



BSI Standards Publication

Semiconductor devices

Part 5-12: Optoelectronic devices — Light emitting diodes — Test method of LED efficiencies

National foreword

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TECHNICAL REPORT



**Semiconductor devices –
Part 5-12: Optoelectronic devices – Light emitting diodes – Test method of LED
efficiencies**

INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

SEMICONDUCTOR DEVICES –

**Part 5-12: Optoelectronic devices – Light emitting diodes –
Test method of LED efficiencies**

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Draft	Report on voting
47E/741/DTR	47E/748/RVDTR

Full information on the voting for its approval can be found in the report on voting indicated in the above table.

The language used for the development of this Technical Report is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/standardsdev/publications.

A list of all parts in the IEC 60747 series, published under the general title *Semiconductor devices*, can be found on the IEC website.

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INTRODUCTION

The latest international standards for light emitting diode (LED) devices are IEC 60747-5-6:2016, IEC 60747-5-8:2019, IEC 60747-5-9:2019, IEC 60747-5-10:2019, and IEC 60747-5-11:2019, where terminology and measuring methods of basic electrical and optical characteristics of LEDs are given.

This technical report gives guidance on the terminology and the measuring methods of various efficiencies of single light emitting diode (LED) chip or package without phosphor. White LEDs for lighting applications are out of the scope of this part of IEC 60747-5-12.

The efficiencies whose measuring methods are described in this technical report are the power efficiency (PE), the external quantum efficiency (EQE), the voltage efficiency (VE), the internal quantum efficiency (IQE), and the light extraction efficiency (LEE). To measure these efficiencies separately, one needs the measurement data of the internal quantum efficiency (IQE).

The IQE is a key performance parameter that represents the quality of epitaxial wafers and contains essential information on operational mechanisms. Requirements for accurate and reliable IQE measurements are suggested. The various IQE measurement methods reported so far are reviewed in detail from a theoretical and practical point of view. Subsequently, the technical limitations for these IQE measurement methods to meet the requirements for accurate and reliable IQE measurements are discussed.

In particular, two different measuring methods of the IQE that can meet the requirements are described in detail both experimentally and theoretically. They are known as the temperature-dependent electroluminescence (TDEL) and the room-temperature reference-point method (RTRM).

A measuring procedure of PE, EQE, VE, IQE, and LEE are demonstrated. But the injection efficiency (IE) and the radiative efficiency (RE) are described for definitions only.

Separate knowledge of various efficiencies of the LED chip or package is able to improve optoelectronic performances of LED chip itself and to design LED application systems such as LED lamps more efficiently and reliably.

SEMICONDUCTOR DEVICES –

Part 5-12: Optoelectronic devices – Light emitting diodes – Test method of LED efficiencies

1 Scope

This technical report discusses the terminology and the measuring methods of optoelectronic efficiencies of single light emitting diode (LED) chip or package without phosphor. White LEDs for lighting applications are out of the scope of this part.

This technical report provides guidance on

- terminology of optoelectronic efficiencies of single LED chip or package without phosphor, such as the power efficiency (PE), the external quantum efficiency (EQE), the voltage efficiency (VE), the light extraction efficiency (LEE), the internal quantum efficiency (IQE), the injection efficiency (IE), and the radiative efficiency (RE) [1]¹;
- test methods of optoelectronic efficiencies of the PE, the EQE, the VE, the LEE, and the IQE [1];
- review of various IQE measurement methods reported so far in view of accuracy and practical applicability;
- the measuring method of the LED IQE based on the temperature-dependent electroluminescence (TDEL) [2];
- the measuring method of the LED IQE based on the room-temperature reference-point method (RTRM) [3];
- the measuring method of the radiative and nonradiative currents of an LED [4];
- the relationship between the IQE and the VE, which leads to introduction of a new LED efficiency, the active efficiency (AE) as $AE = VE \times IQE$.

2 Normative reference

The following document is referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60747-5-6, *Semiconductor devices – Part 5-6: Optoelectronic devices – Light emitting diodes*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at <http://www.electropedia.org/>
- ISO Online browsing platform: available at <http://www.iso.org/obp>

¹ Numbers in square brackets refer to the Bibliography.

3.1 General terms and definitions

3.1.1

radiant power

 Φ_e

change in radiant energy with time

Note 1 to entry: The unit used is: W. Radiant power is also known as "radiant flux".

[SOURCE: IEC 60050-845:2020, 845-21-038, modified – Note 1 has been expanded.]

3.1.2

spectral distribution

density of a radiant power Φ_e , with respect to wavelength, λ , at the wavelength λ

$$\Phi_{e,\lambda} = \frac{d\Phi_e(\lambda)}{d\lambda}$$

[SOURCE: IEC 60050-845:2020, 845-21-029, modified – In the definition, "a radiant or luminous or photon quantity $X(\lambda)$ " has been replaced by "a radiant power Φ_e ". In the formula, X has been replaced by Φ_e . Notes have been deleted.]

3.1.3

mean photon energy

 $h\bar{\nu}$

mean energy that each photon carries

$$h\bar{\nu} = \frac{\Phi_e}{\int \frac{\lambda}{hc} \Phi_{e,\lambda} d\lambda}$$

where

h is the Planck constant;

c is the speed of light in vacuum

[SOURCE: IEC 60747-5-8:2019, 3.1.3]

3.2 Terms and definitions relating to the optoelectronic efficiencies

3.2.1

power efficiency

 η_{PE}

ratio of the radiant power (coupled to free space), Φ_e , to the electrical power consumed by the LED, $V_F I_F$, where V_F is the forward voltage and I_F is the forward current of the LED

$$\eta_{PE} = \frac{\Phi_e}{V_F I_F}$$

Note 1 to entry: Power efficiency is also known as the "wall-plug efficiency". Power efficiency is identical to the "radiant efficiency" when the power dissipated by any auxiliary equipment is excluded from the electrical power.

[SOURCE: IEC 60747-5-8:2019, 3.2.1]

3.2.2 voltage efficiency

η_{VE}

ratio of the mean photon energy emitted from the LED to the electron energy given by the forward voltage of the LED, V_F

$$\eta_{VE} = \frac{h\bar{\nu}}{qV_F}$$

where

q is the elementary charge.

