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INTERNATIONAL STANDARD

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Semiconductor devices –
Part 5-14: Optoelectronic devices – Light emitting diodes – Test method of the surface temperature based on the thermoreflectance method

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

Draft	Report on voting
47E/773/FDIS	47E/784/RVD

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

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- withdrawn,
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SEMICONDUCTOR DEVICES –

Part 5-14: Optoelectronic devices – Light emitting diodes – Test method of the surface temperature based on the thermoreflectance method

1 Scope

This part of IEC 60747-5 specifies the measuring method of the surface temperature of single LED die or package, based on the thermoreflectance (TR) method. TR is the effect that the reflectance of light changes with the temperature of a substance. This part measures relative change in the reflectance of light from a metal film deposited nearby on the metallurgical pn junction as the relative change in the LED junction temperature. The surface temperature can be approximated as the junction temperature when the thermal resistance effect between the metal surface and the pn junction is negligibly small.

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 terms and definitions given in IEC 60747-5-6 and the following 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
sample
measurement object consisting of an LED die and a metal (or any reflective) film formed on the surface of the LED die or package

3.1.2
ambient temperature
T_a
temperature at or near the metal film specified for the purpose of the TR method

3.1.3
beam diameter
light beam diameter for TR measurement applied to the thin metal film

Note 1 to entry: If the light intensity has a Gaussian distribution, the diameter of the circle represented by the envelope of $1/e^2$ of the maximum intensity.

3.1.4
standard metal film
metal bulk film whose reflectance of light is specified for the purpose of calibrating equipment or correcting measured values using the principle of the TR method

3.1.5
thermoreflectance
effect that the reflectance of light changes with the temperature of a substance

3.1.6
thermoreflectance method
optical technique for measuring the relative change in surface reflectance ($\Delta R/R$) due to a change in local surface temperature (ΔT) of a particular sample

Note 1 to entry: As the temperature of the sample changes, so does the index of refraction, and hence the reflectance. In general, the linear relationship between the change in reflectance and the change in temperature can be approximated.

3.1.7
thermoreflectance coefficient
C_{TR}
first order relationship between the change in the reflectance and the change in temperature

Note 1 to entry: For most metals and semiconductor materials of interest, the relationship between the relative change in reflectance and the change in temperature is linear over a measured temperature range and is quantified by the thermoreflectance coefficient, C_{TR} (K^{-1}).

$$C_{\text{TR}} = \frac{1}{R}\frac{\partial R}{\partial T}$$

where R is the reflectance of light at a surface temperature T_{s}. For the light normally incident on the sample, the thermoreflectance coefficient can be used to express the reflectance light intensity as follows:

$$C_{\text{TR}} = \frac{1}{R}\frac{\partial R}{\partial T} = \frac{1}{I_n}\frac{\partial I_n}{\partial T}$$

where I_{n} is the normally reflected intensity at a surface temperature T_{s}.

3.1.8
surface temperature
T_{s}
temperature of the material, such as the bulk metal film, at the point where the light reflectance is measured based on the TR method

3.1.9
reference temperature
T_0
surface temperature of the sample when the reflectance change is zero

Note 1 to entry: As the reference temperature, the ambient temperature of the sample in thermal equilibrium is used.

3.1.10
junction temperature
T_j
temperature of the semiconductor pn junction of the LED die

Note 1 to entry: The junction temperature is in principle different from the surface temperature. The junction temperature is in general approximated by the surface temperature. If necessary, it can be more accurately obtained by using the power dissipation and thermal resistance between the surface of the sample and the pn junction.

Note 2 to entry: The measurement of the junction temperature and thermal resistance are listed in 6.7 of IEC 60747-5-6:2021.

