IEC 60747-5-15

Edition 1.0 2022-01

INTERNATIONAL STANDARD

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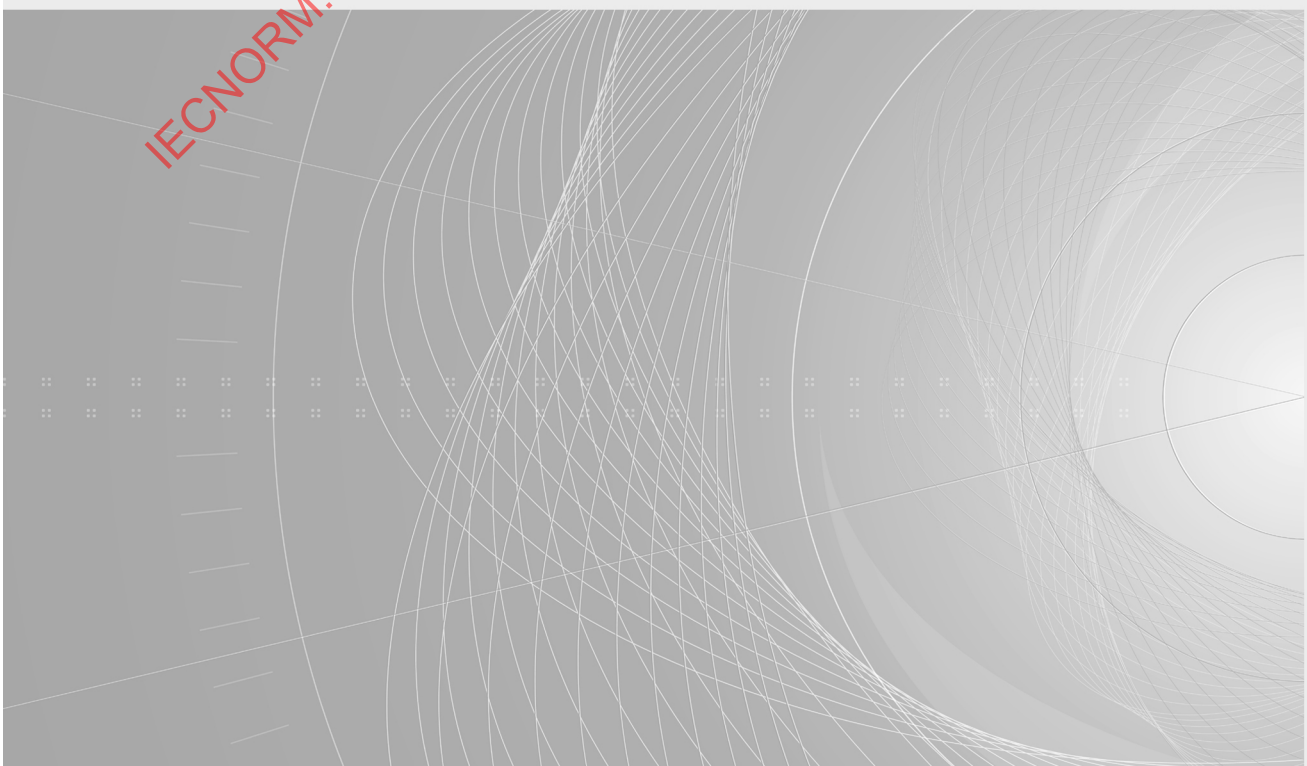
Semiconductor devices –
Part 5-15: Optoelectronic devices – Light emitting diodes – Test method of the flat-band voltage based on the electroreflectance spectroscopy



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INTERNATIONAL ELECTROTECHNICAL COMMISSION

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SEMICONDUCTOR DEVICES –

Part 5-15: Optoelectronic devices – Light emitting diodes – Test method of the flat-band voltage based on the electroreflectance spectroscopy

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IEC 60747-5-15 has been prepared by subcommittee 47E: Discrete semiconductor devices, of IEC technical committee 47: Semiconductor devices. It is an International Standard.

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

Draft	Report on voting
47E/737A/CDV	47E/764A/RVC

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 International Standard 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- withdrawn,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.

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SEMICONDUCTOR DEVICES –

Part 5-15: Optoelectronic devices – Light emitting diodes – Test method of the flat-band voltage based on the electroreflectance spectroscopy

1 Scope

This part of IEC 60747-5 specifies the measuring methods of flat-band voltage of single GaN-based light emitting diode (LED) die or package without phosphor, based on the electroreflectance (ER) spectroscopy. White LEDs for lighting applications are out of the scope of this part of IEC 60747-5.