Note 1 to entry: Voltage efficiency can be greater than 1 at very low forward currents.

[SOURCE: IEC 60747-5-8:2019, 3.2.2]

3.2.3 external quantum efficiency

η_{EQE}

ratio of the number of photons emitted into the free space per unit time to the number of electrons injected into the LED per unit time

$$\eta_{EQE} = \frac{\Phi_e/h\bar{\nu}}{I_F/q}$$

[SOURCE: IEC 60747-5-8:2019, 3.2.3]

3.2.4 internal quantum efficiency

η_{IQE}

ratio of the number of photons emitted from the active region per unit time to the number of electrons injected into the LED per unit time

$$\eta_{IQE} = \frac{\Phi_{e,active}/h\bar{\nu}}{I_F/q}$$

where

$\Phi_{e,active}$ is the radiant power emitted from the active region.

[SOURCE: IEC 60747-5-8:2019, 3.2.4]

3.2.5 light extraction efficiency

η_{LEE}

ratio of the number of photons emitted into the free space to the number of photons emitted from the active region

$$\eta_{LEE} = \frac{\Phi_e}{\Phi_{e,active}}$$

[SOURCE: IEC 60747-5-8:2019, 3.2.5]

3.2.6

injection efficiency

η_E

ratio of the number of electrons injected into the active region per unit time to the number of electrons injected into the LED per unit time

$$\eta_E = \frac{I_{F,active}}{I_F}$$

where

$I_{F,active}$ is the portion of the forward current injected into the active region.

[SOURCE: IEC 60747-5-8:2019, 3.2.6]

3.2.7

radiative efficiency

η_{RE}

ratio of the number of photons emitted from the active region per unit time to the number of electrons injected into the active region per unit time

$$\eta_{RE} = \frac{\Phi_{e,active}/h\nu}{I_{F,active}/q}$$

[SOURCE: IEC 60747-5-8:2019, 3.2.7, modified – The specific use in angle brackets as well as the note have been removed.]

3.3 Terms and definitions relating to measuring the efficiencies

3.3.1

peak EQE point

set of operating conditions of the forward current and radiant power at which the EQE is the maximum for a given temperature.

Note 1 to entry: The forward current and radiant power at the peak EQE point are denoted as I_{peak} and Φ_{peak} , respectively.

[SOURCE: IEC 60747-5-9:2019, 3.1.6]

3.3.2

cryogenic temperature

temperature range below 200 K

[SOURCE: IEC 60747-5-9:2019, 3.1.7]

3.3.3**critical cryogenic temperature** T_c

cryogenic temperature at which the peak EQE shows the maximum value

[SOURCE: IEC 60747-5-9:2019, 3.1.9]

3.3.4**normalized variables of X and Y**

converted quantities of current and radiant power as follows:

$$X = \sqrt{\Phi_e(I_F) / \Phi_e(I_{\text{peak}})}$$

$$Y = I_F / I_{\text{peak}}$$

[SOURCE: IEC 60747-5-10:2019, 3.1.7]

3.3.5**coefficients of a_1 and a_2**

coefficients of the quadratic equation of Y in X , i.e., $Y = a_1 X + a_2 X^2$

Note 1 to entry: a_1 and a_2 change slowly enough according to the forward current as compared to X and Y , but should be treated as a function of the forward current in the data analysis.

[SOURCE: IEC 60747-5-10:2019, 3.1.8]

3.3.6**reference point**

operating point at which a_2 is minimum

Note 1 to entry: a_2 , X , and Y at the reference point are represented by $a_{2,\text{ref}}$, X_{ref} , and Y_{ref} , respectively. The current at the reference point is denoted as $I_{F,\text{ref}}$.

[SOURCE: IEC 60747-5-10:2019, 3.1.9]

3.4 Terms and definitions relating to measuring current components**3.4.1****radiative current** I_{rad}

current that is consumed by the radiative recombination process in the LED

[SOURCE: IEC 60747-5-11:2019, 3.1.2]

3.4.2**nonradiative current** I_{nonrad}

current that is consumed by the nonradiative recombination processes in the LED

[SOURCE: IEC 60747-5-11:2019, 3.1.3, modified – The notes have been removed.]

3.5 Abbreviated terms

AE	active efficiency
CW	continuous wave
EL	electroluminescence

EQE	external quantum efficiency
IDPL	intensity-dependent photoluminescence
IE	injection efficiency
IQE	internal quantum efficiency
LED	light emitting diode
LEE	light extraction efficiency
MQW	multiple quantum well
PE	power efficiency
PL	photoluminescence
QW	quantum well
RE	radiative efficiency
RTRM	room-temperature reference-point method
SRH	Shockley-Read-Hall
TDEL	temperature-dependent electroluminescence
TDPL	temperature-dependent photoluminescence
TD-TREL	temperature-dependent time-resolved electroluminescence
TD-TRPL	temperature-dependent time-resolved photoluminescence
TREL	time-resolved electroluminescence
TRPL	time-resolved photoluminescence
VE	voltage efficiency

4 LED efficiencies

4.1 General

LEDs are now found in numerous applications owing to advantages such as low power consumption, small size, long lifetime, and fast switching. LEDs are available in various spectral ranges including ultraviolet, visible, and infrared wavelengths, based on different material systems [5]-[7]. Although the LEDs have simple pn junctions with a long history of researches since the early 1960s, there still remain multiple issues in relation with the device configurations and materials. In order to analyse any possible device issues, accurate characterization of the device is essential.

Many parameters have been utilized for LED devices to quantify the device performance: parameters obtained from simple current-voltage (I - V) and light-current (L - I) measurements constitute a basis. However, they don't typically give enough details about a device under test [8]-[15]. Since many device parameters are interrelated, more extensive characterization is required to form a complete picture of any possible cause behind a problem in the device and to remedy it [16],[17]. If there is any measure implemented to remedy and enhance the device performance, it is often difficult to judge whether the intended effects have been achieved by simple checking of the output parameters such as I - V , L - I , and the emission spectrum. IEC 60747-5-6:2016 lists terminology and measuring methods of basic electrical and optical characteristics of LEDs as categorized in Table 1.