3.2 Abbreviated terms

LED light emitting diode

TR thermoreflectance

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 steady-state condition. Thermal steady-state condition 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 surface temperature at an operating current of the LED die or package by using a noncontact technique of the TR method [1][1]. The TR method is especially useful in the following cases:

a) the die size is very small, like a micro LED, so even small probe electrical signals can disturb the actual junction temperature value;
b) the linear relationships between the junction voltage and the forward voltage are not guaranteed, such as very high injection current density for high radiant power and high operating temperature.

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

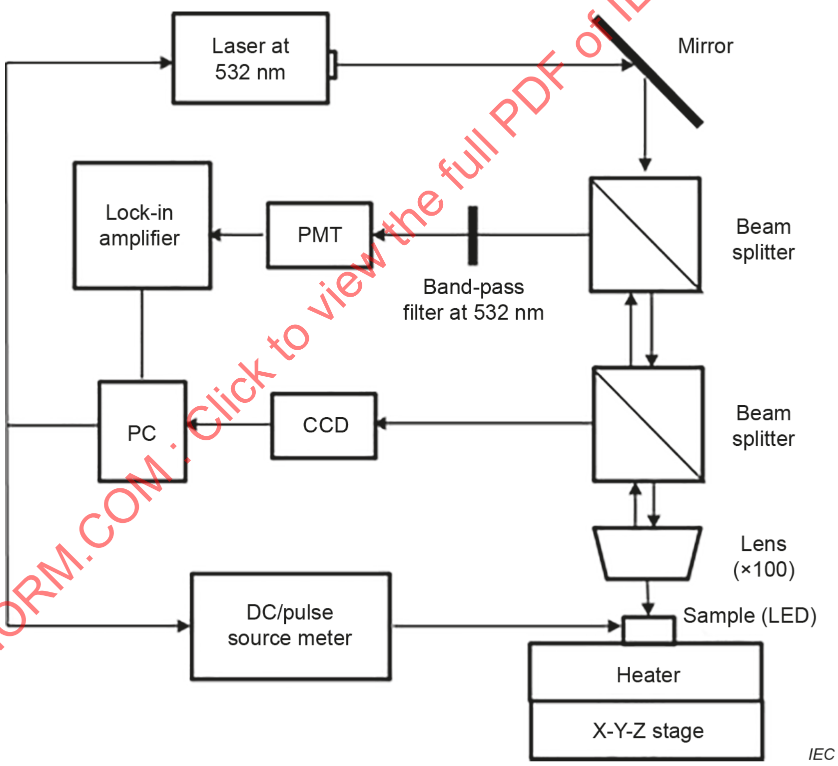
4.3 Measurement

4.3.1 Measurement setup

4.3.1.1 General

All the test should be performed under the well certified and defined conditions to avoid any external disturbances. The LED sample at a constant ambient temperature is driven by forward current and the TR measurement is performed under steady state. Basic characteristic measurements of the LED sample such as current, voltage, spectrum, and radiant power are the same as listed in IEC 60747-5-6:2021.

Figure 1 shows a configuration example of an apparatus using the principle of the TR method. The sample is placed on a hot-plate with good temperature control that is large enough for the sample size. As a light source, a 532 nm laser, which is most sensitive to Au metal, is used. The laser beam is focused on a point as close as possible, within a recommended value of 500 µm, to the region where heat is generated in the LED die so that the thermal resistance between them can be ignored. A photomultiplier tube (PMT) is used as the light-receiving element, and the sensitivity of reflectance measurement is increased by using a lock-in amplifier synchronized with the laser beam pulse. The configuration shown in this figure is the most basic, and a multiple of configurations can be adopted depending on the type of light source or detector used.



Key

CCD charge-coupled device

PMT photomultiplier tube

PC personal computer

Figure 1 – Schematic diagram of the TR setup

4.3.1.2 Light source

A laser or a LED can be used as the light source for the TR measurement. Continuous or pulsed light is used to measure the temperature with the TR method. Periodic light pulses combined with a lock-in amplifier are preferred to reduce reflectance measurement errors. The radiant power of the light source represents the average value. The radiant power density of the light on the surface of the metal film is selected from the viewpoints of suppressing the temperature rise due to light absorption during the reflectance measurement and obtaining a sufficient signal-to-noise ratio.

