The Influence of the Mounting Manner on Thermal and Optical Parameters of Power LEDs

Krzysztof Górecki, and Przemysław Ptak

***Abstract*—The paper refers to the investigation results concerning thermal and optical properties of power LEDs. The measuring-set to measure thermal and optical parameters of the considered semiconductor devices is described and some results of measurements of transient thermal impedance and illuminance emitted by power LEDs operating at different cooling conditions are presented. Investigations were performed both for LEDs operating solely and sets of such diodes situated on the common heat-sink.**

***Index Terms*—power LEDs, thermal parameters, optical parameters, measurements**

I. INTRODUCTION

POWER LEDs are more and more frequently used in the lighting technique [1, 2, 3]. Within last twenty years there has been observed essential improvement of exploitive parameters of considered class of semiconductor devices and a decrease in their price [1, 2, 3]. In numerous publications both properties of single LEDs [4, 5, 6, 7] and LED lamps [8, 9, 10, 11] are considered. As the great advantage of solid-state light sources seems to be long life time [4, 12], the essential problem is to remove heat generated in the considered devices [13, 14]. In papers [6, 7, 15, 16] the strong influence of self-heating phenomena and mutual thermal interactions on the course of characteristics of power LEDs are shown.

In order to assure long life time it is indispensable to take efficient cooling of power LEDs. The structures of LED lamps contain more complex cooling systems are presented among other in paper [17].

Thermal properties of semiconductor devices, e.g. power LEDs, in the steady-state are characterized by thermal resistance R_{th}. The problem of measurement of this parameter is focused on among other in papers [15, 16, 18, 19]. As semiconductor devices operate in dynamic conditions, their thermal properties are described by the transient thermal impedance $Z_{th}(t)$ [20, 21]. The waveform of $Z_{th}(t)$ depends on the construction of the case of the semiconductor device and on elements improving cooling, such as heat-sinks [22, 23].

In this paper, which is an extended version of the paper [35], the measurement set to measure optical and thermal parameters of power LEDs and the obtained results of measurements illustrating the influence of the selection of the cooling system of these LEDs on the considered parameters, are presented.

In the second section the description of the measurement set is presented, in the third section the examined devices are described, and the fourth section contains the results of measurements of thermal and optical parameters of the selected types of power LEDs operating at different cooling conditions.

II. THE MEASUREMENT SET TO MEASURE THERMAL AND OPTICAL PARAMETERS OF POWER LEDS

In order to examine the influence of the mounting manner of the power LED on their thermal and optical parameters, the measurement set of the block diagram shown in Fig. 1 is constructed. This measurement set makes it possible to measure internal temperature of the examined power LED with the use of the indirect electrical method and to measure illuminance emitted by this LED with the illuminometer.

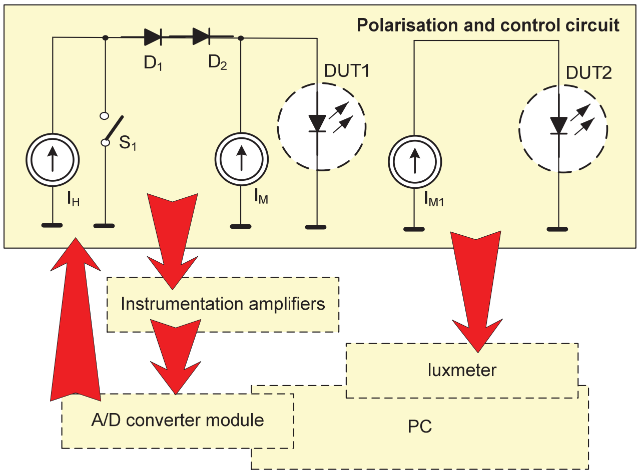

Fig. 1. Block diagram of the measurement set to measure thermal and optical parameters of power LEDs

Considered measurement set contains the computer controlling the work of the measurement set and containing the analog-to-digital converter module, instrumentation amplifiers, the polarization and control circuit of the examined power LED and the illuminometer Sonopan L-100 [24]. The analog-to-digital converter module is characterized for example in the paper [25]. Instrumentation amplifiers assure high input resistance of the measuring-path and adjustment of the level of the measured signal to the range of the measurement of the A/D converter used. The polarization and control circuit contains current sources and switches making possible realization of the method of measurement of transient thermal impedance of the power LED, described in paper [16]

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and the methods of measurement of mutual transient thermal impedance between the LEDs situated on the common basis.

