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

INTERNATIONAL ELECTROTECHNICAL COMMISSION

ICS 31.080.99

ISBN 978-2-8322-1035-9

Warning! Make sure that you obtained this publication from an authorized distributor.

® Registered trademark of the International Electrotechnical Commission

CONTENTS

FOREWORD 5
INTRODUCTION 7
1 Scope 8
2 Normative reference 8
3 Terms and definitions 8
3.1 General terms and definitions 9
3.2 Terms and definitions relating to the optoelectronic efficiencies 9
3.3 Terms and definitions relating to measuring the efficiencies 11
3.4 Terms and definitions relating to measuring current components 12
3.5 Abbreviated terms 12
4 LED efficiencies 13
4.1 General 13
4.2 Theoretical background of optoelectronic efficiencies 15
4.3 Separate measurement of various efficiencies 20
4.4 Requirements for accurate and reliable IQE measurement 20
4.5 Classification of IQE measurement methods 21
5 Conventional IQE measurement methods: features and limitations 22
5.1 Calculation of the LEE 22
5.2 Temperature-dependent photoluminescence (TDPL) 22
5.3 Intensity-dependent photoluminescence (IDPL) or simply photoluminescence (PL) 23
5.4 Temperature-dependent time-resolved photoluminescence (TD-TRPL) 26
5.5 Time-resolved photoluminescence (TRPL) 28
5.6 Time-resolved electroluminescence (TREL) 34
5.7 Constant ABC model 39
5.8 Constant AB model 45
6 Standard IQE measurement method I: TDEL 46
6.1 Temperature-dependent electroluminescence (TDEL) method 46
6.2 Temperature-dependent radiant power 46
6.3 Evaluation of the IQE 47
6.4 Validity of the TDEL: examples of blue LEDs 49
6.5 Sequence of IQE determination by the TDEL 50
6.6 Summary of the TDEL 51
7 Standard IQE measurement method II: RTRM 51
7.1 Room-temperature reference-point method (RTRM) 51
7.2 Recombination coefficients, A, B, and C in semiconductors 52
7.3 Strategy of the IQE measurement just at an operating temperature 53
7.4 Theoretical background of the RTRM 54
7.5 Example of the RTRM 56
7.6 Comparison of IQEs by the TDEL and the RTRM 59
7.7 Summary of the RTRM 60
8 The RTRM versus the TDEL and the constant ABC model: comparisons 60
9 LED performance issues related to the IQE measurement 67
9.1 Various LED efficiency measurement 67
9.2 Radiative and nonradiative currents 70
9.3 The active efficiency (AE): IQE versus forward voltage 74

10 Conclusion: test method of optoelectronic efficiencies of LEDs 80
Bibliography 81

Figure 1 – Sequence of the efficiency measurements 20
Figure 2 – Theoretical model for analysing the TRPL experiment 30
Figure 3 – Schematic TRPL response and its interpretation in terms of various lifetimes 32
Figure 4 – Temporal responses of the TRPL for three samples 33
Figure 5 – Fitted results of the measured TRPL response 34
Figure 6 – Schematic diagram of the pulse current injection 35
Figure 7 – Square of $1/\tau_{EL}$ as a function of current density for a bias voltage 39
Figure 8 – Estimated IQE (left axis) and measured EQE (right axis) versus current density 39
Figure 9 – Experimental EQE curve of a blue LED 42
Figure 10 – Normalized EQE curves (solid lines) and experimental data (rectangular symbols) for different IQE peak values as a parameter for a blue LED emitting at 460 nm 42
Figure 11 – SRH nonradiative carrier lifetime $\tau_{SRH}(=1/A)$ as a function of the C coefficient calculated from Equation (82) 43
Figure 12 – Experimental EQE curve of a blue LED 43
Figure 13 – Temperature characteristics of an LED 47
Figure 14 – IQEs as a function of current at various operating temperatures from room to cryogenic measured by the TDEL method 49
Figure 15 – Two different cases of normalized EQE curves as a function of current at various temperatures 50
Figure 16 – Sequence of the IQE measurement by the TDEL method 51
Figure 17 – Comparison between the conventional ABC model and the improved AB model 54
Figure 18 – Calculation procedure from a relative EQE curve to an IQE curve with the RTRM 54
Figure 19 – IQE calculation procedure as a function of current based on the RTRM 57
Figure 20 – Example of the IQE calculation based on the RTRM 59
Figure 21 – Comparison of the IQEs evaluated by (a) the TDEL and (b) the RTRM 60
Figure 22 – Radiant power versus current of a blue LED sample measured at various temperatures 61
Figure 23 – Normalized intensities on linear and log scales measured at various temperatures 62
Figure 24 – I-V characteristics at various temperatures 63
Figure 25 – Calculated a_2 as a function of current for various temperatures. I_{ref} at 300 K is the current giving the minimum value of a_2 in region II. 64
Figure 26 – IQEs obtained by the RTRM (symbols) and the TDEL (solid lines) at various temperatures 64
Figure 27 – Comparison of the IE obtained from a_2 at 300 K (left axis) and the theoretical IE for constant I_{leak} (right axis) 65
Figure 28 – Normalized EQE and the fitting by the constant ABC model 66
Figure 29 – Ratio of the SRH, radiative, Auger recombination currents to the total current 66