4.3.1.3 Detector

A photodetector having sensitivity to the wavelength of the light source for temperature measurement is used. The photomultiplier tube (PMT) in the spectral range can be used from ultraviolet to near-infrared.

4.3.1.4 Temperature heating system

The sample is placed in a thermal chamber or on a hot plate operating at a constant ambient temperature. As a result, the sample without current injection is in thermal equilibrium with ambient temperature.

4.3.2 Measurement principle

4.3.2.1 General

A LED sample with an exposed metal film, the C_{TR} value of the metal film, the reference temperature T_0, and the reflectance R from the metal film at the reference temperature are investigated before applying the TR method.

By increasing the forward current to the LED die at a constant ambient temperature T_{a}, the surface temperature T_{s} of the metal film rises and arrives at the steady state. The heat spreads and the temperature distribution in the metal surface becomes uniform. The reflectance R of the surface of the metal film changes with a change in temperature due to the thermoreflectance effect. Therefore, by measuring the relative change in surface reflectance ($\Delta R/R$) of the light beam and using the reference temperature, it is possible to measure absolute values of the surface temperature as a function of forward current. Finally, the junction temperature is approximated by the same value of the surface temperature. Figure 2 schematically illustrates how the thermoreflectance coefficient is measured and utilized to obtain the surface temperature and the junction temperature. Condition for approximating the measured surface temperature to the junction temperature will be given in 4.3.2.6.

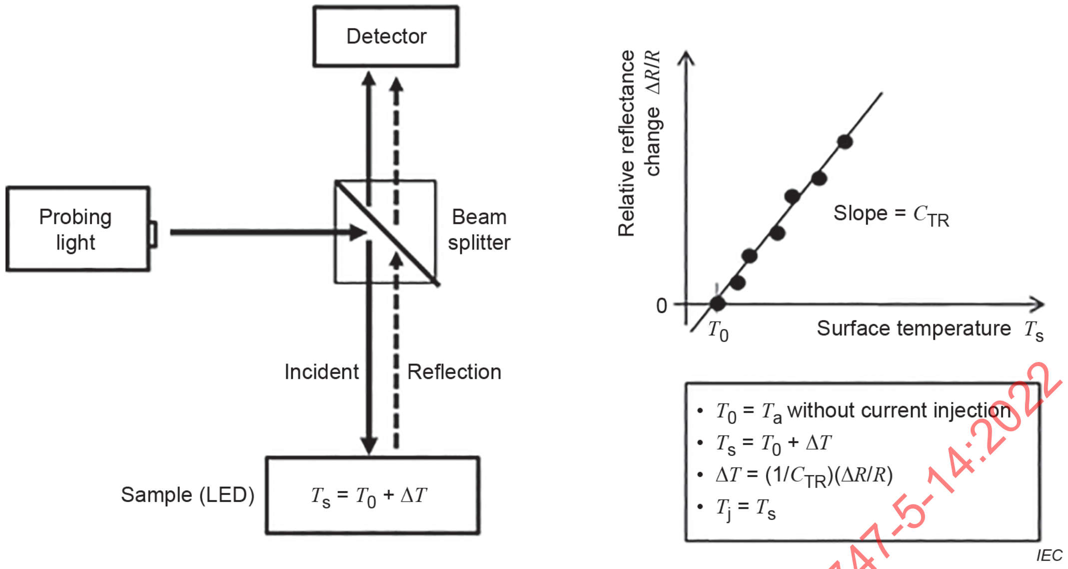


Figure 2 – Schematic illustration of measuring the thermoreflectance coefficient, surface temperature, and junction temperature by the TR effect

4.3.2.2 Ambient temperature measurement

The sample is placed in a thermal chamber or on a hot plate operating at a constant temperature so that the sample is in thermal equilibrium during the ambient temperature measurement. The temperature of the environment is measured by a temperature-measuring device such as thermocouple. The measurement of temperature is carried out in a place as close as possible to the sample. Ambient temperature of the sample can be controlled by varying the temperature of the thermal chamber or the hot plate with high thermal mass.