The measurement of the device's own transient thermal impedance is realized for the diode DUT1 by means of the methods making use of a cooling curve [26]. The measurement is realized in 3 steps. At first, the thermometric characteristics at the supply of the examined device by the current of the small value from the current source I_M is measured. In this step the switch S_1 is closed. In the second step of the measurement, the switch S_1 is open and through the device DUT1 the current from the source I_H flows and heats this device. Having achieved the steady state, the switch S_1 is closed, causing the flow by the diode DUT1 of the current from the source I_M. In every mentioned step, the A/D converter measures the waveform of the voltage on the diode DUT1.

While measuring mutual transient thermal impedance, the diode DUT1 plays a role of a heater and it is supplied in the same way, as during the measurement of the devices' own transient thermal impedance, whereas the diode DUT2 is forward biased with the current of the small value from the source I_{M1}. Yet this measurement the A/D converter module measures the waveforms of voltages on the diodes DUT1 and DUT2. On the basis of the measured waveforms of voltages on the diodes and previously obtained thermometric characteristics, the waveforms of the devices' own and mutual transient thermal impedances are calculated from the equations given in [16].

The examined LEDs are situated in the light-tight container. The waveforms of illuminance emitted by LEDs is measured by the illuminometer, whose cap is found in the case of the light-tight container within 17 cm from the examined device.

In the measurement set there is also a possibility to measure the device case temperature by means of the thermoresistor supplied with the current of the fixed value. In this case, the A/D converter measures values of the voltage on this resistor.

III. INVESTIGATED STRUCTURES OF POWER LEDS

Using the measurement set presented in the previous section, the measurements of thermal, optical and electric parameters of many types of power LEDs operating at different cooling conditions are performed. Investigations were made for LEDs situated in the case TO-220 (the type LP9KLB), in the case EMITTER (the type HPB8B-49K5WHB, OF-HPW-3EL) and in the case STAR (the type OF-HPWW-5SL). For selected exploitive parameters of the considered LEDs are collected in Table I.

TABLE I.
VALUES OF EXPLOITIVE PARAMETERS OF THE CONSIDERED POWER LEDS[27-30]

type	**P_{tot} [W]**	**I_{Fmax} [A]**	**T_{jmax} [^{o}C]**	**Φ_V [lm]**	**R_{thj-c} [K/W]**
HPB8B	5	1.4	135	340	8
OF-HPW-3EL	3	0.8	135	120	9
OF-HPW-5EL STAR	5	1.2	135	175	15
LP9KLB	1	0.35	120	51,6	15

As it is visible in Table I, the power dissipated P_{tot} of examined diodes contains the values within the range from 1 to 5 W, and the maximum value of the forward current I_{Fmax} - from 0.35 to 1.4 A. The obtained luminous flux Φ_V has values from 51.6 to 340 lm, at the admissible value of the internal device temperature T_{jmax} from 120 to 135^{o}C.

The examined power LEDs are installed in turn on two different heat-sinks of the dimensions 175x118x8 mm (the large heat-sink) and of the dimensions 100x75x2 mm (the small heat-sink). On the large heat-sink the diodes: D_1 of the type OF-HPW-5SL in the case STAR, D_2 of the type OF-HPW-3EL in the case EMITTER and D_3 of the type LP9KLB in the case TO-220 are installed. The distances between the devices are: 90mm between D_1 and D_2, 50mm between D_1 and D_3, 40mm between D_2 and D_3. The diode D_3 is situated in the central part of the heat-sink.

On the small heat-sink the diodes: D_1 of the type HPB8B-49K5WHB in the case EMITTER, D_2 of the type OF-HPW-3EL in the case EMITTER, D_3 of the type LP9KLB in the case TO-220 are installed. The distances between the devices are: 18mm between D_1 and D_2, 32mm between D_1 and D_3 and 50mm between D_2 and D_3. The diode D_1 is situated in the central part of the heat-sink.

During the measurements the examined diodes and heat-sinks were arranged horizontally.