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 60747-5-6:2021, *Semiconductor devices – Part 5-6: Optoelectronic devices – Light emitting diodes*

3 Terms, definitions and abbreviated terms

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 Terms and definitions

3.1.1
spectral reflectance
$R(\lambda)$
ratio of reflected radiant flux to incident radiant flux for a wavelength λ

Note 1 to entry: Spectral reflectance is also known as the "spectral reflection factor".

[SOURCE: IEC 60747-5-6:2021, 3.1.8]

3.1.2
flat-band voltage
V_{FB}
voltage at which the mean electric field across the wells can be considered to be zero

3.1.3
built-in voltage
V_{bi}
voltage built into the pn junction of the LED when no external voltage is applied

3.1.4
unintentionally doped width
d_u
width of the unintentionally doped layers in the LED

3.1.5
depleted width by V_{FB}
d_d
width of the layers depleted at V_{FB} excluding the unintentionally doped layers in the LED

3.1.6
total well width
d_w
total width of the wells in the LED

Note 1 to entry: If the width of the single quantum well is d and the number of quantum wells is N, then $d_w = N \cdot d$.

3.2 Abbreviated terms

LED light emitting diode
ER electroreflectance

4 Measuring methods

4.1 Basic requirements

4.1.1 Measuring conditions

a) Temperature

If not specified, measurements shall be made at an ambient (T_a) of (25 ± 3) °C in a condition of natural convection.

b) Humidity

When humidity condition is not specified, relative humidity shall be between 25 % RH and 75 % 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 may 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

Measuring instruments and equipment shall be the same as listed in 6.1.2 of IEC 60747-5-6:2021.

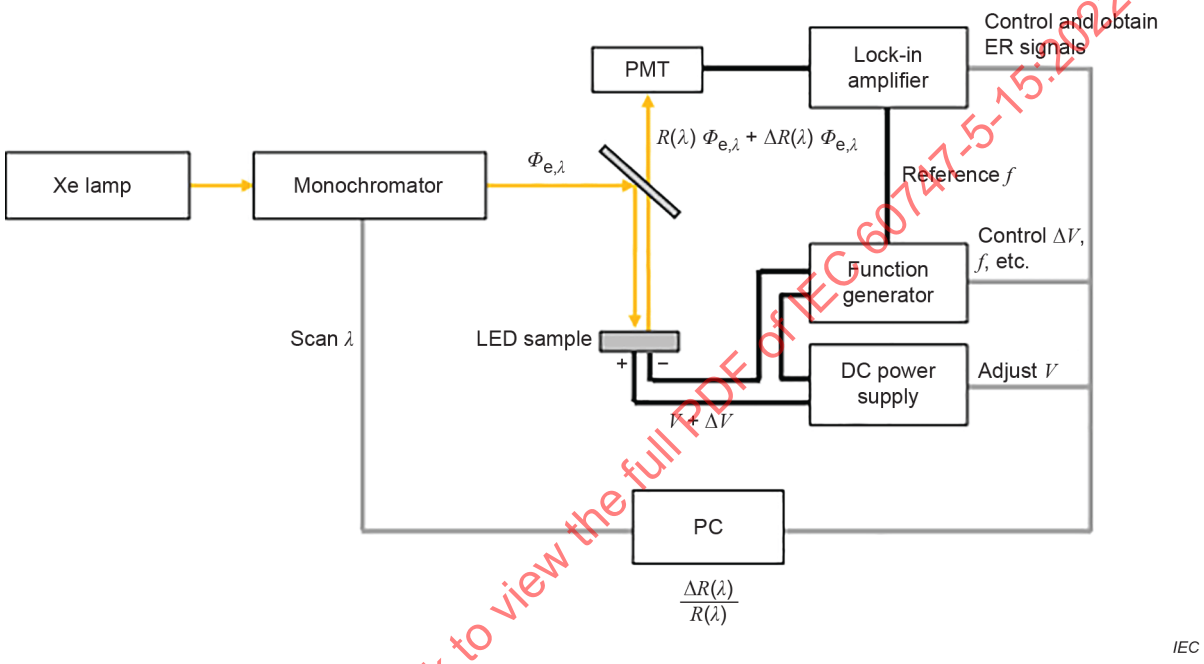
4.2 Purpose

To measure the internal electric field of the GaN-based LED die or package, the method needs the flat-band voltage. Once the flat-band voltage is obtained from the ER spectroscopy, the internal electric field is determined.

