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INTERNATIONAL STANDARD

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Semiconductor devices –
Part 5-16: Optoelectronic devices – Light emitting diodes – Test method of the flat-band voltage of GaN-based light emitting diodes based on the photocurrent spectroscopy

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IEC Secretariat
3, rue de Varembé
CH-1211 Geneva 20
Switzerland

Tel.: +41 22 919 02 11
info@iec.ch
www.iec.ch

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

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SEMICONDUCTOR DEVICES –

Part 5-16: Optoelectronic devices – Light emitting diodes – Test method of the flat-band voltage of GaN-based light emitting diodes based on the photocurrent spectroscopy

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

Draft	Report on voting
47E/788/CDV	47E/797/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/publications.

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SEMICONDUCTOR DEVICES –

Part 5-16: Optoelectronic devices – Light emitting diodes – Test method of the flat-band voltage of GaN-based light emitting diodes based on the photocurrent spectroscopy

1 Scope

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

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*

IEC 60747-5-15:2022, *Semiconductor devices – Part 5-15: Optoelectronic devices – Light emitting diodes – Test method of the flat-band voltage based on the electroreflectance spectroscopy*

3 Terms, definitions and abbreviated terms

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

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

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

3.1 Terms and definitions

3.1.1
spectral radiant flux
$\Phi_{e,\lambda}(\lambda)$

radiant flux per unit wavelength interval at a given wavelength (λ)

Note 1 to entry: Spectral radiant flux is typically denoted by Φ_λ, which is equivalent to $d\Phi/d\lambda$, and is usually expressed in units of watts per nm.

[SOURCE: IEC 62607-3-1:2014 [1][1], 3.20, modified – A symbol has been added.]

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

3.1.2
spectral photocurrent
$I_{\mathrm{ph},\lambda}(\lambda)$

photocurrent per unit wavelength interval at a given wavelength (λ)

Note 1 to entry: Spectral photocurrent is expressed in amperes per nm.

3.1.3
PC signal
spectral photocurrent divided by the spectral radiant flux of the radiation source, which is expressed as a function of wavelength λ, i.e., $I_{\mathrm{ph},\lambda}(\lambda)/\Phi_{e,\lambda}(\lambda)$

3.1.4
differential PC signal
difference between the adjacent PC signals divided by the wavelength step

3.1.5
peak slope
absolute value of the extremum in the differential PC signal

3.1.6
quantum well
potential well which enables quantum confinement of particles in one dimension

[SOURCE: IEC 60050-511:2018 [2], 511-02-09, modified – The note to entry has been removed.]

3.1.7
flat-band voltage
V_{FB}
voltage at which the mean electric field across the wells can be considered to be zero

[SOURCE: IEC 60747-5-15:2022, 3.1.2]

3.2 Abbreviated terms

LED light emitting diode

PC photocurrent

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.

