IEC

# IEC 60747-5-9

Edition 1.0 2019-12

# INTERNATIONAL STANDARD

colour inside

## Semiconductor devices –
## Part 5-9: Optoelectronic devices – Light emitting diodes – Test method of the internal quantum efficiency based on the temperature-dependent electroluminescence



IEC 60747-5-9:2019-12(en)

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# SEMICONDUCTOR DEVICES –

# Part 5-9: Optoelectronic devices – Light emitting diodes – Test method of the internal quantum efficiency based on the temperature-dependent electroluminescence

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The text of this International Standard is based on the following documents:

| CDV | Report on voting |
|---|---|
| 47E/651/CDV | 47E/676/RVC |

Full information on the voting for the approval of this International Standard can be found in the report on voting indicated in the above table.

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# SEMICONDUCTOR DEVICES –

# Part 5-9: Optoelectronic devices – Light emitting diodes – Test method of the internal quantum efficiency based on the temperature-dependent electroluminescence

## 1 Scope

This part of IEC 60747 specifies the measuring method of the internal quantum efficiency (IQE) of single light emitting diode (LED) chips or packages without phosphor. White LEDs for lighting applications are out of the scope of this document. This document utilizes the relative external quantum efficiencies (EQEs) measured at cryogenic temperatures and at an operating temperature, which is called temperature-dependent electroluminescence (TDEL). In order to identify the reference IQE of 100 %, the maximum values of the peak EQE are found by varying the environmental temperature and current.

## 2 Normative references

The following documents are 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 60747-5-6:2016, *Semiconductor devices – Part 5-6: Optoelectronic devices – Light emitting diodes*

## 3 Terms, definitions and abbreviated terms

### 3.1 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



**3.1.1**
**radiant power**
$\Phi_e$
power emitted, transmitted or received in the form of radiation

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

[SOURCE: IEC 60747-5-8:2019, 3.1.1]

**3.1.2**
**internal quantum efficiency**
$\eta_{IQE}$
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

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

where

$\Phi_{\mathrm{e,active}}$ is the radiant power emitted from the active region
$h\bar{\nu}$ is the mean photon energy
$I_{\mathrm{F}}$ is the forward current
$q$ is the elementary charge

Note 1 to entry: It is in general a function of ambient temperature ($T_{\mathrm{a}}$) and forward current ($I_{\mathrm{F}}$).

[SOURCE: IEC 60747-5-8:2019, 3.2.4, modified – The note has been added.]

**3.1.3**
**external quantum efficiency**
$\eta_{\mathrm{EQE}}$
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

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

where

$\Phi_{\mathrm{e}}$ is the radiant power

Note 1 to entry: It is in general a function of ambient temperature ($T_{\mathrm{a}}$) and forward current ($I_{\mathrm{F}}$).

[SOURCE: IEC 60747-5-8:2019, 3.2.3, modified – The note has been added.]

**3.1.4**
**injection efficiency**
$\eta_{\mathrm{IE}}$
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]

**3.1.5**
**radiative efficiency**
$\eta_{\mathrm{RE}}$
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 note has been removed.]

**3.1.6**
**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 $\Phi_{peak}$, respectively.

**3.1.7**
**cryogenic temperature**
temperature range below 200 K

**3.1.8**
**critical cryogenic temperature**
$T_c$
cryogenic temperature at which the peak EQE shows the maximum value

### 3.2 Abbreviated terms

| | |
|---|---|
| EQE | external quantum efficiency |
| IE | injection efficiency |
| IQE | internal quantum efficiency |
| LED | light emitting diode |
| RE | radiant efficiency |
| TDEL | temperature-dependent electroluminescence |



## 4 Measuring methods

### 4.1 Basic requirements

#### 4.1.1 Measuring conditions

a) Temperature

If not specified, measurements shall be made at an ambient temperature ($T_a$) of (25 ± 3) °C in a condition of free air. When the chip is cooled down in a cryostat, the temperature in the cryostat should be noted.

b) Humidity

When the humidity condition is not specified, relative humidity shall be between 45 % RH and 85 % RH.

c) Precaution

In some cases, measurements change because of heat generation in the test LED over time. In that case, it is necessary to decide on the measurement time; otherwise, the measurement shall be performed after reaching thermal equilibrium. Thermal equilibrium can be considered to have been achieved if doubling the time between the application of power and the measurement causes no change in the indicated result within the precision of the measurement instruments.

#### 4.1.2 Measuring instruments and equipment

The measuring instruments and equipment shall be the same as listed in IEC 60747-5-6:2016, 6.1.2.