IV. RESULTS OF MEASUREMENTS

For all the considered power LEDs the waveforms of transient thermal impedance and the waveforms of illuminance are measured. For example, in Fig. 2 the measured waveforms of transient thermal impedance of the diode OF-HPWW-5SL by Optoflash obtained at different cooling conditions of this device are shown. During the measurement the power dissipated in the diode was 5 W.

With the use of the algorithm ESTYM presented among others in papers [25, 22, 31] the values of parameters of the compact model of the transient thermal impedance $Z_{th}(t)$ of the considered device are estimated. This model has the following form [22, 32]

$$Z_{th}(t) = R_{th} \cdot \left[1 - \sum_{i=1}^{N} a_i \cdot \exp\left(-\frac{t}{\tau_{thi}}\right)\right] \qquad (1)$$

where R_{th} denotes thermal resistance, N - the number of thermal time constants τ_{thi}, while a_i is the weight coefficient corresponding to the thermal time constants τ_{thi}. The obtained values of the parameters of the model $Z_{th}(t)$ are collected in Table II.

Analysing Table II it is easy to notice that an increase in the dimensions of the heat-sink causes even a quadruple decrease in the value of thermal resistance of the examined device and about quadruple extension of the longest thermal time constant. The indispensable time to obtain the thermally steady state increases from about 1500 s for the diode operating without any heat-sink, to over 6000 s - for the diode situated on the large heat-sink. When the diode operates at room temperature and the power dissipated in this diode is equal to about 5 W, the internal temperature of this device reaches the steady-state values from about 65 (the diode on the large heat-sink) to over 200°C (the diode without any heat-sink).

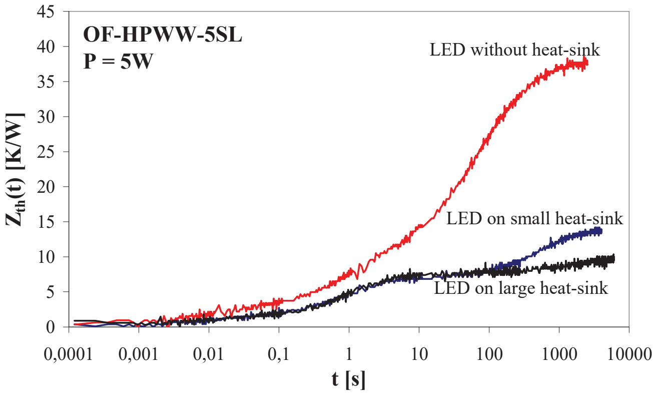

Fig. 2. Measured waveforms of transient thermal impedance of the diode OF-HPWW-5SL at different cooling conditions

TABLE II.
VALUES OF PARAMETERS OF THE Z_{TH}(T) MODEL OF THE DIODE OF-HPWW-5SL OPERATING AT DIFFERENT COOLING CONDITIONS

parameter	**LED without any heat-sink**	**LED on small heat-sink**	**LED on large heat-sink**
R_{th} [K/W]	37.4	13.31	8.91
a_1	0.17	0.332	0.221
τ_{th1} [s]	480.25	896.55	2062
a_2	0.459	0.167	0.045
τ_{th2} [s]	84.53	346	197.25
a_3	0.102	0.095	0.382
τ_{th3} [s]	17.32	5.12	2.353
a_4	0.154	0.289	0.309
τ_{th4} [s]	1.855	0.999	0.588
a_5	0.053	0.057	0.039
τ_{th5} [s]	0.3	0.152	0.0387
a_6	0.029	0.044	0.004
τ_{th6} [ms]	38.76	31.09	19.34
a_7	0.033	0.016	
τ_{th7} [ms]	5.92	6.98	

Simultaneously with the measurement of transient thermal impedance, the waveform of illuminance of the surface lighted up by the examined diode is measured. The obtained results of measurements are shown in Fig. 3.