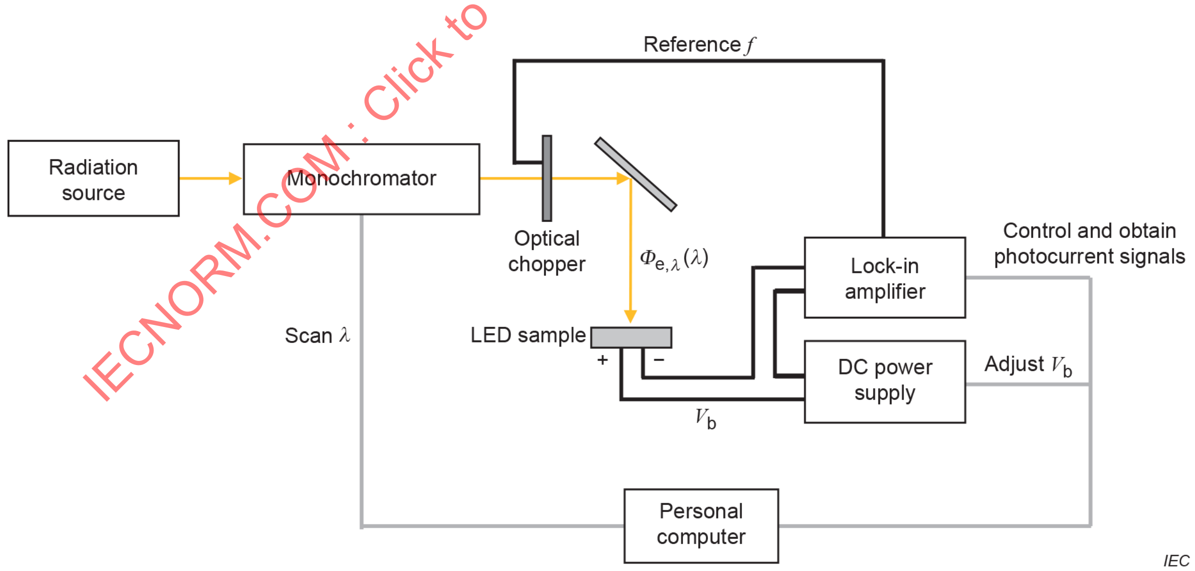
4.2 Purpose

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 PC spectroscopy, the internal electric field is determined if desired.

4.3 Measurement

4.3.1 Measurement setup

The measurement setup for the PC spectroscopy can be designed as shown in Figure 1. Spectrally resolved radiation from a monochromator is modulated by an optical chopper supplied with a reference frequency from a lock-in amplifier. The modulated radiation is incident on the LED sample and a signal from the LED sample is registered by the lock-in amplifier. The spectral radiant flux of the radiation source is measured separately from the monochromator. The spectral photocurrent is the ratio of the signal obtained by the lock-in amplifier to the spectral radiant flux of the radiation source, $I_{ph,\lambda}(\lambda)/\Phi_{e,\lambda}(\lambda)$. The DC power supply changes the bias voltage to the LED sample and a personal computer automates the measurement and collects the data.



Key

$\Phi_{e,\lambda}(\lambda)$ spectral radiant flux

V_b bias voltage

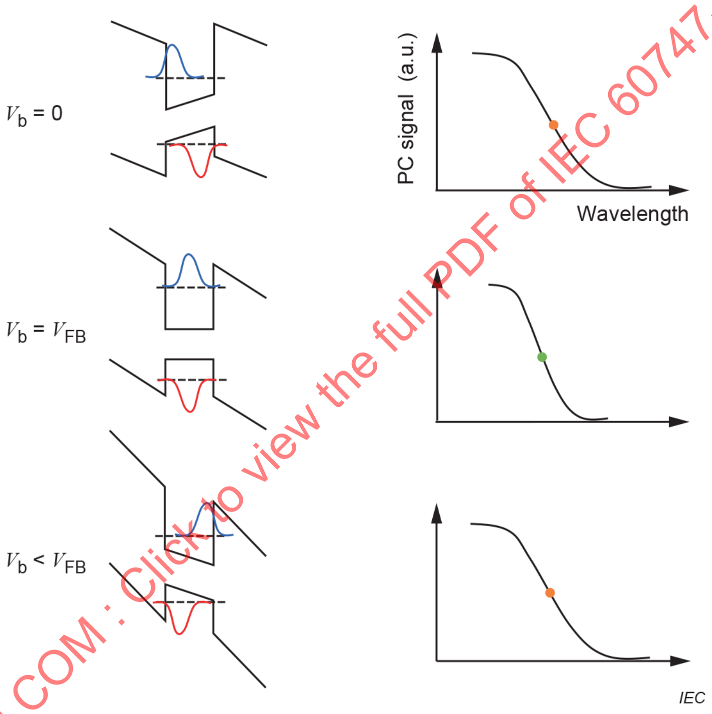
Figure 1 – Schematic diagram of the PC spectroscopy setup

4.3.2 Measurement principle

Near the flat-band voltage VFB, the electric field in the quantum well in the active region of the GaN-based LED is close to zero and the PC signal shows the steepest slope near the absorption edge. When there exists an electric field in the quantum well, the absorption near the effective band edge is broadened due to the quantum-confined Stark effect (QCSE) [3]. Consequently, the absolute slope of the PC signal should exhibit the maximum value at V_{FB}.

Figure 2 schematically illustrates the quantum well and the PC signal under different bias voltages. It is seen that each PC signal has a point of steepest slope (or the peak slope), marked by a dot. Figure 3 schematically depicts how the differential PC signal behaves under different bias voltages. When the bias voltage equals the flat-band voltage, the peak slope becomes the maximum as shown in Figure 4.

A typical value for V_{FB} is negative (i.e., reverse bias) in the case of GaN-based LEDs emitting blue or green wavelength.