4.3.2.3 Reference temperature measurement

The sample under no current injection is in thermal equilibrium during the reference temperature measurement. The reference temperature is set to an ambient temperature. Once the reference temperature of the sample is set, the subsequent TR method should be performed at the place.

4.3.2.4 Thermoreflectance coefficient measurement

The thermoreflectance coefficient is a basic material property that depends on illumination wavelength, ambient temperature, and material surface properties. It is also influenced by the measurement apparatus such as the magnification and numerical aperture of the optics. Thus, the thermoreflectance coefficient is recommended to be calibrated for each experimental setup. In order to achieve the best temperature resolution, it is necessary to use an accurate value for the thermoreflectance coefficient and choose an illumination wavelength that provides a thermoreflectance coefficient close to the maximum value of the material to be analyzed.

The sample is in thermal equilibrium during the thermoreflectance coefficient measurement at different ambient temperatures. The surface temperature of the metal film used for the TR measurement is equal to ambient temperature.

The reflectance of light from the metal film is measured with changing ambient temperature, i.e., the surface temperature. The value of the measured reflectance need not be absolute. When the surface temperature changes slightly from T to $T + \Delta T$, the reflectance changes from R to $R + \Delta R$. Then, the thermoreflectance coefficient is calculated at T as $\Delta R/R$. The thermoreflectance coefficient of the metal bulk film is theoretically a function of temperature T, but experimentally exhibits a constant value over a wide temperature range from room temperature to several hundred degrees Celsius. In most cases, it is recommended to use the average value within the range of use to reduce the experimental error due to surface temperature.

4.3.2.5 Surface temperature measurement

The surface temperature of the metal film is measured by the TR method on the sample operating in steady state. The surface temperature is obtained by calculating a change in temperature at a known reference temperature.

$$T_s = T_0 + \Delta T = T_0 + \frac{1}{C_{TR}} \frac{\Delta R}{R}$$

where R is the reflectance of light at the reference temperature T_o, ΔT and ΔR are changes of temperature and reflectance from T_0 and R, respectively.

When light is normally incident on the sample, the surface temperature can be expressed as light intensity measured by detector as follows:

$$I_n = I_0 + C_{TR}(T_s - T_0)I_0$$

where I_n and I_0 are the light intensities (in arbitrary unit) measured by the detector at the surface temperature T and T_0, respectively.

4.3.2.6 Junction temperature measurement

The temperature measured by the TR method is in principle not the junction temperature but the surface temperature. The junction temperature is theoretically expressed as the surface temperature using the thermal resistance between the junction to the metal surface.

$$T_j = T_s + R_{th(j\text{-}s)} P_D$$

where $R_{th(j\text{-}s)}$ (K/W) is the thermal resistance between the semiconductor junction to the metal surface and P_D (W) is the dissipated power. If the second term is smaller than or equal to 5 % of T_s, the surface temperature T_s can be approximated as the junction temperature T_j. This document assumes this condition, which is typical for most LED dies or packages. Otherwise, the junction temperature T_j shall be evaluated using the thermal resistance $R_{th(j\text{-}s)}$ as listed in IEC 60747-5-6:2021. An example of measuring the junction temperature with different methods can be found in Annex C.

4.3.3 Measurement sequence

The procedure for measuring the junction temperature is shown in Figure 3.

- Step 0: Test environmental specifications

  All the test should be performed under the well certified and defined conditions to avoid any external disturbances. Test environmental specifications are listed in Table 1.

  Turn on the temperature heating system, the light source, and the detector. Place the sample on the measurement jig and thermocouple near the sample for ambient temperature measurement. Adjust the light beam and focus on the surface temperature measurement position so as not to exceed or lack the scale required for sample temperature measurement. Record the average radiant power.