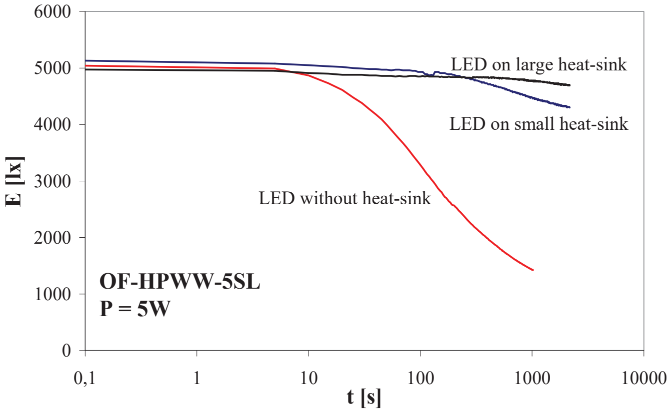

Fig. 3. Measured waveforms of illuminance of the diode OF-HPWW-5SL at different cooling conditions

As it is seen in Fig. 3, the result of a self-heating phenomenon decreases the value of illuminance. The observed decrease in the value of this parameter is greater, when cooling conditions of the examined device are worse. For example, for the diode situated on the large heat-sink illuminance in the steady-state is only just about 6% smaller than in the first phase of heating of the considered diode. In the case of the diode situated on the small heat-sink a decrease in the value of illuminance amounts to 16%, and for the diode operating without any heat-sink – up to 72%.

The investigation results presented in Figs.2 and 3 refer to the operation of the diode at the maximum admissible value of dissipated power in this device. In Figs.4 and 5 the measured dependences of the case temperature of the considered diode (Fig. 4), measured by means of the thermoresistor and illuminances (Fig. 5) on the forward current at the steady-state are presented.

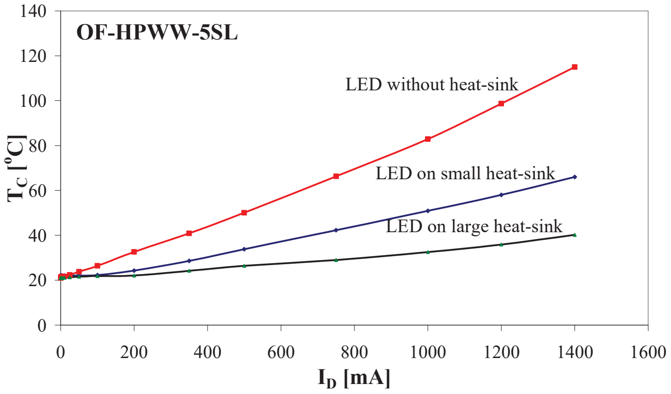

Fig. 4. Measured dependence of the case temperature of the diode OF-HPWW-5SL on its forward current at different cooling conditions

As one can notice in Fig. 4, the case temperature of the considered device is increasing, almost lineally in the function of the forward current. An increase of the case temperature caused by self-heating depends on the cooling conditions. The almost lineal character of the considered dependence testifies to a weak influence of the forward current on thermal resistance of the examined device.

Fig. 5 illustrates the fact well-known from literature [14, 16, 33] that illuminance can be regulated by means of the forward current of the diode. It is worth, however, paying attention to the fact that only during the operation of considered diode on the large heat-sink (small value of thermal resistance), the dependence E(I_D) is a function monotonically increasing. In the extreme case, when the diode operates without any heat-sink, the considered dependence possesses the maximum. This means that after exceeding certain value of the forward current, in this case 0.8 A, an increase of the current causes a decrease of illuminance. Now then, it is not a justifiable operation of this device for the current I_D > 0.8 A, because in this range one obtains the smaller value of illuminance, the power consumption from the power source increases, and simultaneously leads to the shortened life time as a result of high internal temperature of the device.

Apart from self-heating, also mutual thermal coupling influences internal temperature of the power LED. Its intensity is characterized by mutual transient thermal impedance [16]. In Fig. 6 the measured waveforms of the devices' own (Z_{th11}(t)) and mutual (Z_{th12}(t) and Z_{th13}(t)) transient thermal impedance between the LEDs situated on the common small heat-sink are presented. The measurement was performed at dissipation of power equal to 5 W in the diode HPB8B-49K5WHB in the case EMITTER. The role of sensors fulfilled diodes OF-HPW-3EL and LP9KLB.