Key

V_b bias voltage

V_{FB} flat-band voltage

Dotpeak slope

Figure 2 – Schematic illustration of the InGaN/GaN quantum well and the PC signal under different bias voltages

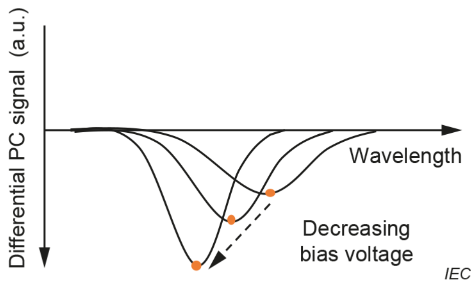


Figure 3 – Schematic illustration of how the differential PC signal behaves as the bias voltage is decreased

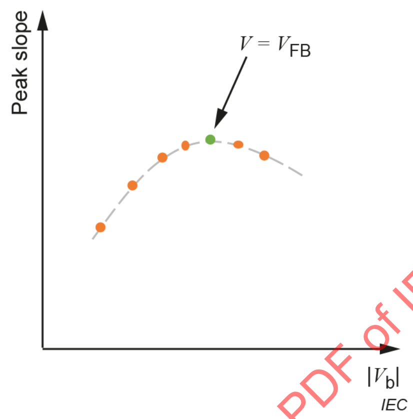


Figure 4 – Schematic illustration of the peak slope as a function of bias voltage

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. Since the modulated signal is detected by a lock-in amplifier, the effect of the background illumination is suppressed and can be neglected in general. However, if minimizing the effect of the background illumination is further desired, the measurement can be conducted in a dark box.

– Step 1: Measure the spectral radiant flux of the radiation source. Either a spectrometer or a power meter after the monochromator can be used. In order to avoid saturation in the quantum wells, it is desirable to check whether a spectral photocurrent is increased by the same factor as the increase in spectral radiant flux, i.e., $I_{\text{ph},\lambda}(\lambda)/\Phi_{e,\lambda}(\lambda)$ is constant at a certain λ.

– Step 2: Set a bias voltage for the PC measurement.

– Step 3: Measure the PC signal.

  Measure first the spectral photocurrent as a function of wavelength. Plot the PC signal vs. wavelength after dividing the spectral photocurrent by the spectral radiant flux of the radiation source, i.e., $I_{\text{ph},\lambda}(\lambda)/\Phi_{\text{e},\lambda}(\lambda)$.

– Step 4: Plot the differential PC signal vs. wavelength.

– Step 5: Check whether the peak slope in the differential PC signal vs. wavelength decreases.

If the peak slope has not decreased, decrease the bias voltage (i.e., more reverse bias) and go to step 2. A bias step of 1 V to 2 V is typically used. If the peak slope has decreased, go to step 6.

– Step 6: Increase the bias voltage (i.e., less reverse bias) so that one may measure at the intermediate biases around the maximum peak slope to improve the accuracy.
– Step 7: Repeat steps 2, 3, and 4 until the desired accuracy in bias voltage is satisfied. To improve the accuracy, one needs to bisect the bias step around the maximum peak slope and find any new maximum.
– Step 8: Find the flat-band voltage V_{FB} from the bias that gives the maximum peak slope.
– Step 9: Create the test report.

Figure 5 summarizes the measurement sequence of the internal electric field in the GaN-based LED.