4.3 Measurement

4.3.1 Measurement setup

The measurement setup for the ER spectroscopy should be designed as shown in Figure 1 in principle. The input voltage to the LED sample is modulated by a function generator, i.e., the supplied voltage to the LED sample is V + ΔV, where V is the DC voltage and ΔV is the modulation voltage. Spectrally resolved light from a monochromator is incident on the LED sample. A photomultiplier tube measures the reflected light from the LED, $R(\lambda)\Phi_{e,\lambda} + \Delta R(\lambda)\Phi_{e,\lambda}$, and a lock-in amplifier amplifies the signal. The ratio of the modulated signal to the DC signal is the desired ER signal, $\Delta R(\lambda)/R(\lambda)$.



Key

$\Phi_{e,\lambda}$	spectral distribution
$R(\lambda)$	spectral reflectance at λ
PMT	photomultiplier tube
PC	personal computer

Figure 1 – Schematic diagram of the ER setup

4.3.2 Measurement principle

Near the flat-band voltage V_{FB}, the electric field in the quantum well in the active region of the GaN-based LED is close to zero and the response to the modulation voltage ΔV becomes minimal.

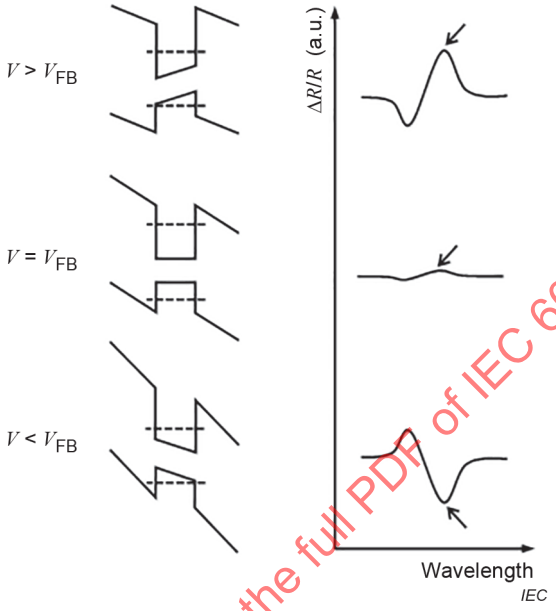
Theoretically, the ratio $\Delta R/R$ can be written as

$$\frac{\Delta R}{R} = \left[a\left(\frac{\delta E}{\delta F}\right) + b\left(\frac{\delta I}{\delta F}\right) + c\left(\frac{\delta \Gamma}{\delta F}\right)\right]\Delta F ,$$

where a, b, and c are fitting parameters, E, I, and Γ are the transition energy, the oscillator strength, and the broadening parameter. F is the electric field in the quantum well and ΔF is the modulated field due to ΔV. Near the flat-band voltage V_{FB}, changes in transition energy,

$\Delta R/R$ becomes minimal at V_{FB} [1][1].

Figure 2 schematically illustrates the quantum well and the ER signal $\Delta R/R$ under different DC voltages. $\Delta R/R$ at different bias voltages have been translated by a constant amount along the y-axis. It is seen that $\Delta R/R$ is inverted (or changes the phase) when the DC voltage is varied across V_{FB}. From this inversion in phase, V_{FB} is found from the ER spectroscopy.



Key

V	bias DC voltage
V_{FB}	flat-band voltage
$\Delta R/R$	electroreflectance signal

Figure 2 – Schematic illustration of the quantum well and the ER signal under different voltages

From V_{FB} thus found, the internal electric field F_{int} is determined using the following formula if the microscopic parameters such as d_u, d_d, and d_w are known [2], [3]:

$$F_{int} = \frac{V_{FB} - V_{bi}}{d_u + \frac{d_d}{2} - d_w}.$$

A typical value for V_{FB} is negative (i.e., reverse bias) in the case of GaN-based LEDs emitting blue or green wavelength. Consequently, the internal electric thus obtained field is given in negative value. The internal electric field thus found is from the p-side to the n-side.

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

4.3.3 Measurement sequence

The measurement should proceed according to the following sequential steps. A test example is given in Annex A.

- Step 0: Test environmental specifications

  All of the tests should be performed under well certified and defined conditions to avoid any external disturbances. An example of the test's environmental specifications is listed in Annex A.
- Step 1: Set a bias voltage for the ER measurement.
- Step 2: Measure the spectral reflectance $\Delta R/R$ as a function of wavelength. Plot $\Delta R/R$ vs. wavelength.
- Step 3: Check whether the phase inversion occurs in the plot of $\Delta R/R$ vs. wavelength.

