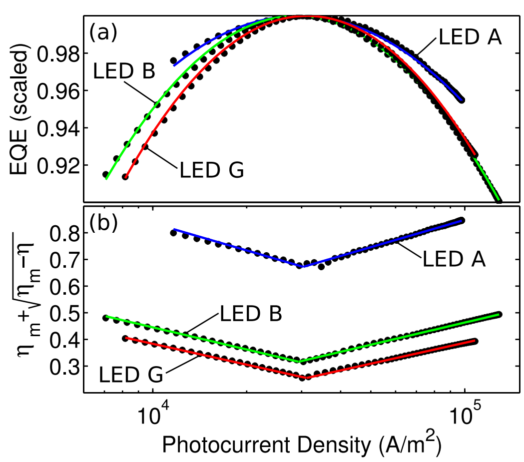

FIG. 2. (a) Scaled external quantum efficiency vs. measured photocurrent density and (b) square-root transformed data and fitted linear curves for LEDs A, B, and G. The dots represent measurement data and solid lines the least-squares polynomial estimates. The maximum EQE and the corresponding scaled photocurrent density can be read from the x and y axes in (b), and the second derivative D_2' can be calculated directly as $-2k^2$, where k is the slope of the linear curve. The EQE in (a) for LEDs A, B, and G have been normalized by their maximum values 0.67, 0.32, and 0.26, respectively.

TABLE I. Results for the parameters obtained using the direct method. Table shows the emission wavelength (λ), estimated EXE, measured maximum EQE (η_m), and estimated maximum IQE (IQE$_m$) for all the measured LEDs. For demonstration, we also show the estimated A and B parameters using $d = 10$ nm and $C = 1.5 \times 10^{-42}$ m^6/s as external values.

	λ (nm)	EXE	η_m	IQE$_m$	A (10^6 1/s)	B (10^{-17} m^3/s)
			Commercially packaged LED			
LED A	450	0.91	0.67	0.74	3.0	1.2
			Planar LEDs with SiN interlayer			
LED B	417	0.50	0.32	0.64	5.6	1.0
LED C	417	0.54	0.34	0.63	5.7	0.98
LED D	417	0.55	0.31	0.56	7.2	0.87
			Planar LEDs, no SiN interlayer			
LED E	405	0.38	0.23	0.61	6.5	0.97
LED F	405	0.36	0.22	0.61	6.5	1.0
LED G	405	0.43	0.26	0.60	6.9	0.95

curve as $D_2' = D_2/(P_m \ln 10)^2$, where D_2' is the second derivative of the EQE at its maximum on a logarithmic scale. For obtaining D_2' directly from the data, Fig. 2(b) shows the EQE transformed as $\eta_m + \sqrt{\eta_m - \eta}$, which enables reading directly the parameters η_m, P_m, and $D_2' = -2k^2$, where k is the slope of the obtained linear curve. The slope k is calculated from the measurement data on either side of η_m as

$$k = \frac{\Delta\sqrt{\eta_m - \eta}}{\Delta(\log_{10}(P))}. \tag{8}$$

Table I shows the EXE and maximum IQE obtained from the $\eta(P)$ measurement for the LEDs. The peak efficiency ranges from 0.67 (at $P = 3.5$ A/cm^2) of the commercial packaged LED to 0.22 (at $P = 2.5$ A/cm^2) of the unpackaged planar samples. The maximum IQE of 0.74 and EXE of 0.91 obtained for the commercial packaged blue LED are comparable with values presented in Ref. 2, where a maximum IQE of 0.63 and a maximum EXE of 0.80 were demonstrated for a near-UV LED as measured by the low temperature photoluminescence method. In Ref. 3, on the other hand, peak IQE of 0.67 and EXE of 0.85 were measured for a violet-blue LED by low-temperature electroluminescence method. The high extraction efficiency indicates very efficient photon recycling and small optical losses in the LED package. Moreover, it indicates that the IQE is the main limiting factor of the EQE.

The parameters obtained for planar unpackaged near-UV LED chips with (B-D) and without (E-G) a SiN interlayer show very little variation from chip to chip. The extraction efficiency of the unpackaged chips B-G is smaller than that of the commercial LED A, of the order of 0.40–0.50, due to the lack of packaging optics. The IQE is also slightly lower than in the commercial packaged blue LED, presumably due to lower material quality or a less optimal location of the emitting material in the emitter cavity. Interestingly, the EXE of the LED chips with a SiN interlayer (B-D) is higher than of the chips without a SiN interlayer (E-G), as reported also in Ref. 14. The table also shows the order-of-magnitude estimates for the A and B coefficients obtained by assuming that the C parameter corresponds to the Auger coefficient of

1.5×10^{-42} m^6/s as reported, e.g., in Refs. 15–17 and that the effective thickness of the active region is 10 nm. The total active region thickness is 25 nm in the planar LEDs, but we used $d = 10$ nm because as demonstrated in Ref. 18, generally not all QWs in the active region emit light. The order-of-magnitude estimates for A and B can be compared, e.g., with those presented in Refs. 17, 19, and 20.

The most important assumption in our model is that the optical emission depends quadratically on the carrier density which is usually considered a reasonable assumption in the relatively low carrier density regime. References 9 and 21, however, demonstrate that the n^2 proportionality breaks down at high currents. In estimating the SRH, radiative, and Auger recombination parameters one further assumes that they are the mechanisms that dominate in determining the Taylor coefficients of Eq. (1).

Estimates for χ and IQE may also contain error due to the measurement error in η_m and D_2'. The errors scale approximately linearly with the measurement error in η_m and D_2' with coefficients of proportionality ranging between 0.3 and 3. For the measured LEDs, a relative error of 2% in the measured values of η_m and D_2' results in a maximum relative error of 3% in the determined values of IQE and EXE.

In conclusion, we have proposed a direct electrical measurement method for determining the extraction efficiency and internal quantum efficiency of III-Nitride LEDs. The method is based on measuring the EQE of the LED as a function of optical output power near the EQE maximum and extracting IQE and EXE from the EQE curve. Our method enables a straightforward alternative to previous methods relying on low temperature measurements or extensive simulations and it also enables a convenient and universal comparison of arbitrary III-N LED structures. In addition to measuring IQE and EXE, the method can be currently used to obtain order-of-magnitude estimates of the recombination parameters and it is expected that the accuracy of the order-of-magnitude estimates can be improved by complementary measurements.

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