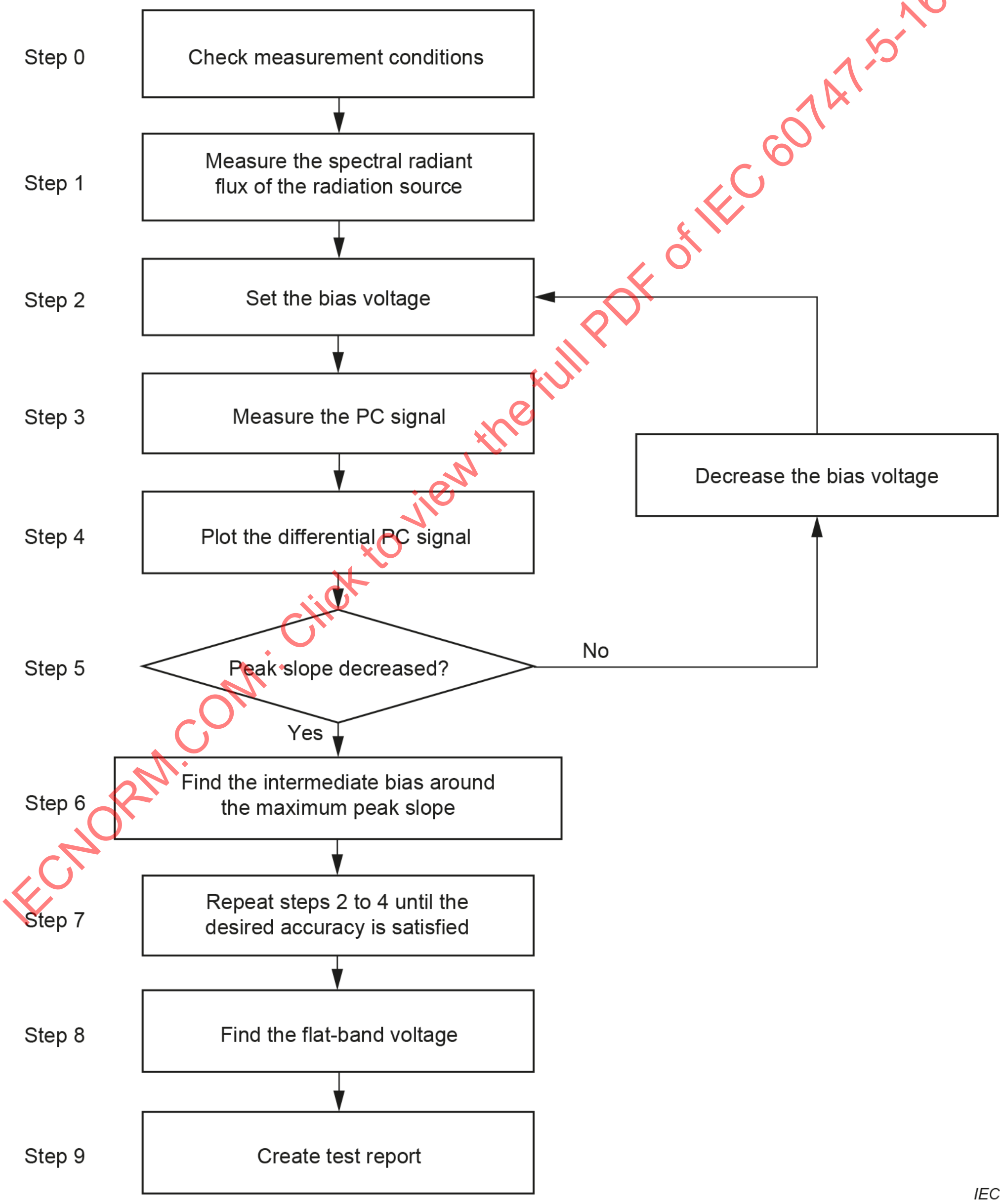


Figure 5 – Sequence of the measurement of the flat-band voltage using the PC spectroscopy

5 Test report

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

For comparison of the PC and ER spectroscopies for obtaining the flat-band voltage, refer to Annex B.

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: 400 Hz

– Step 1: Measure the spectral radiant flux of the radiation source.

Figure A.1 shows the spectral radiant flux of the Xe lamp in the wavelength range of interest.

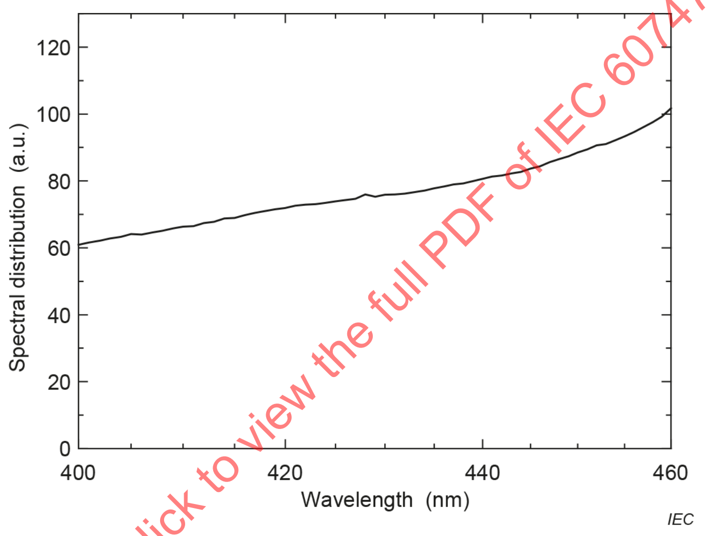


Figure A.1 – Spectral radiant flux of the Xe lamp

– Step 2: Set a bias voltage for the PC measurement.

