IEC TR 60747-5-12

Edition 1.0 2021-10

TECHNICAL REPORT

colour inside

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

IEC TR 60747-5-12:2021-10(en)

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INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

ICS 31.080.99
ISBN 978-2-8322-1035-9

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

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SEMICONDUCTOR DEVICES –

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FOREWORD

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The text of this Technical Report is based on the following documents:

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.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under webstore.iec.ch in the data related to the specific document. At this date, the document will be

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- withdrawn,
- replaced by a revised edition, or
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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 × 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

$h\overline{v}$

mean energy that each photon carries

$$h\overline{v} = \frac{\Phi_e}{\int \frac{\lambda}{hc}\Phi_{e,\lambda}d\lambda}$$

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}

$$\eta_{\mathrm{VE}} = \frac{h\overline{v}}{qV_{\mathrm{F}}}$$

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

$$\eta_{\mathrm{EQE}} = \frac{\Phi_{\mathrm{e}} / h\overline{v}}{I_{\mathrm{F}} / q}$$

[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

$$\eta_{\mathrm{IQE}} = \frac{\Phi_{\mathrm{e,active}} / h\overline{v}}{I_{\mathrm{F}} / q}$$

where

$\Phi_{\mathrm{e,active}}$ 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

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

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

3.2.6
injection efficiency
η_{IE}
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

$$\eta_{\mathrm{IE}} = \frac{I_{\mathrm{F,active}}}{I_{\mathrm{F}}}$$

where

$I_{\mathrm{F,active}}$ 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

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

[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:

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

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

[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 $a_{2,ref}$, X_{ref}, and Y_{ref}, respectively. The current at the reference point is denoted as $I_{F,ref}$.

[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.