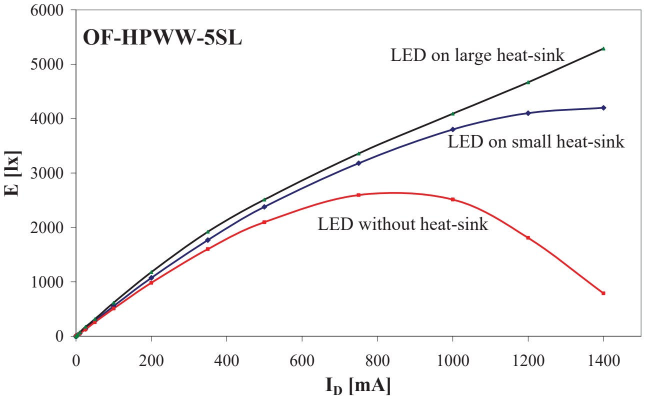

Fig. 5. Measured dependence of illuminance of the diode OF-HPWW-5SL on its forward current at different cooling conditions

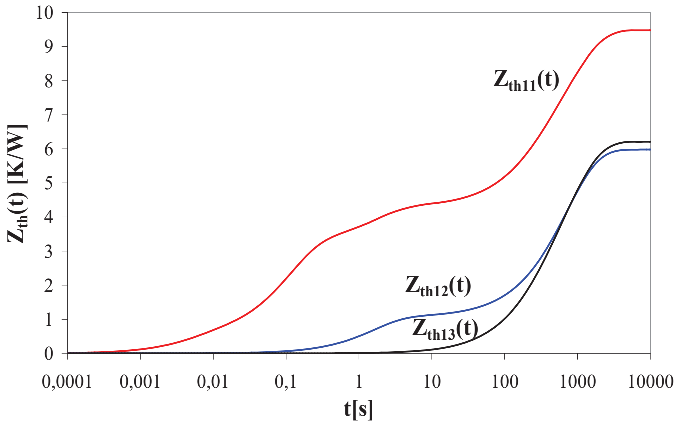

Fig. 6. Measured waveforms of the devices' own and mutual transient thermal impedance of the diodes situated on small heat-sink

As it is visible, as a result of self-heating in the diode HPB8B-49K5WHB, operating on the heat-sink, the internal temperature of the diodes situated on the common heat-sink also increases. It is worth to noticing that the steady-state of transient thermal impedance of the heater is about over 60% higher than the mutual transient thermal impedance between the heater and sensors. Internal temperatures of the diode OF-HPW-3EL, situated within 18 mm from the heater, more quickly start to rise than the internal temperature of the diode LP9KLB, distant from the heater by about 50 mm.

Mutual thermal coupling between the LEDs situated on the common heat-sink causes an increase in the internal temperature of these diodes and a decrease in the value of illuminance. In Fig. 7 the measured waveforms of illuminance emitted by every considered LED (from three) operating one by one on the small heat-sink (curves D_1, D_2 and D_3) and illuminance measured during the operation of all the considered diodes simultaneously (the curve $D_1 + D_2 + D_3$) are presented. Additionally, the curve sum marks the arithmetical sum of temporary values of illuminance emitted by each diode operating one by one.

As it is visible, in the first phase of the operation, illuminance obtained from the three diodes operating at the same time equal to the sum of the value of illuminance obtained from every LED operating independently. In the function of the time, illuminance decreases as the result of self-heating and mutual thermal coupling and in the steady-state it is equal to only just 85% of the sum of the values of this parameter for diodes operating independently at the same cooling conditions. The value of the internal temperature of the diode D_2, in which the greatest power is emitted, exceeds 85°C.

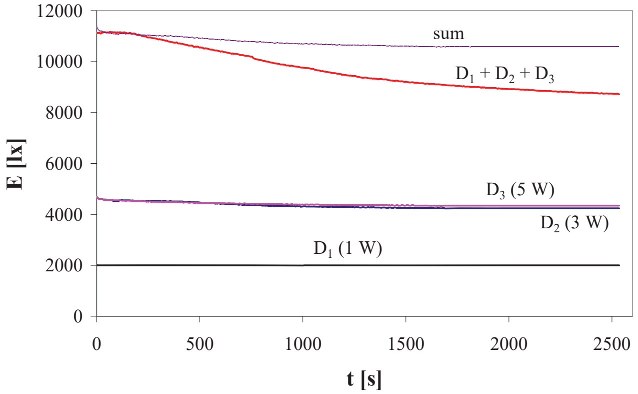

Fig. 7. Measured waveforms of illuminance of the diodes operating on the small heat-sink separately and together