- Step 1: Set the heating temperature T_h without applying forward current to the sample. Wait until the normally reflected intensity I_n is stable so that the ambient temperature T_a may be equal to the surface temperature T_s. It is recommended to wait at least 5 minutes unless otherwise specified. Measure the ambient temperature T_a by the thermocouple. The standard thermocouple types K, T, J, and E with appropriate measurement tolerances such as ±2,2 °C are recommended.
- Step 2: Select the position of the surface temperature measurement as close as possible to the semiconductor junction. Measure the reflectance R at the metal material. Measure the spectral reflectance R at a surface temperature T_s. Repeat the step 1 until the ambient temperature reaches the maximum heating temperature T_{max} for the C_{TR} measurement.
- Step 3: Plot $(\Delta R/\Delta T_s)/R$ as a function of surface temperature T_s.
- Step 4: Calculate the thermoreflectance coefficient C_{TR} by approximating $(\Delta R/\Delta T_s)/R$ as a linear function of the surface temperature T_s.
- Step 5: Repeat step 1 at the room temperature. Set the surface temperature T_s as the reference temperature T_0. Measure the reflectance R at T_0.
- Step 6: Set the sample forward current I_F.
- Step 7: Measure the relative change in the reflectance at the reference temperature, i.e., $\Delta R/R$.
- Step 8: Calculate the surface temperature change from $\Delta T_s = (\Delta R/R)/C_{TR}$ and the surface temperature at the forward current, i.e. $T_s = T_0 + \Delta T_s$.
- Step 9 (optional): Set the junction temperature T_j to the surface temperature T_s. The result is shown in Figure B.2.
- Step 10: Create the test report.