### 4.2 Purpose

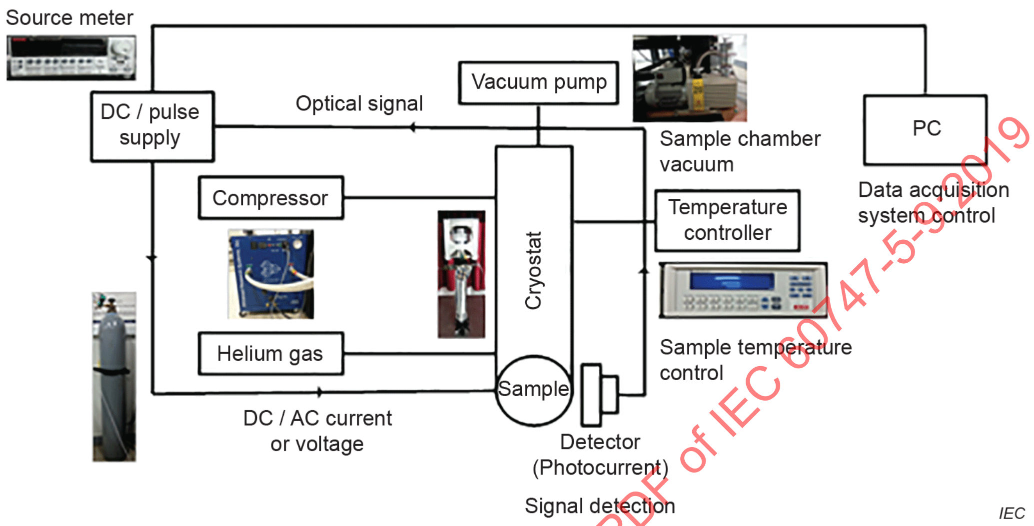
To measure the IQE at an operating temperature of the LED chips and packages, the method needs a radiant power as a function of the forward current at various temperatures from the room temperature to the cryogenic temperature. The IQE is determined by analysing the relative EQE converted from the radiant power.

## 4.3 Measurement

### 4.3.1 Measurement setup

#### 4.3.1.1 General

All of the tests should be performed under well-certified and defined conditions to avoid any external disturbances. The basic measurement setup schematics are depicted in Figure 1.




**Key**

PC: personal computer

**Figure 1 – Example of the measurement setup with the TDEL**

#### 4.3.1.2 Cryostat

The cryostat changes the temperature from the operating temperature to the cryogenic temperature. The lowest cryogenic temperature should be less than or equal to 25 K. A $T_c$ of 25 K is typically recommended. In some cases, when the criteria for saturation properties are not satisfied (steps 5 and 6 in Figure 5), a $T_c$ of 10 K is recommended.

### 4.3.2 Measurement principle

#### 4.3.2.1 Effect of temperature on radiant power

Figure 2 is a schematic diagram of the radiant power as a function of current at various temperatures. As the temperature decreases, the radiant power increases.

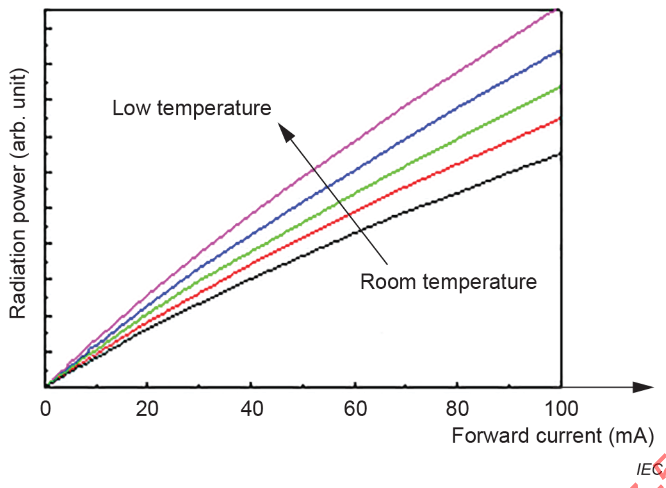



**Figure 2 – Schematic diagram of radiant power as a function of forward current at various temperatures**



#### 4.3.2.2 Conversion of radiant power to relative EQE

The relative EQE is defined as the ratio of the radiant power to the forward current.