Table 1 – LED items and their measuring methods listed in IEC 60747-5-6:2016

LED Characteristics	Items	Measurement Method
Electrical	Forward voltage (V_F)	6.2
	Reverse voltage (V_R)	6.3
	Differential resistance (r_f)	6.4
	Reverse current (I_R)	6.5
	Capacitance (C_t)	6.6
Temperature	Junction temperature (T_j)	6.7
	Thermal resistance ($R_{th(j-x)}$)	6.7
Frequency	Response time	6.8
	Frequency response and cut-off frequency (f_c)	6.9
Optical	Luminous flux (Φ_V)	6.10
	Radiant power (Φ_e)	6.11
	Luminous intensity (I_V)	6.12
	Radiant intensity (I_e)	6.13
	Luminance (L_V)	6.14
Spectral	Emission spectrum, peak emission wavelength (λ_p), spectral half bandwidth ($\Delta\lambda$)	6.15
Chromatic	Chromaticity	6.16
Directional	Directivity	6.17
	Illuminance (E_V)	6.18
Quality Evaluation	Quality evaluation test and inspection	8

Of various device parameters, efficiencies contain the most important information on the device performance and any possible problem in it. IEC 60747-5-8 defines various efficiencies relevant to the LED devices. The overall efficiency of the LED device is characterized by the power efficiency (PE), η_{PE} . The PE is rather simple to measure and serves as a useful parameter representing how efficient the device is in converting the electrical power to the desired radiant power. However, in many cases, one needs to know more details than the PE to infer limiting factors in device performance.

The PE can be decomposed into its constituent factors, which are the voltage efficiency (VE), η_{VE} , and the external quantum efficiency (EQE), η_{EQE} . The EQE is then decomposed into the light extraction efficiency (LEE), η_{LEE} , and the internal quantum efficiency (IQE), η_{IQE} . The IQE is in turn separated into the injection efficiency (IE), η_{IE} , and the radiative efficiency (RE), η_{RE} . The PE, VE, and EQE are measurable by using experimental data of current, voltage, radiant power, and spectra. On the other hand, a standard method of measuring the IQE has not been known since the advent of LEDs in 1960s, before the publication of IEC 60747-5-9:2019 and 60747-5-10:2019.

The EQE is a measurable quantity once the mean photon energy is obtained. It can be limited by either the IQE or the LEE. Thus, a separate measurement of the IQE and the LEE is extremely useful not only to improve the device performance but also to elucidate the operating mechanisms of an LED device. The optimization of the epitaxial structure and the growth condition is a typical method for achieving a high IQE. A high LEE is achieved by reducing the

total internal reflection at the LED surface. The LEE and the IQE can be separately obtained from the EQE if one of them is known. In general approaches, the LEE is theoretically calculated and the IQE is experimentally measured. Theoretical calculation of the LEE is limited to specific cases in practice. This is because the LEE is very sensitive to the microscopic parameters such as the complex refractive index of each material, the layer structure, or the randomly textured surface [18]-[20]. Thus, direct measurement of the IQE as a function of current is more practical and has been pursued actively.

This technical report focuses on direct measurement methods of the IQE as a function of current in single LED chip or package without phosphor. Various characterization techniques for measuring the LED IQE are critically reviewed and compared. After the limitations of the existing IQE measurement techniques are reviewed, the room-temperature reference-point method (RTRM) is presented as a most accurate and practical IQE measurement method. The RTRM is then applied to various LED devices to show how the IQE measurement techniques can be utilized to analyse their optoelectronic performances quantitatively.

4.2 Theoretical background of optoelectronic efficiencies

Usually, an LED is electrically driven by a power supply producing the voltage V_F and the forward current I_F . The total electrical power supplied is $V_F I_F$. The LED operation is more clearly understood when $V_F I_F$ is expressed as $(qV_F)(I_F/q)$, where q is the elementary charge of 1.6×10^{-19} C: I_F/q is the total number of electrons injected into an LED per second, and qV_F is an average electrical potential energy of each electron given by the forward voltage V_F . In the ideal case, each electron energized by a power supply emits one photon without any energy loss so that both quantum particles should have the same energy qV_F . In a real case, however, there are many sorts of electrical and optical energy loss mechanisms during the electrical-to-optical energy-conversion process.

For LEDs, various efficiencies can be defined as a measure of different conversion processes [5]-[7]. The overall efficiency of an LED device can be characterized by the PE. The PE, η_{PE} , is defined as the ratio of the radiant power (coupled to the free space), Φ_e , to the input electrical power $V_F I_F$, i.e.,

$$\eta_{PE} \equiv \frac{\text{radiant power}}{\text{electrical power}} = \frac{\Phi_e}{V_F I_F} \quad (1)$$

The PE represents how efficiently an LED device can convert the electrical energy to the optical energy and thus is the most important efficiency parameter. The electrical energy that is not converted to the optical energy is wasted as heat. There are various factors that can affect the PE and these factors are characterized by various other efficiency parameters. From now on, the efficiency parameters that constitute the PE are described in detail.

The VE, η_{VE} , represents the ratio of the average photon energy emitted from the LED to the average electron energy supplied by the power source:

$$\eta_{VE} \equiv \frac{\text{mean photon energy}}{\text{mean electron energy}} = \frac{h\bar{\nu}}{qV_F}, \quad (2)$$

where $h\bar{\nu}$

and recombination process. Recently, it was also pointed out that space charges of electrons and holes accumulated near the active region also contribute additional forward voltage for a desired forward current I_F [21]-[23]. In order to improve the voltage efficiency, both low forward turn-on voltage and small series resistance are required. The VE is experimentally measurable so that the value can be improved by a sort of feedbacks to fabrication processes and LED chip designs.