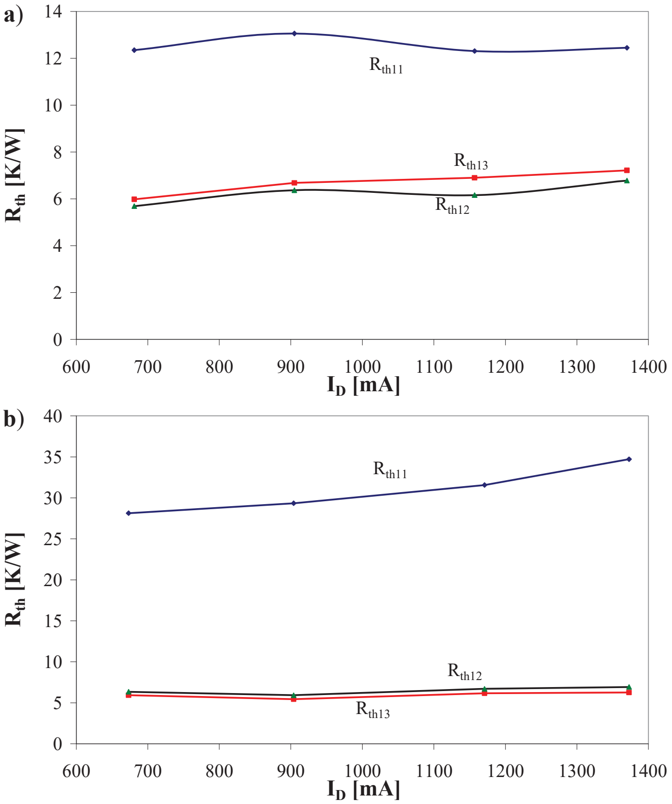

Fig. 8. Measured dependences of the device's own and mutual thermal resistances on the forward current at high (a) and low (b) pressure between the case of the diode and the heat-sink

Thermal parameters strongly depend on pressure between the examined device and the heat-sink [34]. In Fig. 8 the results of measurements of the dependences of the devices' own and mutual thermal resistance of LEDs situated on the small heat-sink in the forward current are shown. Fig. 8a presents the results corresponding to strong tightening of the case of the diode to the heat-sink, and in Fig. 8b - to weak tightening of the case of this device to the heat-sink.

As one can see in Fig. 8, the change of pressure between the case of the examined diode and the heat-sink can cause even a triple change in the value of thermal resistance of the heater, and simultaneously it hardly influences mutual thermal resistance between the diodes situated the common heat-sink.

Fig. 9 shows the measured dependence of illuminance of the diode OF-HPW-5EL situated on the small heat-sink. In this figure dashed lines denote the results obtained at strong tightening, whereas solid lines – the results obtained at weak tightening. Blue colour corresponds to the results obtained without thermal phenomena taken into account and measured immediately after switching on the power supply, whereas red colour – the results obtained at the thermally steady state.

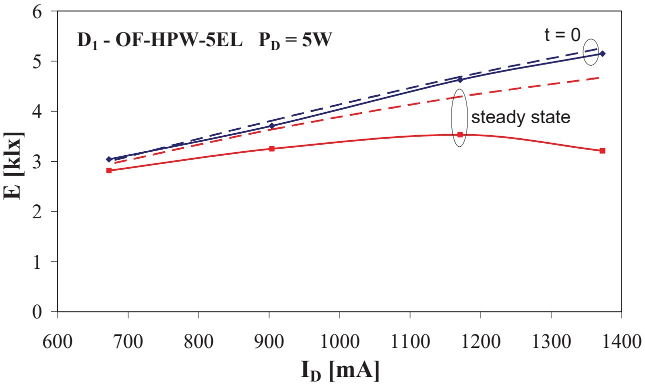

Fig. 9. Measured dependence of illuminance of the diode OF-HPW-5EL situated on the small heat-sink on its forward current at different tightening.

As it is visible, in the case when thermal phenomena can be omitted (blue lines) the obtained dependences $E(I_D)$ at different tightening between the LED's case and the heat-sink are practically the same. An increase in the forward current causes a decrease in illuminance. At weak tightening it is easy to observe that at the steady state the dependence $E(I_D)$ possesses the maximum at $I_D \approx 1.2$ A. At the maximum value of current $I_D \approx 1.4$ A a decrease observed in the value of illuminance caused by thermal phenomena is higher than 40%. By suitable pressure of the examined LED the higher value of illuminance and the limited influence of self-heating phenomena on this optical parameter can be obtained.