#### 4.3.2.3 Criterion of the measurement validity

In general, the peak value of the relative EQE of a LED chip starts to increase as the temperature is decreased from the room temperature. The behaviour of the peak relative EQE can be split into two categories with decreasing temperature: one is the case where the peak value continuously increases or eventually saturates with the decreasing temperature, i.e., $T_c$, the temperature at which the maximum relative EQE value is observed, is the lowest cryogenic temperature used. The other is the case where the peak relative EQE reaches a maximum and decreases as the temperature is decreased further, i.e., $T_c$ is higher than the lowest cryogenic temperature used. In order to find a reference point in the relative EQE data that can be assumed as an IQE of 100 %, both the injection efficiency (IE) and the radiant efficiency (RE) shall be 100 %.

Examples of the generally observed categories are explained as follows:

a) Category 1: $T_c$ is the lowest cryogenic temperature used

The peak value of the relative EQE continuously increases with the decreasing temperature as seen in Figure 3a). In Figure 3a), $T_c$ = 25 K. Normalize all the relative EQE data by the maximum value of the relative EQE obtained at $T_c$ and express them in %. Check:

i) whether or not the rate of change of the normalized peak EQE is less than or equal to 0,10 %/K between the lowest and the next lowest cryogenic temperatures;

ii) whether or not the change of the normalized EQE obtained at $T_c$ remains within 1 % for currents twice and half the current level for the peak EQE point.

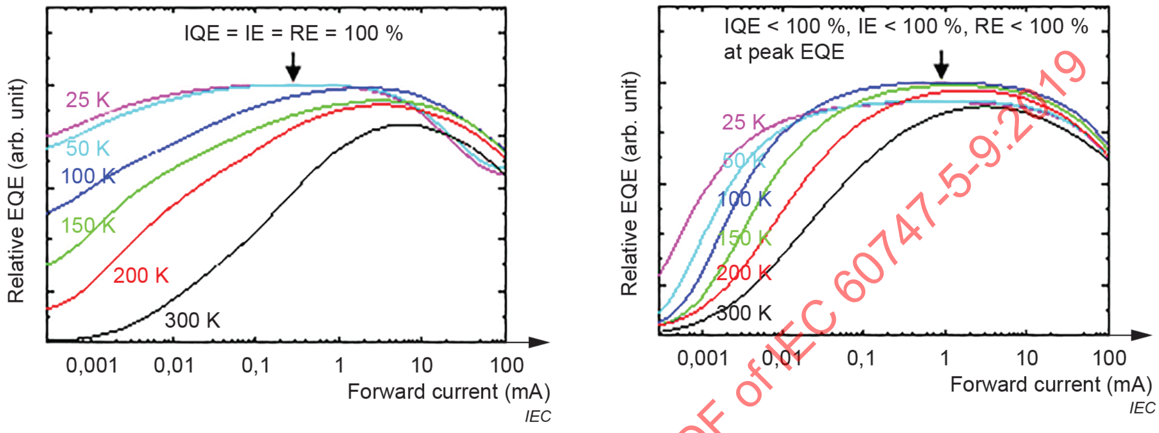
Criterion i) is to ensure that the RE is 100 % and criterion ii) is to ensure that the IE is also 100 %. Only when both criteria are satisfied, can the IQE of 100 % be assumed at the peak EQE point.

NOTE 1 The assumption that the IQE is 100 % at the peak EQE point implies that the defects, which act as nonradiative recombination centres, fully freeze out and no longer play the role at $T_c$. At the same time, the constancy of the peak EQE against the current implies that all the carriers are injected into the same place of the active region.

b) Category 2: $T_c$ is higher than the lowest cryogenic temperature used

As the temperature decreases, the peak point of the relative EQE initially increases and then decreases as seen in Figure 3b). In this case, $T_c$ does not match the lowest cryogenic temperature. $T_c$ = 100 K in Figure 3b). Therefore, an IQE of 100 % cannot be assumed at the peak EQE point at $T_c$ because both the IE and the RE are not 100 %.

NOTE 2 The fact that $T_c$ does not match the lowest cryogenic temperature indicates that there still exist leakage paths causing nonradiative recombinations even at the lowest cryogenic temperature, invalidating the assumption that all the defects freeze out at the lowest cryogenic temperature.




a) Category 1, where the IQE is measurable

b) Category 2, where the IQE is not measurable

**Figure 3 – Examples of relative EQEs showing whether the IQE is measurable or not**

#### 4.3.2.4 Evaluation of IQE at operating temperature

In category 1, the peak point of the relative EQE at $T_c$ can be assumed as an IQE of 100 % only when both criteria i) and ii) in 4.3.2.3 a) are satisfied simultaneously. For all other operating points of current and temperature, the relative EQE value normalized to the peak relative EQE at $T_c$ then corresponds to the IQE (Figure 4). If the criteria i) and ii) are not satisfied simultaneously, stop the measurement.