– Step 3: Measure the PC signal.

Plot the PC signal vs. wavelength after dividing the spectral photocurrent by the spectral radiant flux of the radiation source.

– Step 4: Plot the differential PC signal vs. wavelength.

– Step 5: Check whether the peak slope in the differential PC signal vs. wavelength decreases. If not, decrease the bias voltage and repeat Steps 2, 3 and 4 to find the maximum.

– Steps 6 and 7: Repeat steps 2, 3, and 4 to improve the accuracy by reducing the bias steps around the maximum peak slope.

Figure A.2 depicts the result of the PC spectroscopy at different bias voltages after dividing the spectral radiant flux of the radiation source. The differential PC signal is given in Figure A.3.

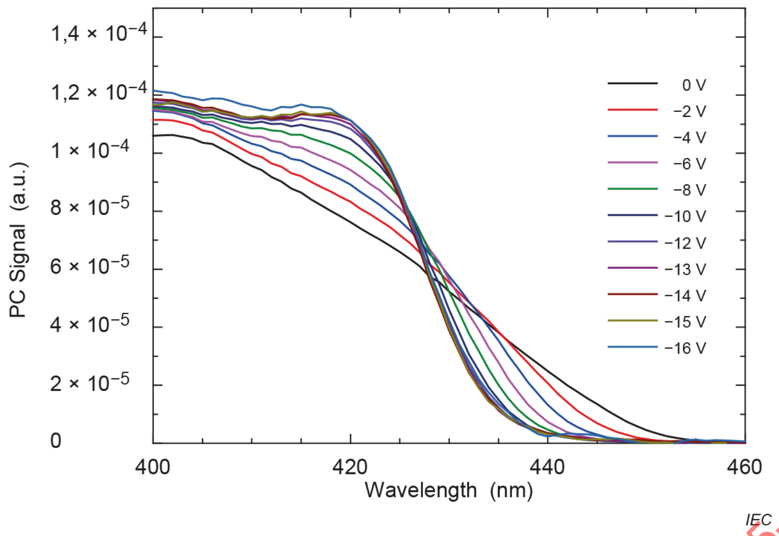


Figure A.2 – PC signal vs. wavelength at different bias voltages

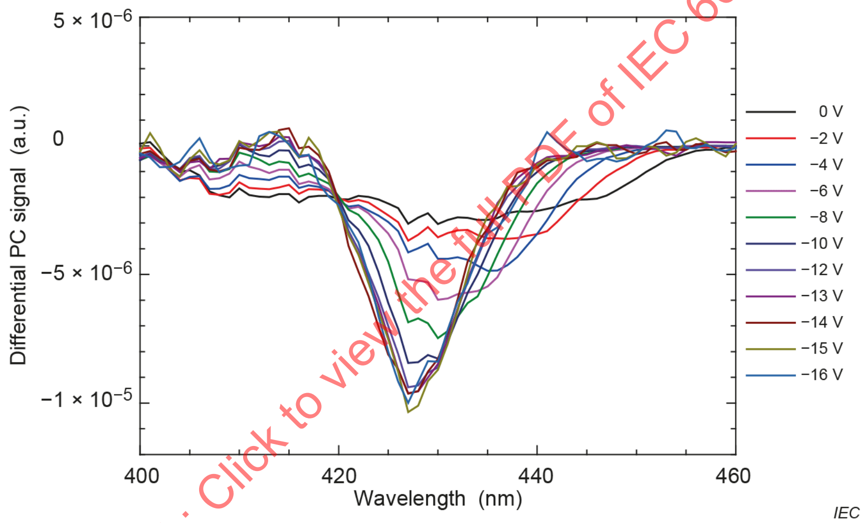


Figure A.3 – Differential PC signal vs. wavelength at different bias voltages

– Step 8: Find the flat-band voltage VFB after plotting the peak slope as a function of reverse-bias voltage.