Fig. 10 illustrates the influence of pressure between the case of one LED (D_1) and the small heat-sink on the dependence of the internal temperatures T_J of this diode and the other LEDs situated on the same heat-sink on the forward current of the diode D_1. In this case, the diode D_1 operates as a heater and the other diodes operate as sensors. Additionally, in the same figure the dependence of the heat-sink temperature T_R is also marked. Fig. 10a corresponds to strong tightening, whereas Fig. 10b – to weak tightening.

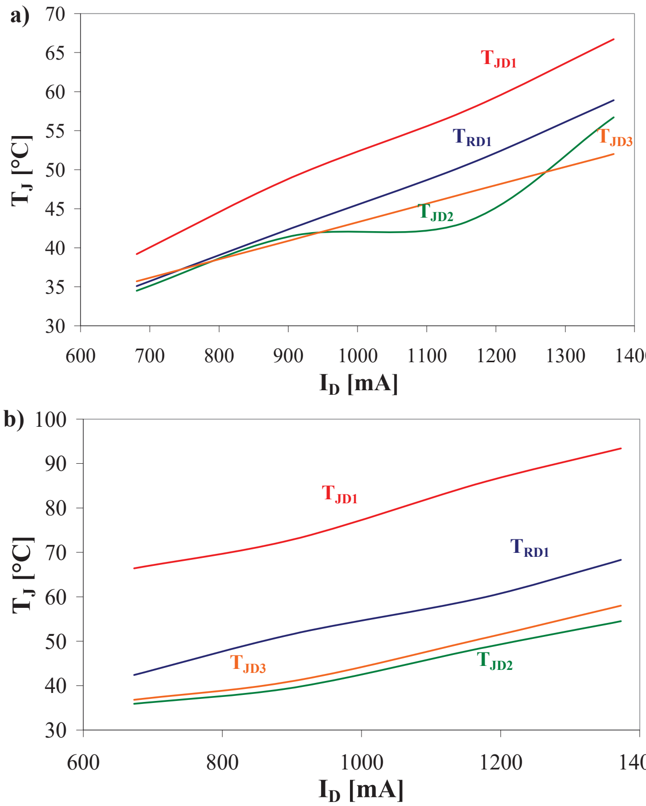

Fig. 10. The measured dependences of the internal device temperatures of power LEDs situated on the small heat-sink on the forward current of the diode D_1 at high (a) and low (b) pressure between the case of the diode and the heat-sink

It is easy to observe that the tightening strongly influences the obtained values of the device internal temperature. At strong tightening the excess of device internal temperature over the ambient one is even twice smaller than for weak tightening. The selection of suitable pressure of the examined LED element enables you to operate with higher forward currents I_D. The junction temperature increase can be observed only for the device which is used as a heater, in this case the diode D_1. The internal temperature of LEDs operating as sensors change not significantly when tightening changes.

V. CONCLUSIONS

In the paper the measurement set to measure optical and thermal parameters of power LEDs is presented. By means of this set the illuminance emitted by the considered devices and their own and mutual transient thermal impedances and thermal resistances of the considered devices are measured. The results of measurement illustrating the influence of the cooling conditions of the selected types of power LEDs on the mentioned parameters and their case temperatures are presented and discussed. It was shown that the dimensions of the heat-sink and the pressure between LED's case and the heat-sink strongly influence the device internal temperature value.

From the presented results of investigations it results that self-heating phenomena and the mutual thermal coupling between the diodes situated on the common heat-sink influence not only a change of the internal temperature values of the considered devices, but also cause essential depreciation of illuminance. In the extreme case, as result of thermal phenomena, one observes a decrease in the value of illuminance at an increase of the forward current of the examined LEDs. It is also worth underlining that as a result of thermal phenomena, time indispensable to obtain the steady state value of optical parameters of power LEDs can be very long, even up to 2 hours.

The measurement set developed by the authors can be useful for designers of solid-state light sources on the stage of testing efficiency of the designed cooling system and testing efficiency of the brightness control circuit.

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