In category 2, the IQE cannot be measured. Stop the measurement.

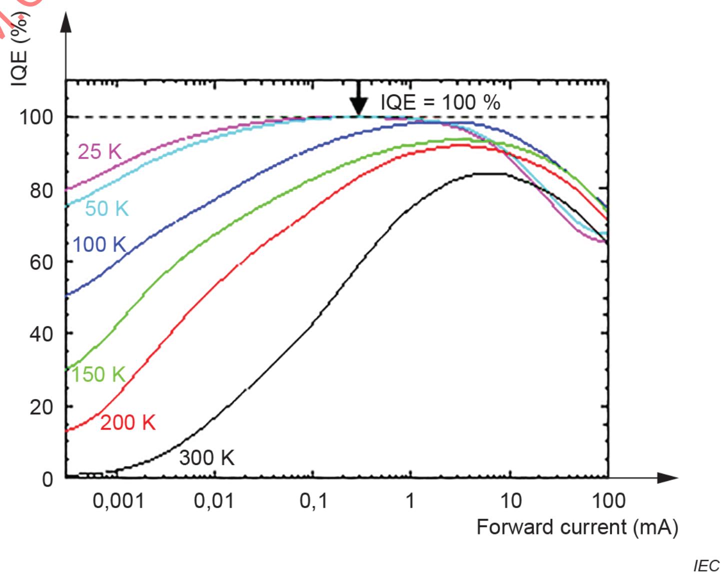



**Figure 4 – IQE measurement with TDEL**

### 4.3.3 Measurement sequence

The IQE measurement using the TDEL should proceed according to the following nine sequential steps as shown in Figure 5. Test examples are given in Annex A.

- Step 0: Test environmental specifications

  All of the tests should be performed under the well-certified and defined conditions to avoid any external disturbances. Examples of the test's environmental specifications are listed in Annex A.

- Step 1: Measure the radiant power depending on temperature and current

  The radiant power is measured at several temperatures from room temperature to cryogenic temperature as a function of forward current.

  i) Measuring temperature

     The temperature interval should be chosen as closely as possible. For example, the measurement can be performed from 300 K to ≤ 25 K at a recommended interval of ≤ 25 K. It can be measured at a wide interval above 150 K. However, it is better to measure closely below 150 K. For the IQE measurement, it is a prerequisite that $T_c$ be the lowest temperature. Thus, it should be checked carefully whether or not $T_c$ is the lowest temperature.

  ii) Range of forward current

     Radiant power is measured as a function of current from 0 to $I_{max}$ and a set of $N$ data consisting of radiant power ($\Phi_e$) and forward current is obtained at each temperature. The radiant power does not have to be the absolute value. It is recommended to divide by at least 100 or more in the current range from 0 to $I_{max}$.

NOTE 1 $I_{max}$ is the maximum forward current applied to the test LED.

NOTE 2 $N$ is the total number of operating points of the forward current.

- Step 2: Draw a relative EQE curve

  The relative EQE is obtained by dividing the radiant power by the forward current, i.e. $\eta_{EQE}(I_F) = \Phi_e(I_F)/ I_F$.

- Step 3: Check $T_c$

  This step is to verify whether or not $T_c$ is the lowest cryogenic temperature used. If yes, proceed to step 4 (category 1). If no, stop evaluation of IQE (category 2).

- Step 4: Normalize the relative EQE data at other operating points of current and temperature with respect to the maximum value of the relative EQE at $T_c$ and express the data in %.

- Step 5: Check whether or not the absolute rate of change of the normalized peak EQE is less than or equal to 0,10 %/K between the lowest and the next lowest cryogenic temperatures. If yes, proceed to step 6. If no, stop evaluation of IQE.

- Step 6: Check whether or not the change of the normalized EQE obtained at $T_c$ is less than or equal to 1 % for currents twice and half the current level for the peak EQE point. If yes, proceed to step 7. If no, stop evaluation of IQE.

- Step 7: Obtain the IQE data at an operating condition from the normalized EQE data at step 4.

- Step 8: Create the test report.