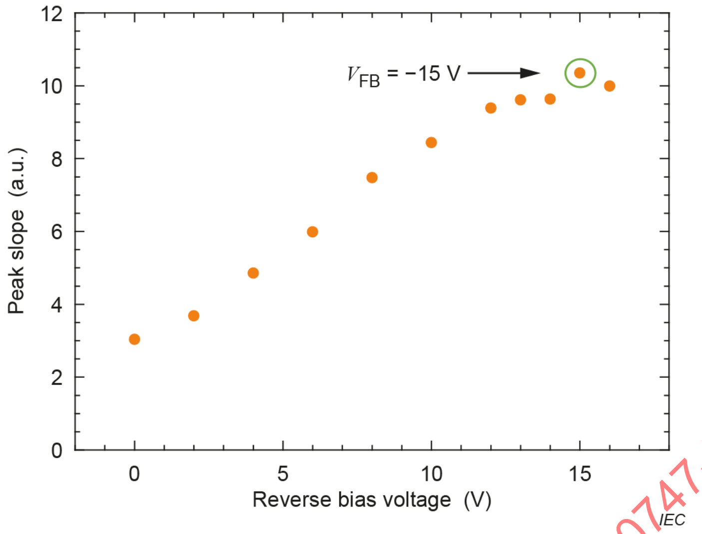


Figure A.4 – Peak slope as a function of reverse-bias voltage

– Step 9: 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		
Flat-band voltage	V		

Annex B
(informative)

Comparison of PC and ER spectroscopies

The PC spectroscopy measures the change in absorption coefficient while the ER measures the change in refractive index. Thus, theoretically, the PC and ER spectroscopic data are not independent and connected by the Kramers-Kronig relations. Consequently, in principle, one can calculate the one data set from the other using the Kramers-Kronig relations [4].

In reality, the actual calculation involves errors associated with the limited measurement spectral range and the assumptions of ideal conditions entailed during calculations. Also, the LEDs based on the InGaN/GaN quantum wells grown on the c-axis typically require relatively high reverse-bias voltages to achieve the flat-band condition, where the internal electric field the quantum wells experience becomes zero. Any leakage current caused by the high reverse-bias voltage can aggravate the error.

Each spectroscopic method requires a similar but still slightly different measurement setup. Other than the radiation source such as a Xe lamp and a monochromator for spectroscopy, the ER spectroscopy requires a function generator to modulate the LED sample and the high-sensitivity photodetector such as a photomultiplier tube (PMT) to detect the modulated reflectance from the LED sample in 4.3 of IEC 60747-5-15:2022. A lock-in amplifier is connected to the PMT to register the modulated signal to suppress the noise.

The PC spectroscopy also requires a radiation source, a monochromator, and a lock-in amplifier to collect the signal with suppressed noise. However, contrary to the ER spectroscopy, the PC spectroscopy measures the photocurrent generated by the LED sample. Thus, a high-sensitivity photodetector to measure the reflectance from the LED sample is not required, which is a big advantage for the PC spectroscopic experimental setup. Since the modulation is made by the optical chopper to the incident optical beam in the PC spectroscopy, a function generator is not required, either.

For the simplicity in the experimental setup, often the PC spectroscopy is preferred to the ER spectroscopy. However, after the measurement is done, one shall process the data to obtain the necessary information, which is the flat-band voltage in this case. In determining the flat-band voltage, the PC spectroscopy tracks the peak slope, which requires a mathematical operation of taking the differential from the experimental data. On the other hand, the ER spectroscopy only follows the peak value in the ER data without requiring any further mathematical operation, which makes the extraction of the necessary information simpler than the PC spectroscopy.

The final data required to determine the flat-band voltage have different properties, too. The final data for the PC spectroscopy are the peak slopes as a function of the bias voltage as seen in Figure A.4. The bias voltage where the maximum is achieved is sought in the PC spectroscopy from the graph such as shown in Figure A.4. Finding a systematic way of determining where the maximum occurs seems to require an additional fitting using a polynomial function, which is not desired for the ease and simplicity of the method. Therefore, one simply reads the bias voltage where the maximum occurs, making the accuracy of the method based on the PC spectroscopy be the voltage step used in the experiment.

On the other hand, the final data in the ER spectroscopy, which is the peak value in the ER signal, crosses zero as the bias voltage is changed. Shown in Figure B.1 is the ER signal as a function of bias voltage for the same LED sample used for the PC measurement shown in Annex A. From Figure B.1, the peak values are obtained and plotted as a function of bias voltage in Figure B.2. The phase inversion in Figure B.1 is represented by zero crossing in Figure B.2. Finding the bias voltage where the zero crossing occurs can be achieved rather simply by linear interpolation. For the case shown in Figure B.2, the flat-band voltage of -15,1 V is thus obtained. In this way, the ER measurement can overcome the disadvantage from a little more complex measurement step.