The mean photon energy $h\bar{\nu}$ is defined as follows:

$$h\bar{\nu} \equiv \frac{\Phi_e}{\int_0^\infty \frac{\lambda}{hc} \Phi_{e,\lambda}(\lambda) d\lambda}, \quad (3)$$

Here, h is the Planck constant, c is the speed of light in vacuum, and λ is the free-space wavelength. Note that the integral $\int_0^\infty \frac{\lambda}{hc} \Phi_{e,\lambda}(\lambda) d\lambda$ represents the number of photons emitted from the LED per second. The average photon energy should be approximately equal to the bandgap energy of the active region of the LED.

Another is the EQE, η_{EQE} , defined as the ratio of the number of photons emitted into the free space per unit time to the number of electrons injected into the LED per unit time, i.e.,

$$\eta_{EQE} = \frac{\Phi_e/h\bar{\nu}}{I_F/q}, \quad (4)$$

where

$\Phi_e/h\bar{\nu}$ is the number of photons emitted into free space per second;

I_F/q is the number of electrons injected into LED per second.

Note from Formulae (2) and (4) that the multiplication of the VE and the EQE gives the PE, i.e.,

$$\eta_{PE} = \eta_{VE} \cdot \eta_{EQE}. \quad (5)$$

The IQE, η_{IQE} , is defined as the ratio of the number of photons emitted *from the active region* per unit time to the number of electrons injected into the LED per unit time:

$$\eta_{IQE} = \frac{\Phi_{e,active}/h\bar{\nu}}{I_F/q}, \quad (6)$$

where

$\Phi_{e,active}$ is the radiant power emitted from the active region;

$\Phi_{e,active}/h\bar{\nu}$ is the number of photons emitted from active region per second;

I_F/q is the number of electrons injected into LED per second.

The IQE is greatly dependent on crystal growth and the epitaxial layer structure. The IQE is one of the key performance indicators of LEDs.

The ratio of the number of photons emitted *into the free space* to the number of photons emitted from the active region is defined as the light extraction efficiency (LEE), η_{LEE} :

$$\eta_{LEE} = \frac{\Phi_e}{\Phi_{e,active}} \quad (7)$$

where

Φ_e is the number of photons emitted into free space per second;

$\Phi_{e,active}$ is the radiant power emitted from the active region.

The LEE is a measure of the photon loss during the propagation from the active region into free space. In an ideal LED, all photons emitted by the active region should escape from an LED die. However, in a real LED, not all the radiant power emitted from the active region is emitted into the free space by such factors as total internal reflection. The trapped light inside the LED chip is eventually absorbed by the device, generating heat. Increasing the LEE is one of the main endeavours many chip manufactures are dedicated to so that they could improve the PE.

Using the EQE and the IQE, the LEE can be expressed as

$$\eta_{LEE} = \frac{\eta_{EQE}}{\eta_{IQE}}$$

Or

$$\eta_{EQE} = \eta_{IQE} \cdot \eta_{LEE} \quad (8)$$

The IE, η_E , is defined as the ratio of the electrons injected into the active region per unit time to the number of electrons injected into the LED per unit time, expressed as

$$\eta_E = \frac{I_{F,active}}{I_F} \quad (9)$$

where

$I_{F,active}$ is the number of electrons injected into active region per second;

I_F is the number of electrons injected into LED per second.

Here, $I_{F,active}$ is the portion of the forward current injected into the active region. The IE is a measure for how many electrons recombine in the active QW region compared with the total injected electrons into an LED. It depends on the current level as well as the LED structure itself. The IE is determined by nonradiative recombination rates occurring outside the active QW regions. Possible leakage currents are semiconductor surface current, defect-related tunnelling current, and electron overflow from the QW active region to p-clad region [24]-[26]. The surface leakage current is initially observed at around zero bias voltage and it shows relatively symmetric current-voltage curve for forward and reverse biases. Special surface treatment and passivation techniques have been utilized to suppress the surface leakage current. The electron blocking layer in the epitaxial growth has been introduced to reduce the electron overflow from the active region to the p-type clad layer at high-level current injection [27]. Current spreading is important to improve the current injection efficiency in terms of reducing current density over an entire LED surface. The nonuniform current injection increases

both the Joule heating and the nonradiative recombination processes and eventually lowers the light power efficiency [28],[29].

With respect to $I_{F,active}$, one can define the RE, η_{RE} :

$$\eta_{RE} = \frac{\Phi_{e,active}/h\nu}{I_{F,active}/q}, \quad (10)$$

where

$\Phi_{e,active}/h\nu$ is the number of photons emitted from active region per second;

$I_{F,active}/q$ is the number of electrons injected into active region per second.

which is different from the IQE by the factor IE:

$$\eta_{IQE} = \eta_{IE} \cdot \eta_{RE} \quad (11)$$

For a high RE, it is necessary to increase the radiative recombination rate and decrease the nonradiative recombination rate.

Lastly, the active efficiency (AE), η_{AE} , can be defined as the ratio of the radiant power emitted *from the active region* to the electrical power supplied to the LED:

$$\eta_{AE} = \frac{\Phi_{e,active}}{V_F I_F}, \quad (12)$$

where

$\Phi_{e,active}$ is the radiant power emitted from the active region;

$V_F I_F$ is the electric power.

which is different from the IQE in that the active region is analysed in a view of the power rather than the particle rate. The AE is a concept similar to the responsivity in a photodiode.

In summary, the overall PE can be rewritten as follows:

$$\begin{aligned} \eta_{PE} &= \eta_{VE} \cdot \eta_{EQE} \\ &= \eta_{VE} \cdot \eta_{IQE} \cdot \eta_{LEE} \\ &= \eta_{VE} \cdot \eta_{IE} \cdot \eta_{RE} \cdot \eta_{LEE} \\ &= \eta_{AE} \cdot \eta_{LEE} \end{aligned} \quad (13)$$

Or put in differently,

$$\begin{aligned} \eta_{PE} &= \frac{\Phi_e}{V_F I_F} \\ &= \frac{h\nu}{q V_F} \cdot \frac{I_{F,active}}{I_F} \cdot \frac{\Phi_{e,active}/h\nu}{I_{F,active}/q} \cdot \frac{\Phi_e}{\Phi_{e,active}} \end{aligned} \quad (14)$$

The efficiency definitions are summarized in Table 2.