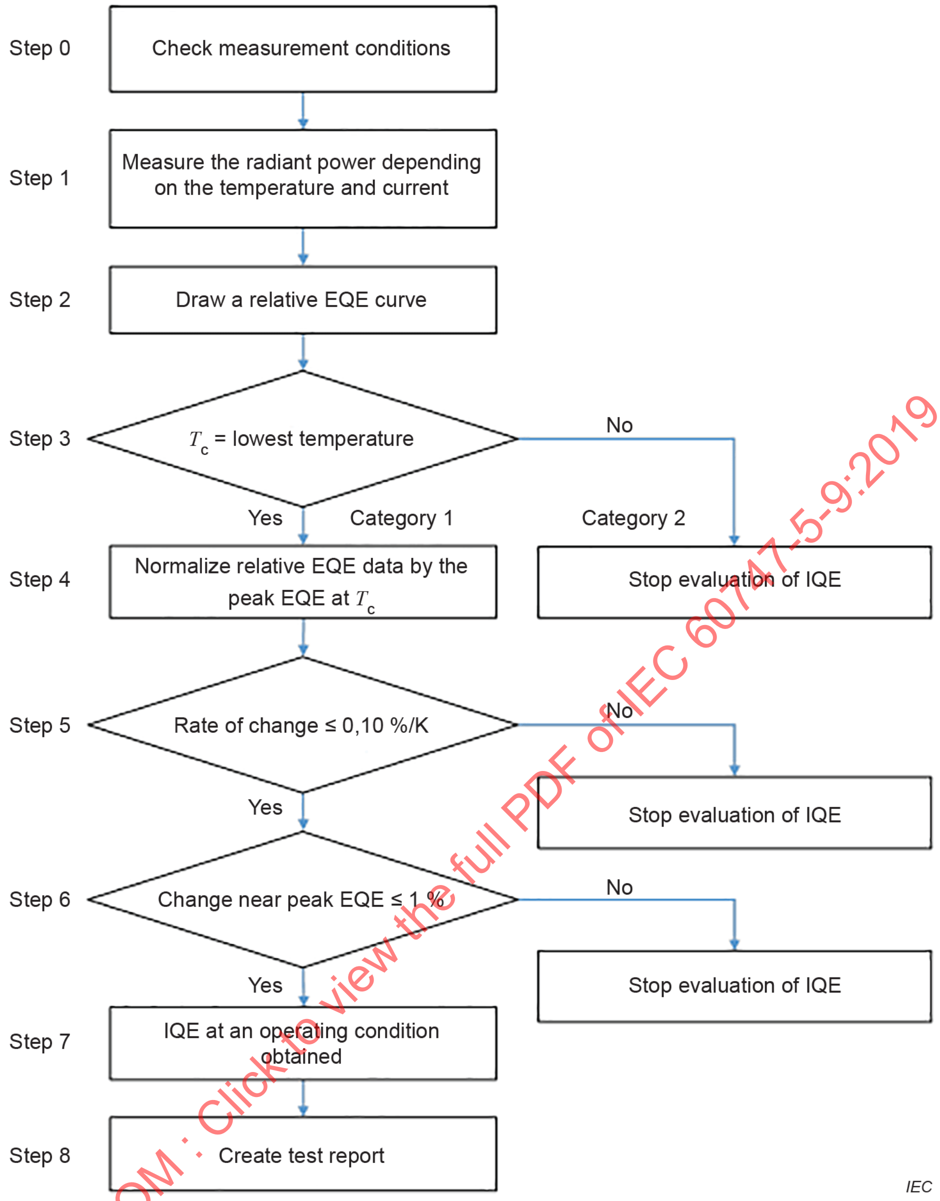



**Figure 5 – Sequence of IQE determination with TDEL**



## 5 Test report

The test report should include the items shown in Table A.1.

# Annex A
(informative)

# Test examples

## A.1 Test example (category 1)

- Step 0: Test environmental specifications
  - sample: a lateral-electrode type InGaN/GaN MQW LED grown on a c-plane sapphire substrate
  - chip size: 740 μm × 600 μm;
  - peak wavelength: ~450 nm at $T$ = 293 K;
  - humidity: 50 % RH;
  - current driving condition: pulsed current driving condition (pulse period: 100 μs, duty cycle: 1 %);
  - detector for radiant power measurement: Si photodiode;
  - equipment for electrical characteristics measurement: Keithley [1] semiconductor parameter analyser;
  - maximum driving current, $I_{max}$ = 450 mA;
  - total number of data points, $N$ = 100.
- Step 1: Measure the radiant power depending on temperature and current as shown in Figure A.1.