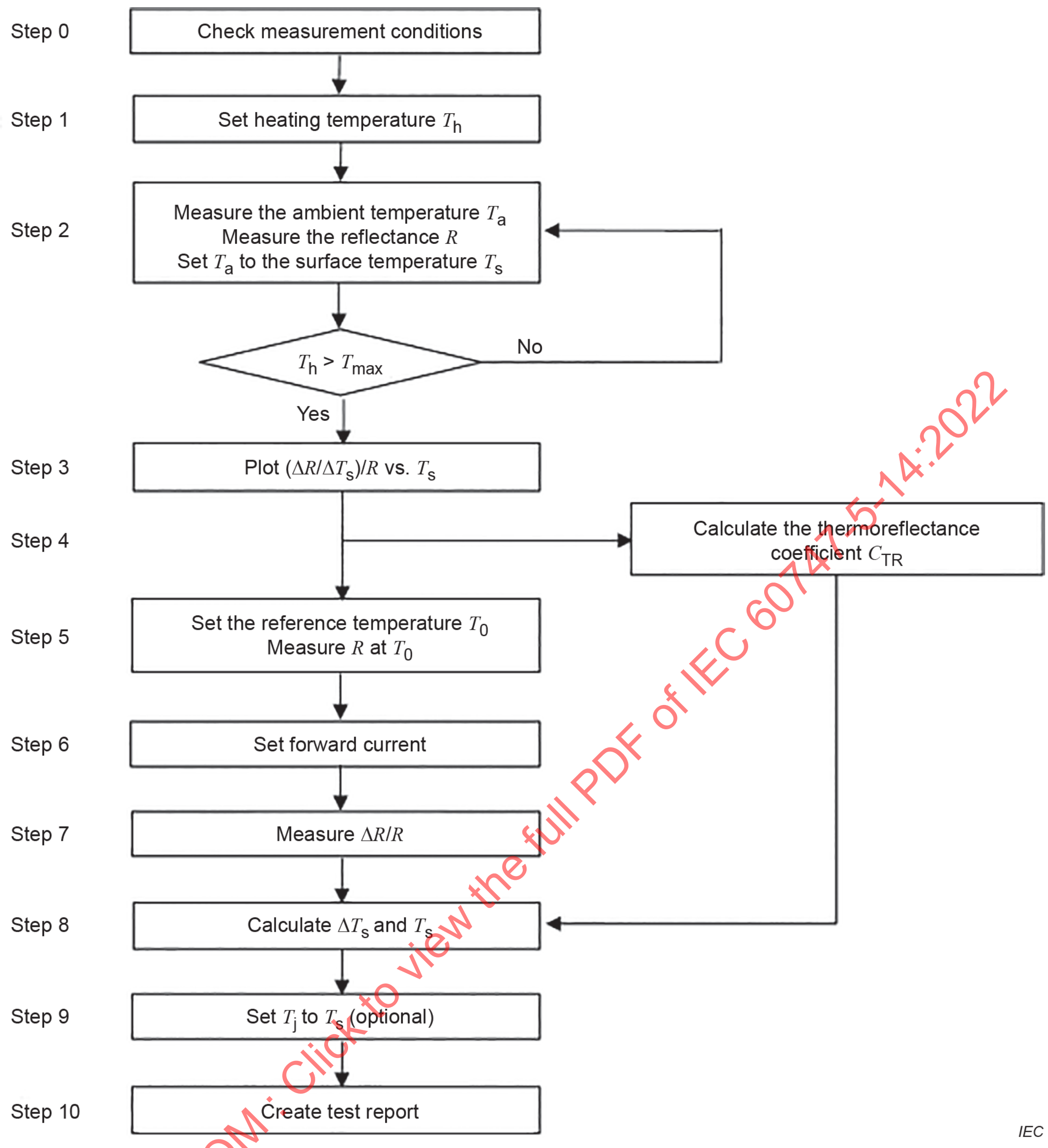


Figure 3 – Sequence of the measurement of the junction temperature using the TR method

5 Test report

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

Table 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	μmxμm		
Electrode type	-		Ex. Lateral, Flip-chip, or vertical
Package type	-		Ex. SMD, size
Peak wavelength of LED	nm		Specify current I_F
Peak wavelength of light source	nm		Specify light source Ex. Laser or LED
Beam diameter of light source	μm		
Average power of light source	mW		Specify laser driving conditions: EX. f = 1 kb/s, duty = 50 %
Detector type	-		Ex. PMT, Si PIN-PD
Surface material	-		Specify material: Ex. Metal, thickness
Thermoreflectance coefficient (C_{TR})	K^{-1}		Ex. ±1 % error
Thermocouple	Type		Ex. K-, T-, J-, E-type
Humidity	% RH		
Reference temperature (T_o)	℃		
Maximum applied current (I_{max})	mA		
Forward current (I_F)	mA		
Surface temperature (T_s) at I_F	℃		
Junction temperature (T_j) at I_F	℃		Specify (1) $T_j = T_s$ or (2) $T_j = T_s + R_{th(j-s)} P_D$

Annex A
(informative)

Measurement of the thermoreflectance coefficient of a standard metal film

The Au bulk film is selected as a standard metal film. The thermoreflectance values of standard metal films are measured by using the TR measurement system as shown in Figure 1. The irradiance of the light on the surface of the metal film is selected from the viewpoint of i) suppressing the temperature rise due to light absorption during the reflectance measurement and ii) obtaining an enough signal-to-noise ratio.

Test environmental specifications are as follows:

– standard metal film: 230 nm thick Au bulk film deposited by an e-beam evaporator on a 2-inch (100) Si-wafer;
– humidity: 50 % RH;
– reference temperature: T_0 = 30 °C;
– source: 532 nm wavelength laser driven at 1 kHz and duty 50 %;
– average laser power: (0,85 ± 0,05) mW;
– laser beam diameter: 3 µm;
– detector: Photomultiplier tube (PMT);
– measurement range of surface temperature T_s: T_0 (30 °C) − T_{max} (120 °C);
– Measurement step of surface temperature T_s: ΔT_s = 10 °C.