Table 2 – Summary of efficiency items defined in IEC 60747-5-8:2019

Items	Definitions
Power efficiency (PE)	$\eta_{PE} = \frac{\Phi_e}{V_F I_F},$ where Φ_e is the radiant power; $V_F I_F$ is the electrical power.
Voltage efficiency (VE)	$\eta_{VE} = \frac{h\bar{\nu}}{qV_F},$ where $h\bar{\nu}$ is the mean photon energy; qV_F is the mean electron energy. $h\bar{\nu} \equiv \frac{\Phi_e}{\int_0^\infty \frac{\lambda}{hc} \Phi_{e,\lambda} d\lambda}$
External quantum efficiency (EQE)	$\eta_{QE} = \frac{\Phi_{e,active}/h\bar{\nu}}{I_F/q},$ where $\Phi_e/h\bar{\nu}$ is the number of photons emitted into free space per second; I_F/q is the number of electrons injected into LED per second.
Internal quantum efficiency (IQE)	$\eta_{QE} = \frac{\Phi_{e,active}/h\bar{\nu}}{I_F/q},$ where $\Phi_{e,active}/h\bar{\nu}$ is the number of photons emitted from active region per second; I_F/q is the number of electrons injected into LED per second.
Light extraction efficiency (LEE)	$\eta_{LEE} = \frac{\Phi_e}{\Phi_{e,active}}$ where Φ_e is the number of photons emitted into free space per second; $\Phi_{e,active}$ is the number of photons emitted from active region per second.
Injection efficiency (IE)	$\eta_{IE} = \frac{I_{F,active}}{I_F},$ where $I_{F,active}$ is the number of electrons injected into active region per second; I_F is the number of electrons injected into LED per second.

Items	Definitions
Radiative efficiency (RE)	$\eta_{RE} = \frac{\Phi_{e,active}/h\bar{\nu}}{I_{F,active}/q}$ where $\Phi_{e,active}/h\bar{\nu}$ is the number of photons emitted from active region per second; $I_{F,active}/q$ is the number of electrons injected into active region per second.

4.3 Separate measurement of various efficiencies

The PE can be obtained in a straight-forward way by using Equation (1). Measuring the radiant power Φ_e and electrical V_F and I_F is already defined in IEC 60747-5-6:2016 (see Table 1). In order to define the EQE, one needs to find the mean photon energy $h\bar{\nu}$, using Equation (3). Once the mean photon energy is obtained, the EQE can be obtained by Equation (4). Using the obtained PE and EQE, the VE can now be calculated by using Equation (5) as $\eta_{VE} = \eta_{PE}/\eta_{EQE}$.

To separate the efficiencies further, the IQE is required. Methods of obtaining the IQE are discussed in detail in the following sections. Once the IQE is determined by a method such as the RTRM, the LEE can now be obtained by using Equation (8): $\eta_{LEE} = \eta_{EQE}/\eta_{IQE}$.

The sequence of the efficiency measurements is summarized in Figure 1.

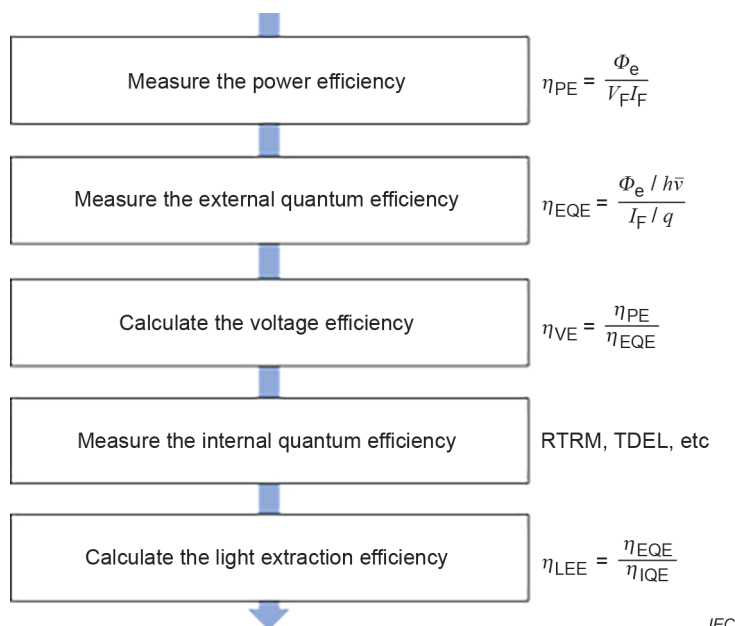


Figure 1 – Sequence of the efficiency measurements

4.4 Requirements for accurate and reliable IQE measurement

The IQE of an LED is a key parameter that represents the quality of epitaxial layers and contains essential information on operational mechanisms. Furthermore, knowing the IQE allows quantitative measurements of various efficiencies defined for LEDs. As seen in Table 2, the IQE, defined as the ratio of the number of internally emitted photons to the number of electrically injected (or optically generated) carriers, is the product of the IE and the RE. The IQE varies with the operating conditions of forward injection current I_F and temperature T as expressed below:

$$\eta_{\text{QE}}(I_{\text{F}}, T) = \eta_{\text{E}}(I_{\text{F}}, T) \cdot \eta_{\text{RE}}(I_{\text{F}}, T) \quad (15)$$

The IE is a measure of how many electrons recombine in the active region compared to the total electrons injected into an LED. It generally depends on the current level as well as the LED structure itself. The RE represents the ratio of the radiative recombination rate to the total recombination rate (i.e., the sum of the radiative and nonradiative recombination rates) in the active region. For an accurate estimation of the IQE, it is necessary to consider the IE and the RE separately and quantitatively.

The IQE measurement methods satisfying the following requirements are very desirable in view of accuracy, simplicity, reproducibility, and experimental-system cost: (i) Use only experimentally measurable physical quantities such as current and radiant power (optical power) *without* assuming any physical parameters, e.g., chip sizes, epitaxial layer structures, carrier recombination rates, and complex refractive indices; (ii) Measure the *relative* radiant power rather than the *absolute* radiant power to reduce measurement errors; (iii) Use measurement conditions of the *operational* temperature and pumping scheme. The electroluminescence (EL) at room temperature is the most preferable combination compared with others; Finally, (iv) use CW pumping and its steady-state response of the spontaneous emission, which eliminates the need for complicated and expensive experimental setups such as a short-pulse current driver, a high-speed photodetector, and an impedance matching technique for a good RF signal integrity.