  If the phase inversion has not occurred, decrease the bias voltage (i.e., more reverse bias) and go to step 2. If the phase inversion has occurred, go to step 4.
- Step 4: Find the flat-band voltage V_{FB}.

  Plot the peak value $\Delta R/R$ in as a function of bias voltage. To find the intercept point with the x-axis, interpolate the data if necessary.
- Step 5 (optional): Calculate the internal electric field.
- Step 6: Create the test report.

Figure 3 summarizes the measurement sequence of the internal electric field in the GaN-based LED.

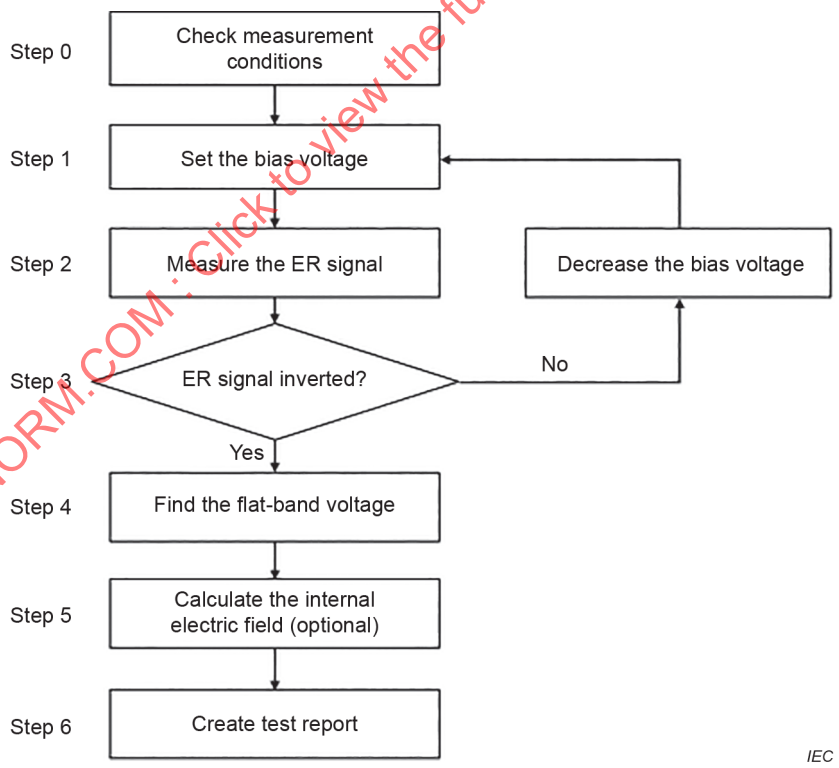


Figure 3 – Sequence of the measurement of the flat-band voltage

5 Test report

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

Annex A
(informative)

Test example

- Step 0: Test environmental specifications
  - sample: An InGaN/GaN multiple-quantum-well LED grown on a c-plane sapphire substrate;
  - die size: 800 µm × 800 µm;
  - peak wavelength: ~440 nm at T = 25 °C;
  - humidity: 50 % RH;
  - modulation frequency f: 500 Hz;
  - modulation voltage ΔV: 100 mV (peak-to-peak);
- Step 1: Set a bias voltage V.
- Step 2: Measure the spectral reflectance $\Delta R/R$ from the ER spectroscopy.

  Plot the spectral reflectance $\Delta R/R$ vs. wavelength.
- Step 3: Check whether the phase inversion occurs in the plot of $\Delta R/R$ vs. wavelength.

  Decrease the bias voltage and repeat Steps 1 and 2 until the phase inversion occurs.

  Figure A.1 shows the result of the ER spectroscopy at different bias voltages. The arrow indicates the peak in the ER signal to check the phase inversion. The phase inversion occurs between −10 V and −11 V. Several more bias voltages have been used after the phase inversion to highlight the changes.