Figure A.1 shows the measured results of thermoreflectance coefficient of a standard Au film. From the linear fit, the C_{TR} value is estimated to be C_{TR} = -(2,99 ± 0,09) × 10^{-4} K^{-1}.

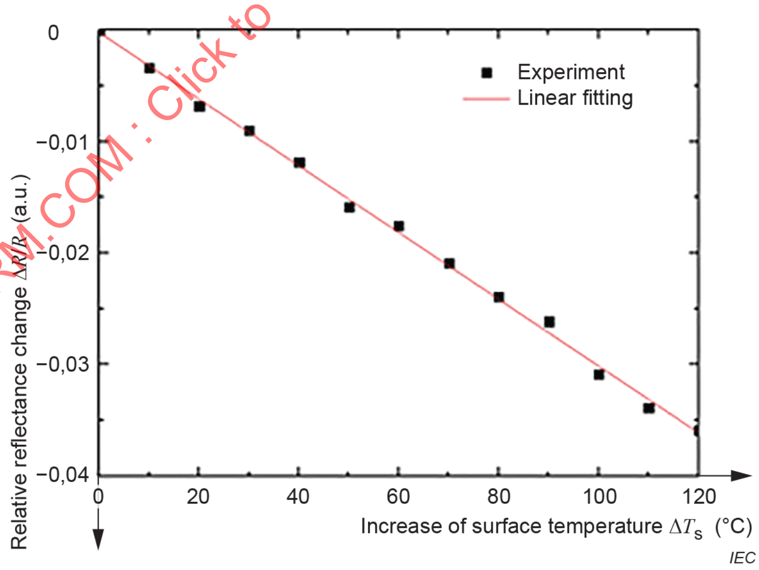


Figure A.1 – Experimental result of thermoreflectance coefficient of a standard Au film

Annex B
(informative)

Test example

A Flip-chip type blue LED was mounted on an Au bulk film which was deposited on a Cu submount. Au bulk film was made by the same process as the standard metal film described in Annex A. The thermoreflectance value of Au film was measured using the TR measurement system as shown in Figure 1. The thermoreflectance coefficient of Au film was the same as the standard Au film experimentally shown in Annex A.

A K-type thermocouple was soldered to the Au film at the edge of the submount. The laser beam used for the TR measurement was focused on the Au surface as close as possible to the LED die. Figure B.1 is a photograph of the sample used in the experiment.

- Step 0: Test environmental specifications
  - Sample: Flip-chip type blue LED mounted on thick Au bulk film deposited on Cu sub-mount
  - Die size: 1 500 µm × 1 500 µm
  - Peak wavelength: ~447 nm at T = 20 °C
  - Mount size: 3 000 µm × 3 000 µm
  - Others are listed in Table B.1
- Step 1: Measure the thermoreflectance coefficient C_{TR} of the Au bulk film.
  - $C_{TR} = -(2{,}99 \pm 0{,}09) \times 10^{-4}\ K^{-1}$
- Step 2: Set the reference temperature T_o.
  - T_0 = 30 °C
- Step 3: Set the sample forward current I_F.
  - I_F = 500 mA
- Step 4: Measure the relative change in the reflectance.
  - $\Delta R/R = -1{,}85 \times 10^{-2}$
- Step 5: Calculate the surface temperature change.
  - $\Delta T_s = (\Delta R/R)/C_{TR}$ = 62 °C
- Step 6: Calculate the surface temperature at the forward current I_F.
  - $T_s = T_0 + \Delta T_s$ = 92 °C
- Step 7: Set the junction temperature T_j to the surface temperature T_s.
  - $T_j = T_s$ = 92 °C
- Step 8: Create the test report.
  - Fill in Table B.1.
- Step 9 (optional): Repeat step 3 through step 7 by changing the forward current I_F. Plot T_j as a function of I_F.