Figure 30 – Radiant power and forward voltage as a function of forward current 68
Figure 31 – Calculation of the mean photon energy from the emission spectra 69
Figure 32 – LED efficiencies as a function of forward current 70
Figure 33 – Sequence of the radiative and nonradiative current measurements 72
Figure 34 – IQE and forward voltage as a function of forward current 72
Figure 35 – Radiative current and forward voltage as a function of forward current 73
Figure 36 – Nonradiative current and forward voltage as a function of forward current 73
Figure 37 – Total forward current, radiative current, and nonradiative current plotted as a function of forward voltage 74
Figure 38 – Distribution of the IQE and V_F for 31 blue MQW LEDs 76
Figure 39 – Optoelectronic characteristics of three samples under consideration 77
Figure 40 – Separated radiative and nonradiative current densities of samples 1 and 2 78
Figure 41 – Separated radiative and nonradiative current densities of samples 1 and 3 79

Table 1 – LED items and their measuring methods listed in IEC 60747-5-6:2016 14
Table 2 – Summary of efficiency items defined in IEC 60747-5-8:2019 19
Table 3 – Various LED IQE measurement methods 22
Table 4 – Parameters in IQE and current density versus voltage curves 77
Table 5 – Comparison of recombination mechanisms between samples 79

INTERNATIONAL ELECTROTECHNICAL COMMISSION

_____

SEMICONDUCTOR DEVICES –

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

FOREWORD

1) The International Electrotechnical Commission (IEC) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object of IEC is to promote international co-operation on all questions concerning standardization in the electrical and electronic fields. To this end and in addition to other activities, IEC publishes International Standards, Technical Specifications, Technical Reports, Publicly Available Specifications (PAS) and Guides (hereafter referred to as “IEC Publication(s)”). Their preparation is entrusted to technical committees; any IEC National Committee interested in the subject dealt with may participate in this preparatory work. International, governmental and non-governmental organizations liaising with the IEC also participate in this preparation. IEC collaborates closely with the International Organization for Standardization (ISO) in accordance with conditions determined by agreement between the two organizations.
2) The formal decisions or agreements of IEC on technical matters express, as nearly as possible, an international consensus of opinion on the relevant subjects since each technical committee has representation from all interested IEC National Committees.
3) IEC Publications have the form of recommendations for international use and are accepted by IEC National Committees in that sense. While all reasonable efforts are made to ensure that the technical content of IEC Publications is accurate, IEC cannot be held responsible for the way in which they are used or for any misinterpretation by any end user.
4) In order to promote international uniformity, IEC National Committees undertake to apply IEC Publications transparently to the maximum extent possible in their national and regional publications. Any divergence between any IEC Publication and the corresponding national or regional publication shall be clearly indicated in the latter.
5) IEC itself does not provide any attestation of conformity. Independent certification bodies provide conformity assessment services and, in some areas, access to IEC marks of conformity. IEC is not responsible for any services carried out by independent certification bodies.
6) All users should ensure that they have the latest edition of this publication.
7) No liability shall attach to IEC or its directors, employees, servants or agents including individual experts and members of its technical committees and IEC National Committees for any personal injury, property damage or other damage of any nature whatsoever, whether direct or indirect, or for costs (including legal fees) and expenses arising out of the publication, use of, or reliance upon, this IEC Publication or any other IEC Publications.
8) Attention is drawn to the Normative references cited in this publication. Use of the referenced publications is indispensable for the correct application of this publication.
9) Attention is drawn to the possibility that some of the elements of this IEC Publication may be the subject of patent rights. IEC shall not be held responsible for identifying any or all such patent rights.

IEC TR 60747-5-12 has been prepared by subcommittee 47E: Discrete semiconductor devices, of IEC technical committee 47: Semiconductor devices. It is a Technical Report.

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

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

IMPORTANT – The "colour inside" logo on the cover page of this document indicates that it contains colours which are considered to be useful for the correct understanding of its contents. Users should therefore print this document using a colour printer.

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*

[1] Numbers in square brackets refer to the Bibliography.