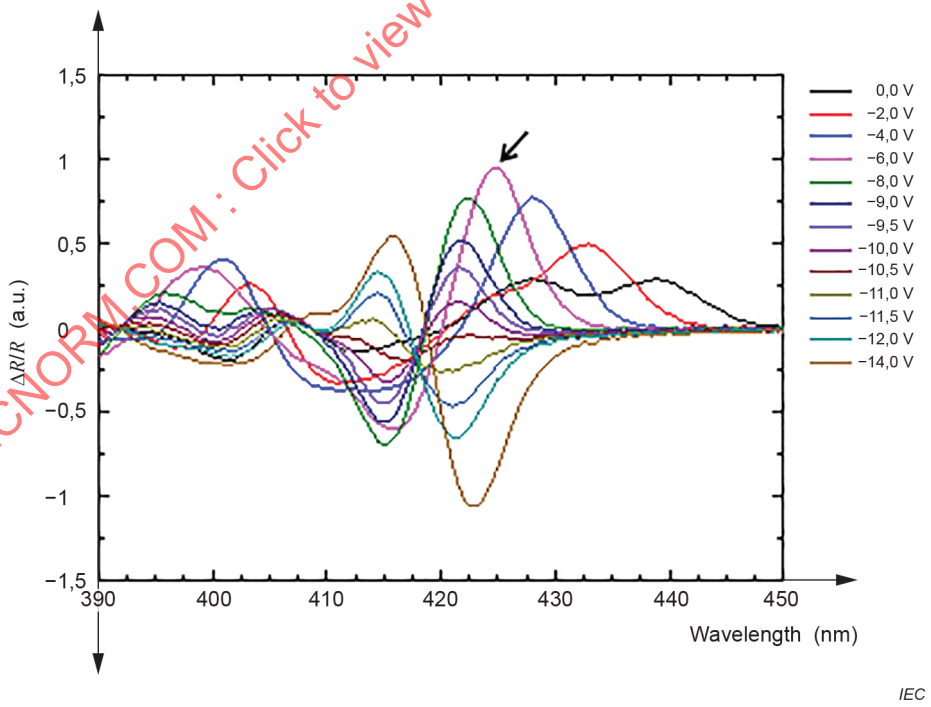
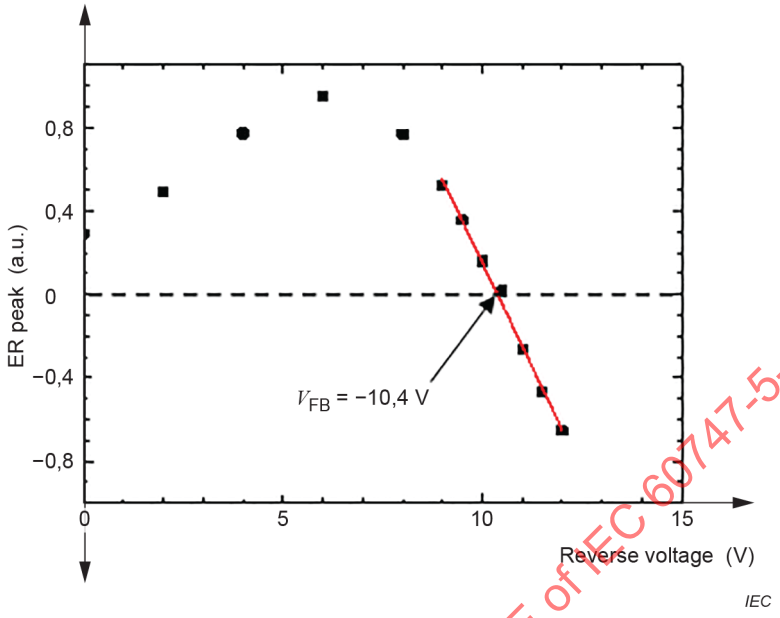


Figure A.1 – $\Delta R/R$ versus wavelength at different bias voltages

- Step 4: Plot the magnitude of the ER peak versus bias voltage.

  As shown Figure A.2, interpolate to find the x-intercept if necessary and identify the flat-band voltage V_{FB}.



Key

ER electroreflectance

V_{FB} flat-band voltage

Figure A.2 – ER peak as a function of reverse-bias voltage

- Step 5: Calculate the internal electric field.

  The parameters for this sample are d_u = 112,3 nm, d_w = 19,2 nm, and d_d = 18,4 nm with V_{FB} = −10,4 V and V_{bi} = 3,3 V. Using the following formula:

$$F_{int} = \frac{V_{FB} - V_{bi}}{d_u + \frac{d_d}{2} - d_w},$$

  the internal electric field is F_{int} = −1,32 MV/cm.

- Step 6: Create the test report.

Table A.1 – Summary of test report

Item	Unit	Value	Comment
LED maker	-		Specify the name of the company
Model name	-		Specify the model name
Die size	μm x μm		
Package type	-		Ex. SMD
Peak wavelength	nm		
Operating temperature	°C		
Humidity	% RH		
Modulation frequency	Hz		
Modulation voltage	mV		
Flat-band voltage	V		
d_u	nm		
d_d	nm		
d_w	nm		
Internal electric field	MV/cm		