In Clauses 5 and 6, the IQE measurement methods that have been frequently utilized up to now are reviewed. The technical limitations involved in these methods are compared and discussed. In order to overcome such limitations and satisfy the aforementioned requirements, a unique method of the IQE measurement, named as the room-temperature reference-point method (RTRM), has been proposed recently. The RTRM is described separately in detail.

4.5 Classification of IQE measurement methods

The discrete and accurate measurement of the LED IQE as a function of optical pumping power, injection current, or carrier density has been a constant challenge. The IQE measurement can be done theoretically or experimentally. The theoretical approach is based on calculation of the LEE and the experimental approaches utilize the EQE data measured at various conditions. Different measurement methods of the IQE as a function of input pumping rate have been reported so far as summarized in Table 3. The IQE measurement methods are named differently according to the input pumping scheme, the output temporal responses, and the sample temperatures. There are two input pumping schemes: one is the optical pumping with a laser and the other is the electrical pumping by the current. Their respective output spontaneous emissions are known as the photoluminescence (PL) and the electroluminescence (EL). The laser light intensity and electrical current are usually varied in order to change the input pumping rate. In time scale, the input pumping signal and its optical response can be either continuous wave (CW) or short-pulse trains. Sometimes sample temperatures can be varied from the cryogenic temperatures to room temperature. Each IQE measurement method in Table 3 is named to represent the input pumping scheme, temporal response, and sample temperature.

The IQE measurement methods can be largely divided into five categories: (i) calculation of the LEE, (ii) PL methods, (iii) EL methods, (iv) temperature-dependent (TD) methods, and (v) time-resolved (TR) methods. Each method has its own pros/cons, features, and limitations in applications. Each method is described in the next section.

Table 3 – Various LED IQE measurement methods

Theoretical	Calculation of the LEE						
Experimental	Type		Pumping variable	Time scale		Sample temperature	
				CW	Dynamic	Fixed	Varied
	Pumping method	Optical	Laser intensity	PL	TRPL	PL,TRPL	TDPL, TD-TRPL
		Electrical	Current	EL	TREL	EL,TREL	TDEL, TD-TREL

CW: continuous wave; PL: photoluminescence; EL: Electroluminescence; TR: time-resolved; TD: temperature-dependent; and RTRM: room-temperature reference-point method

5 Conventional IQE measurement methods: features and limitations

5.1 Calculation of the LEE

The method based on calculation of the LEE [category (i) in 4.5] indirectly measures the IQE by dividing the measured EQE with the calculated LEE. Thus, it requires both the accurate measurement of the absolute radiant power and the precise knowledge of model parameters for LEE calculation. This method has been frequently applied due to its simplicity. But unwanted errors can be easily involved in calculation due to unclear model parameters such as chip shape and dimensions, fine textured structures in chip surfaces or substrate, epitaxial structures and their material constants, e.g., complex refractive indices [30]-[41]. This method is almost impossible to use without knowing the detailed structure and operating conditions. Therefore, there are limitations to adopting this method as an international standard for measuring the IQE of any LED chips. It is preferable to measure the IQE of an LED chip only from the stably obtainable experimental data.

5.2 Temperature-dependent photoluminescence (TDPL)

The PL methods [category (ii) in 4.5] are nondestructive and the IQE of the active layers can be evaluated on an epitaxial wafer without fabricating the actual devices. The most popularly utilized IQE measurement method based on the PL is the continuous-wave (CW) temperature-dependent photoluminescence (TDPL) method [42]-[57].

An advantage of TDPL is that the IQE (η_{QE}) can be directly determined experimentally without the aid of any calculations or physical-parameter assumptions.

Experimentally the PL efficiency (η_{PL}) is defined by the ratio of the integrated PL intensity (I_{PL}) to the laser excitation intensity (I_{laser}), i.e. $\eta_{\text{PL}} = I_{\text{PL}}/I_{\text{laser}}$. Sometimes, η_{PL} is normalized to its peak value among all experimental data. In the TDPL, it is considered that $\eta_{\text{PL}}(T, I_{\text{laser}})$ is linearly proportional to $\eta_{\text{QE}}(T, I_{\text{laser}})$ and the LEE (η_{LEE}) is independent of temperature and laser excitation intensity. In addition, the IQE is assumed as 100 % at the maximum PL efficiency for various experimental conditions of environmental temperatures and laser excitation intensities, i.e. $\eta_{\text{QE}}(T_{\text{low}}, I_{\text{laser,max}}) = 100\%$.

Following these assumptions, the IQEs from the experimental PL efficiencies measured at various temperatures and laser intensities are obtained. Usually, the maximum PL efficiency ($\eta_{\text{PL,max}}$) is found at a cryogenic temperature (T_{low}) and a certain excitation level ($I_{\text{laser,max}}$).

Then, $\eta_{\text{QE}}(T, I_{\text{laser}})$ is calculated by

$$\eta_{\text{QE}}(T, I_{\text{laser}}) \Big|_{\text{TDPL}} = \frac{\eta_{\text{PL}}(T, I_{\text{laser}})}{\eta_{\text{PL,max}}(T_{\text{low}}, I_{\text{laser,max}})} \quad (16)$$

In order to apply Equation (16), it is necessary to confirm $\eta_{\text{QE}}(T_{\text{low}}, I_{\text{laser,max}}) = 100\%$ satisfying $\text{IE} = \text{RE} = 100\%$ at the maximum PL efficiency ($\eta_{\text{PL,max}}$). One of the informative methods investigating the carrier recombination processes only in the QW active layers is the resonant PL. In the resonant PL, the photon energy of the optical pumping source is between the bandgap energy of the well and that of the barrier to selectively excite the carriers only in the QWs. This is intended to eliminate the influence of carriers excited and transported in regions other than the active layer. According to this idea, it is generally assumed that $\text{IE} = 100\%$, i.e., all the carriers generated in the active layers recombine there. However, in contrast to this assumption, it has been reported experimentally that the carrier escape from the QWs does take place with a strong dependence on the duration of excitation and bias conditions [57].