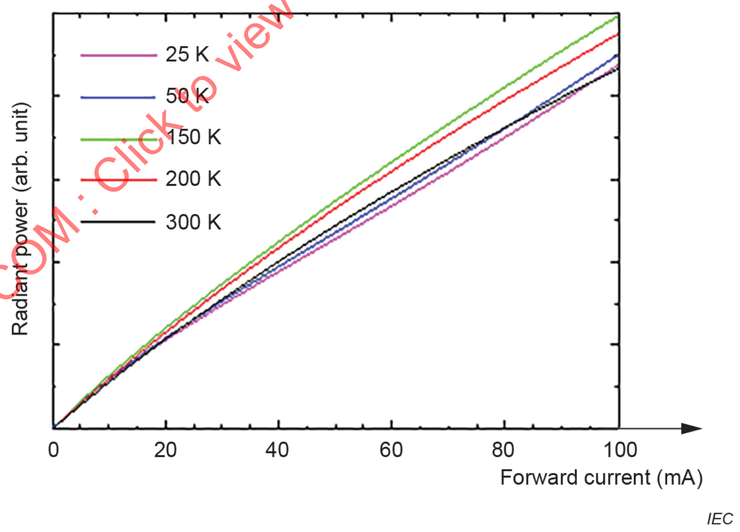



**Figure A.1 – Radiant power as a function of forward current at various temperatures (category 1)**

1 Keithley semi-conductor parameter analyser is the trade name of a product supplied by Tektronix. This information is given for the convenience of users of this document and does not constitute an endorsement by IEC of the product named. Equivalent products may be used if they can be shown to lead to the same results.

- Step 2: Draw a relative EQE curve as shown in Figure A.2.

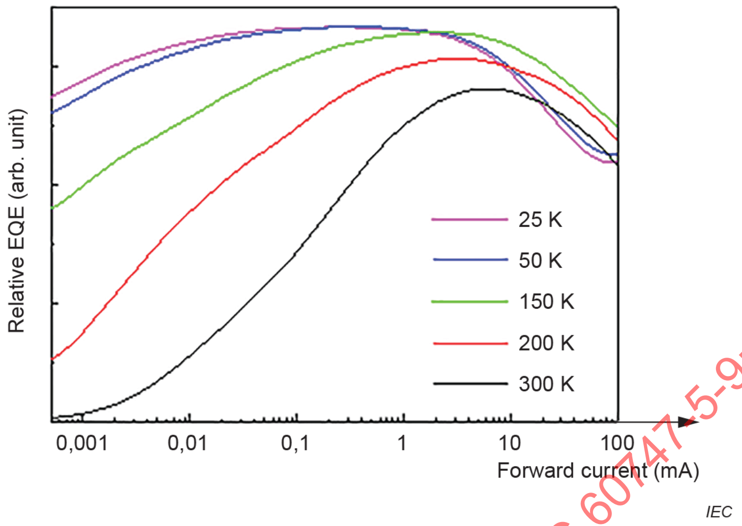



**Figure A.2 – Relative EQE as a function of forward current at various temperatures (category 1)**

- Step 3: Check $T_c$ as shown in Figure A.3. $T_c$ = 25 K, the lowest temperature used.

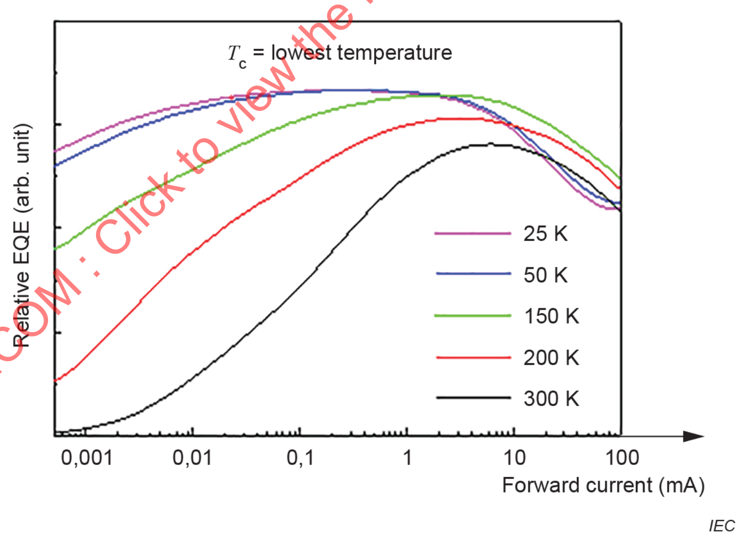



**Figure A.3 – Check $T_c$ in relative EQE curves (category 1)**

- Step 4: Evaluation of the relative EQE as shown in Figure A.4.