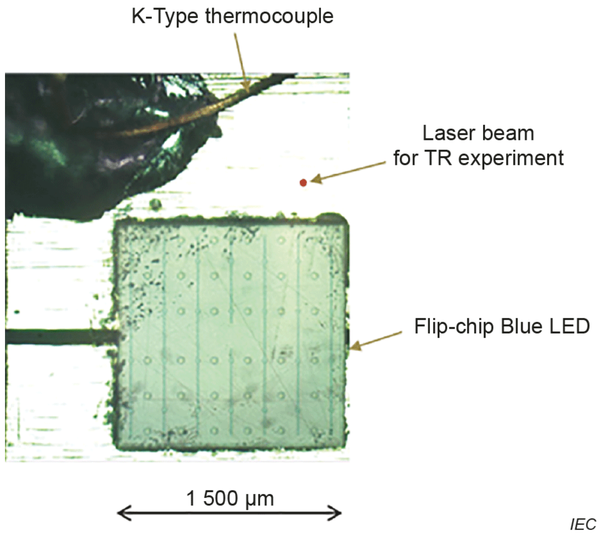


Figure B.1 – Photograph of a sample prepared for the junction temperature measurements

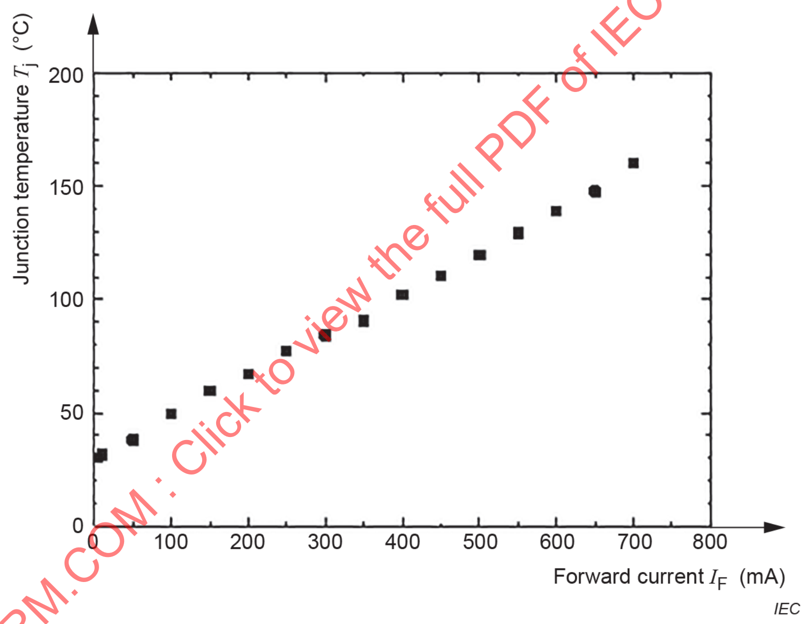


Figure B.2 – Junction temperature measured by the TR method of the sample shown in Figure B.1

Table B.1 – Summary of test report in example

Item	Unit	Value	Comment
LED maker	-	-	Specify the name of the company
Model name	-	-	Specify the model name
Die size	µm x µm	1 500 × 1 500	
Electrode type	-	Flip-chip	
Package type	-	SMD	
Peak wavelength of LED	nm	446	at I_F
Peak wavelength of light source	nm	532	Solid-state laser
Beam diameter of light source	µm	3	
Average power of light source	mW	0,8	
Detector type	-	PMT	
Surface material	-	Au	270 nm thick bulk film
Thermoreflectance Coefficient (C_{TR})	K^{-1}	$-2,99 \times 10^{-4}$	±3 % error
Thermocouple	Type	K	
Humidity	% RH	50	
Reference temperature (T_0)	°C	30	
Maximum applied current (I_{max})	mA	700	
Forward current (I_F)	mA	500	
Surface temperature at I_F	°C	92	
Junction temperature at I_F	°C	92	Set T_j to T_s