A technique confirming the IE of 100% in the resonant PL has been proposed, which is comparing three characteristics, i.e., the PL efficiency and the open-circuit voltage in the resonant PL experiment and the EL efficiency in the EL experiment. It was experimentally reported that the efficiency droop behaviours of a 440-nm InGaN-based blue LED as functions of temperature and pumping level were quite similar in both the resonant PL and EL experiments [55]. This observation strongly indicates that the carrier spill-over or carrier overflow from the QWs due to limited carrier recombination rates inside the QWs is considered as an important origin of the efficiency droop in both the resonant PL and EL experiments. As a result, it should be remembered that carrier overflow is possible even at the resonant PL experiments, resulting in $\text{IE} < 100\%$.

To find the reference point satisfying $\text{RE} = 100\%$, the second assumption is used. At cryogenic temperatures, the nonradiative recombination centres in the active layers, which induce the Shockley-Read-Hall (SRH) recombination, are "frozen" and become inactive. Moreover, the direct Auger recombination rate in conventional semiconductors decreases exponentially with decreasing temperature so that the contribution of the Auger recombination rate can also be neglected at the reference point. By assuming that both the SRH and Auger recombination rates are negligibly small at cryogenic temperatures, the RE is considered as 100% [43],[44]. In experiments, the assumption of $\text{RE} = 100\%$ is confirmed from the fact that the peak EQEs at cryogenic temperatures do not increase further and maintain the maximum value with decreasing temperatures. On the other hand, the assumption of $\text{IE} = 100\%$ is experimentally confirmed from the fact that the peak PL efficiencies where the RE is considered as 100% do not vary and maintain the maximum value with pumping laser intensity.

However, in many cases, it has been reported that the laser intensity is changed at a specific cryogenic temperature or vice versa [45]. It should be remembered that these experiments cannot be used for the IQE measurement because the IE and the RE cannot be guaranteed as 100% simultaneously at the maximum PL efficiency.

5.3 Intensity-dependent photoluminescence (IDPL) or simply photoluminescence (PL)

Another method based on the PL at room temperature for determining the IQEs has been reported by fitting the laser pump intensity to powers of the integrated PL intensity. This is named as the intensity-dependent photoluminescence (IDPL) or simply the PL in Table 3 [58]-[61]. In the IDPL or PL method, the well-known constant ABC model for the carrier rate equation is theoretically utilized.

The dependence of the PL intensity on the laser pump power is formulated by using photon and carrier rate equations in the active layer with the assumption that both the optical absorption coefficient of the pump laser light and the carrier recombination coefficients are independent of the laser pump power or the carrier density there. In addition, it is implicitly assumed that the IE is constant (a value of either one or less than one). This implies that all or a constant

percentage of carriers generated in the active layers recombine there. The theoretical background of the IDPL is described next.

The rate equation of the carrier density $n(t)$ in the active QW is written by the relationship between the carrier injection rate G_{inj} and the total recombination rate R as follows:

$$\frac{dn}{dt} = G_{inj} - R \quad (17)$$

A laser pumping with the total generation rate of G is considered. Then, a part of the total generated carriers in the active layers are recaptured and recombine there, which is the IE, η_E :

$$G_{inj} = \eta_E G. \quad (18)$$

The total generation rate G is given by

$$G = (1 - R_{surface}) \frac{\alpha P_{laser}}{A_{spot} h \nu_L} = \frac{(1 - R_{surface}) \alpha}{A_{spot}} \frac{P_{laser}}{h \nu_L}, \quad (19)$$

where $R_{surface}$, α , $h \nu_L$, and P_{laser} are the reflectivity on the semiconductor surface, the absorption coefficient in the active QWs, the photon energy, and the excitation laser power, respectively [61].

According to the well-known constant-ABC model, there are three main recombination mechanisms, namely, the nonradiative SRH recombination, the radiative recombination, and the Auger recombination, the recombination rates of which are proportional to n , n^2 , and n^3 , respectively:

$$R = An + Bn^2 + Cn^3, \quad (20)$$

where A , B , and C are the recombination coefficients representing the SRH, radiative, and Auger recombinations, respectively.

At a steady state where $dn/dt = 0$ in Equation (17), the carrier injection rate is the same as the recombination rate, i.e., $G_{inj} = \eta_E G = R$. Then, Equations (18), (19) and (20) lead to the following:

$$\frac{P_{laser}}{h \nu_L} = \frac{A_{spot}}{\eta_E (1 - R_{surface}) \alpha} (An + Bn^2 + Cn^3) = \frac{1}{\eta_E \eta_L} (An + Bn^2 + Cn^3), \quad (21)$$

where $\eta_L = (1 - R_{surface}) \alpha / A_{spot}$. The integrated PL power (P_{PL}) over the wavelength is detected by a photodetector and is given by

$$\frac{P_{PL}}{h \bar{\nu}} = (\eta_{det} \eta_{LEE} V_{active}) Bn^2 = \eta_D Bn^2, \quad (22)$$

where $\eta_D = \eta_{\text{det}} \eta_{\text{LEE}} V_{\text{active}} \cdot \eta_{\text{det}}$ and V_{active} are the total detector coupling efficiency and the active volume, respectively.