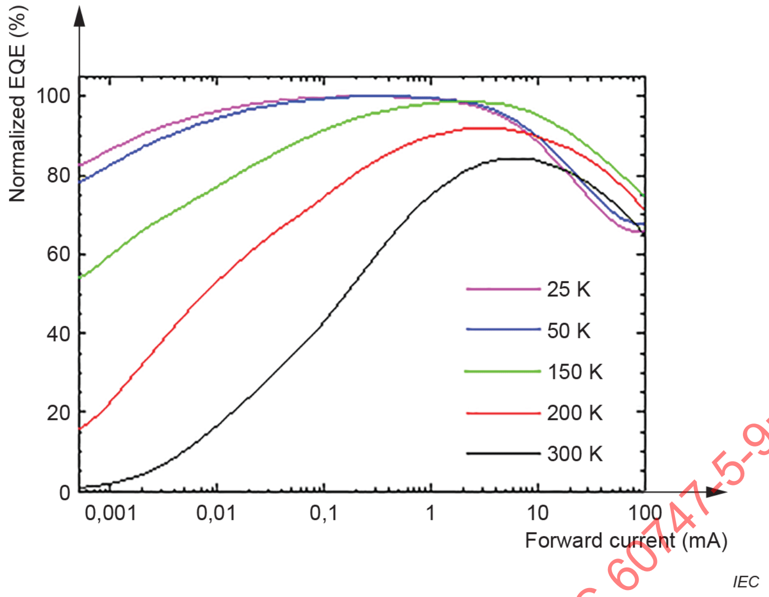



**Figure A.4 – Evaluation of the relative EQE (category 1)**

- Step 5: Check whether or not the absolute rate of change of the normalized peak EQE is less than or equal to 0,10 %/K between the lowest and the next lowest cryogenic temperatures. In Figure A.4, the absolute rate of change of the normalized EQE peak is less than 0,10 %/K between 25 K and 50 K.
- Step 6: Check whether or not the change of the normalized EQE obtained at $T_c$ is less than or equal to 1 % for currents twice and half the current level for the peak EQE point. In Figure A.4, the maximum EQE occurs at 0,2 mA at $T_c$ = 25 K. At 0,4 mA and 0,1 mA, the change in the normalized EQE is less than 1 %.
- Step 7: Normalized EQE data are the IQE data at an operating condition since the data passed both steps 5 and 6. The final IQE data are shown in Figure A.5.

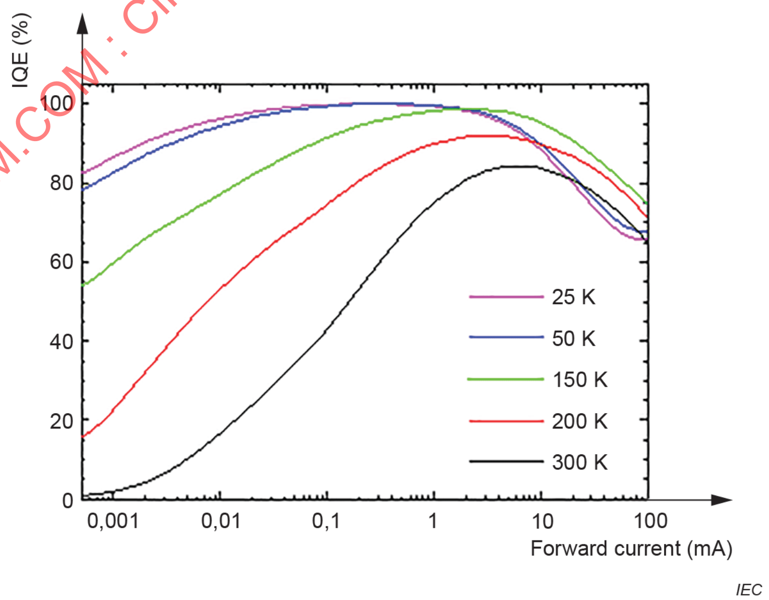



**Figure A.5 – IQE as a function of forward current at various temperatures including an operating temperature (category 1)**

## A.2 Test example (category 2)

- Step 0: Test environmental specifications
  - sample: A lateral-electrode type InGaN/GaN MQW LED grown on a *c*-plane sapphire substrate;
  - chip size: 740 µm × 600 µm;
  - peak wavelength: ~450 nm at $T$ = 293 K;
  - humidity: 50 % RH;
  - current driving condition: pulsed current driving condition (pulse period: 100 µs, duty cycle: 1 %);
  - detector for radiant power measurement: Si photodiode;
  - equipment for electrical characteristics measurement: Keithley semiconductor parameter analyser;
  - maximum driving current, $I_{max}$ = 450 mA;
  - total number of data points, $N$ = 100.
- Step 1: Measure the radiant power depending on temperature and current as shown in Figure A.6.

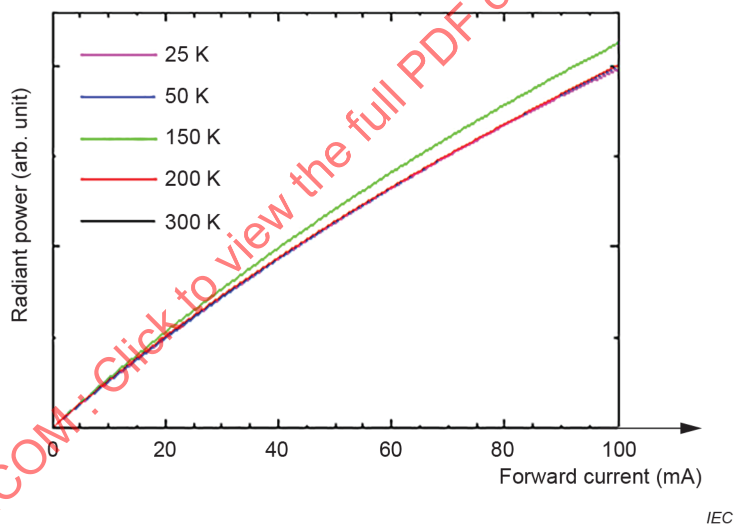



**Figure A.6 – Radiant power as a function of forward current at various temperatures (category 2)**

- Step 2: Draw a relative EQE curve as shown in Figure A.7.

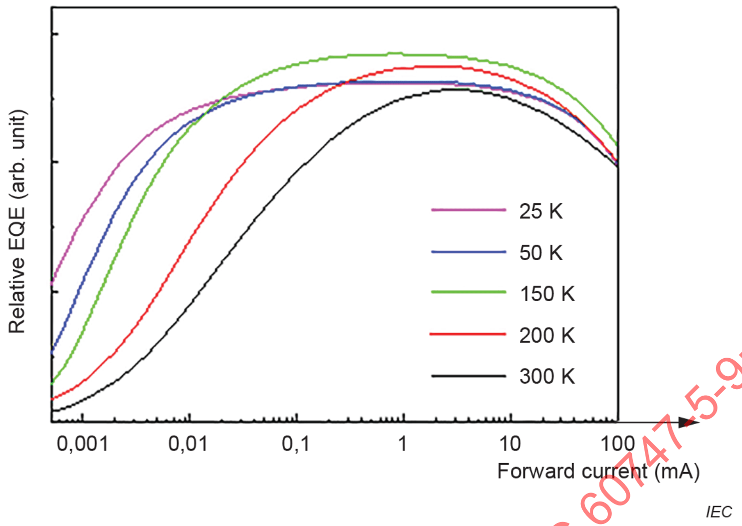



**Figure A.7 – Relative EQE as a function of forward current at various temperatures (category 2)**

- Step 3: Check $T_c$ as shown in Figure A.8. $T_c$ = 150 K in this example. Since $T_c$ is not the lowest temperature used, stop evaluation of the IQE.

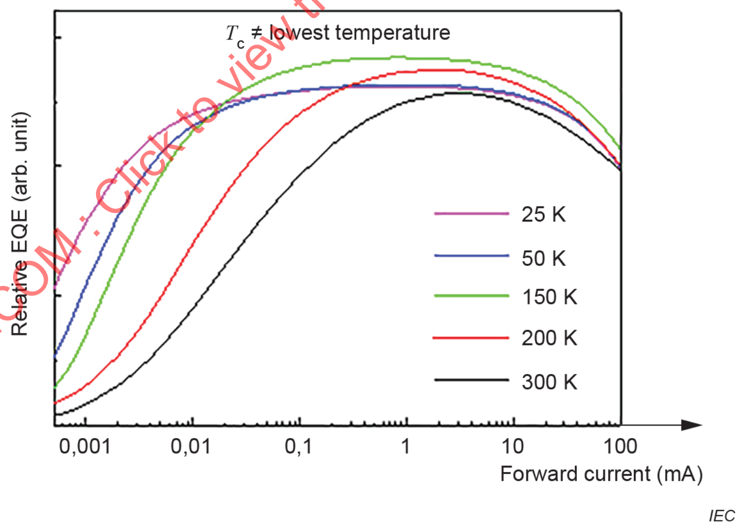



**Figure A.8 – Check $T_c$ in relative EQE curves (category 2)**