The RE (η_{RE}) is given by the radiative recombination rate over the total carrier recombination rate in the active layers and the IQE (η_{QE}) is obtained by the radiative recombination rate to the total generation rate (G):

$$\eta_{\text{RE}} = \frac{Bn^2}{G_{\text{inj}}} = \frac{Bn^2}{R} = \frac{Bn^2}{An + Bn^2 + Cn^3}; \quad (23)$$

$$\eta_{\text{QE}} = \frac{Bn^2}{G} = \eta_E \frac{Bn^2}{G_{\text{inj}}} = \eta_E \frac{Bn^2}{R} = \eta_E \frac{Bn^2}{An + Bn^2 + Cn^3} = \eta_E \eta_{\text{RE}}. \quad (24)$$

The PL efficiency (η_{PL}) is defined as the ratio of the radiative photon rate to the excitation laser photon rate:

$$\begin{aligned} \eta_{\text{PL}} &= \frac{P_{\text{PL}}/h\nu}{P_{\text{laser}}/h\nu_L} = \frac{\eta_E (1 - R_{\text{surface}}) \alpha_L (\eta_c \eta_{\text{LEE}} V_{\text{active}}) Bn^2}{A_{\text{spot}} (An + Bn^2 + Cn^3)} = \eta_E \eta_L \eta_D \frac{Bn^2}{An + Bn^2 + Cn^3} \\ &= \eta_L \eta_D \eta_E \eta_{\text{RE}} = \eta_L \eta_D \eta_{\text{QE}} \end{aligned} \quad (25)$$

From Equation (25), it can be seen that η_{PL} is not equal but linearly proportional to η_{QE} . In order to find an exact value of η_{QE} , it is necessary to know η_E and η_{RE} separately.

Next, the experimental values of the laser intensity are theoretically related to the PL intensity. From Equation (22), the carrier density n in the active layer is expressed by the PL intensity:

$$n = \frac{1}{\sqrt{(\eta_D B) h\nu}} \sqrt{P_{\text{PL}}}. \quad (26)$$

The laser intensity P_{laser} in Equation (21) can be rewritten by

$$\begin{aligned} P_{\text{laser}} &= \frac{h\nu_L}{\eta_E \eta_L} R = \frac{h\nu_L}{\eta_E \eta_L} (An + Bn^2 + Cn^3) \\ &= \frac{h\nu_L}{\eta_E \eta_L} \frac{A}{\sqrt{(\eta_D B) h\nu}} \sqrt{P_{\text{PL}}} + \frac{h\nu_L}{\eta_E \eta_L} \frac{1}{(\eta_D) h\nu} (\sqrt{P_{\text{PL}}})^2 + \frac{h\nu_L}{\eta_E \eta_L} \frac{C}{\sqrt{(\eta_D B)^3 (h\nu)^3}} (\sqrt{P_{\text{PL}}})^3 \\ &= P_1 \sqrt{P_{\text{PL}}} + P_2 (\sqrt{P_{\text{PL}}})^2 + P_3 (\sqrt{P_{\text{PL}}})^3 \end{aligned} \quad (27)$$

where

$$P_1 = \frac{h\nu_L}{\eta_E \eta_L} \frac{A}{\sqrt{(\eta_D B) h\nu}}, \quad P_2 = \frac{h\nu_L}{\eta_E \eta_L} \frac{1}{(\eta_D) h\nu}, \quad P_3 = \frac{h\nu_L}{\eta_E \eta_L} \frac{C}{\sqrt{(\eta_D B)^3 (h\nu)^3}}. \quad (28)$$

Then, η_{RE} in Equation (23) can be expressed by using Equation (27) as

$$\eta_{RE} = \frac{Bn^2}{An + Bn^2 + Cn^3} = \frac{P_2(\sqrt{P_{PL}})^2}{P_1\sqrt{P_{PL}} + P_2(\sqrt{P_{PL}})^2 + P_3(\sqrt{P_{PL}})^3}. \quad (29)$$

As a result,

$$\eta_{QE} = \eta_{IE}\eta_{RE} = \eta_{IE} \frac{P_2(\sqrt{P_{PL}})^2}{P_1\sqrt{P_{PL}} + P_2(\sqrt{P_{PL}})^2 + P_3(\sqrt{P_{PL}})^3}. \quad (30)$$

It is expected from Equation (26) that R_{laser} can be expressed by the power-dependence of $\sqrt{P_{PL}}$ with P_1 , P_2 , and P_3 as constant fitting parameters. In fact, many parameters in P_1 , P_2 , and P_3 may be dependent on the laser power R_{laser} . There have been many reports on the carrier-density dependent characteristics of η_{IE} , A , B , C , α , and η_{LEE} . Thus, it should be noted that the constant fitting parameters P_i be much slowly varying with $\sqrt{P_{PL}}$. After the fitting process, η_{RE} can be calculated as a function of R_{laser} from Equation (29). Once the IE is known, then the IQE can be calculated from Equation (30).

In the fitting process, it is implicitly assumed that the IE is constant (approximately 1). As a result, the RE is equal to be the IQE and the PL efficiency degradation at high pumping rates is due to the Auger nonradiative recombination process. However, it is not clear whether the increase in the Auger nonradiative recombination rate or the decrease in the IE is the origin of the IQE degradation at high pumping rates. As a result, these assumptions make it difficult to evaluate the IQE with the PL method. On the other hand, it is expected that the IDPL (or simply PL) method would be very helpful to estimate the active-layer quality as high radiative recombination rate.

5.4 Temperature-dependent time-resolved photoluminescence (TD-TRPL)

The time-resolved photoluminescence (TRPL) measurement, an observation of the temporal response of the PL, has been known as a useful experimental tool to study new materials [62]-[76]. This is because the temporal information combined with the spectral data can help determine the carrier dynamics involved in optical processes such as the lifetimes of minority carriers, free and bound excitons, localized excitons, and tunnelling. The temperature-dependent time-resolved photoluminescence (TD-TRPL) method has been widely used to determine the radiative and nonradiative carrier lifetimes separately in conjunction with the measured IQE values. In the TD-TRPL method, measurement of the IQE follows the same procedure as the TDPL method previously explained.

The transient luminescence intensity $I(T, t)$ obtained by the data of TRPL is analysed by using the carrier rate equation in the active layer. As a very rough approximation, it is assumed that all carriers generated in the active layers recombine there (i.e., IE = 100 %). Moreover, the radiative carrier lifetime $\tau_r(T)$ and nonradiative carrier lifetime $\tau_{nr}(T)$ are usually assumed to be constant independent of carrier density n in the active layer. Then, the carrier rate equation just after the laser pulse is turned off ($t = 0^+$) and its solution is obtained as follows: