Materials Science-Poland, 37(4), 2019, pp. 628-638
http://www.materialsscience.pwr.wroc.pl/
DOI: 10.2478/msp-2019-0075

Modelling thermal properties of large LED modules

PRZEMYSŁAW PTAK[1], KRZYSZTOF GÓRECKI[1,*], BARBARA DZIURDZIA[2]

[1]Gdynia Maritime University, Department of Marine Electronics, Gdynia, Poland
[2]AGH University of Science and Technology, Department of Electronics, Cracow, Poland

In this paper a problem of modelling thermal properties of large LED modules is considered. The compact thermal model of such modules is proposed. The form of this model is presented and a method of parameters estimation is described. The practical usefulness of this model is verified experimentally by comparing the results of calculations and measurements of internal temperature of selected LEDs included in LED modules. The modules were fabricated by Fideltronic, Poland and measurements of temperature distribution on the surface of the modules at selected variants of power dissipation were performed at the Gdynia Maritime University. Good agreement between the results of measurements and modelling was obtained.

Keywords: *LED module; compact thermal model; computations; measurements*

1. Introduction

In the lighting technique, both single power LED and LED modules can be used [1–4]. Usually, in LED lamps, round LED modules of the diameter not exceeding 4 cm are used [5]. Nowadays, large LED modules, whose area exceeds even 100 cm^2, are also offered. In these modules diodes are situated in parallel to the axis of the LED module [6, 7].

LED modules can accept different shapes and they can be situated on the Metal Core Printed Circuit Board (MCPCB) base with different thicknesses of the aluminum-layer. It is justified, that large LED modules contain from several to tens LEDs in order to limit the value of feeding current [5, 8–13]. Distances between each pair of LEDs in the module do not exceed several centimeters, which causes that mutual thermal couplings between diodes situated on the same basis occur [5, 14, 15]. As was reported in the papers [14, 16], an excessive increase in the value of forward current causes some thermal phenomena that result in a decrease in the luminous flux emitted by LEDs.

It is worth noting that temperature strongly influences characteristics, operating parameters and reliability of discrete semiconductor devices and modules, such as IGBT [17] and LED modules [5, 9, 18]. Therefore, the information about the value of internal temperature of semiconductor devices contained in the mentioned modules is very important. Thermal properties of LEDs are characterized by thermal parameters, to which self-transient thermal impedance (describing self-heating phenomena) and mutual transient thermal impedance (characterizing mutual thermal coupling between elements of this module) belong.

To enable calculation of the value of internal temperature of each LED being a part of the LED module, it is indispensable to take into account the dependence of internal temperature of each diode on the power dissipated in the whole module [15, 19, 20]. The authors in their previous papers [5, 9, 16, 21] proposed electro-thermo-optical models of LED modules taking into account self-heating phenomena and mutual thermal couplings, and verified them for small LED modules, whose diameter did not exceed 5 cm. In such models, temperature of the common base and internal temperatures of all diodes are used, whereas transient thermal impedances of all the diodes are the same. Analyzing temperature distribution in large LED modules it is easy to observe that it is non-uniform, which makes difficult calculations of internal

---

[*] E-mail: k.gorecki@we.am.gdynia.pl

temperature of diodes operating on the common basis. In thermal modelling of LED modules one should take into account self-heating phenomena and mutual thermal couplings, which additionally complicate the form of this model.

In this paper, a compact thermal model of the large LED module is proposed. This model makes it possible to calculate internal temperature of every diode taking into account self-heating phenomena and mutual thermal couplings between LEDs contained in this module. The form of the new model, the method of estimating values of parameters of this model and the results of calculations and measurements illustrating usefulness of this model are presented.

2. Tested module

The tested modules were assembled by Fideltronik, Poland [22]. Each module contained 16 high power LEDs of the type XPGBWT-H1-CCKP-AFHE5KE40 connected in series and mounted on a metal core PCB of the dimensions 22.2 cm × 5 cm [23]. The PCB comprised an aluminum-core base layer, a thin thermally conductive dielectric layer and a copper-circuit layer of thicknesses 1.5 mm, 0.100 and 0.035 mm respectively. The modules were soldered using two different techniques: convection reflow and vapor phase reflow in vacuum [6, 7, 24–27]. Alpha Metals OM340 solder paste of InnLotTM type was used for the LEDs assembly [28]. Every LED diode had one thermal pad and two electrical pads.

The studied LEDs were characterized by the maximum admissible forward current $I_{Dmax} = 1.5$ A at forward voltage $V_F = 3.1$ V. The value of thermal resistance between the junction and the thermal pad was $R_{thj-s} = 4$ K/W. The maximum admissible junction temperature $T_{jmax} = 150$ °C. Dimensions characterizing the tested module are shown in Fig. 1.

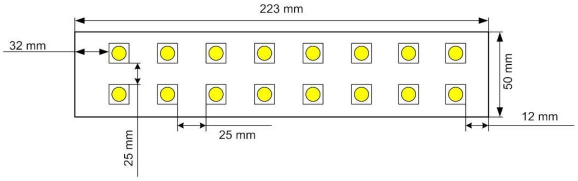


Fig. 1. Dimensions of the tested module.

3. The model form

The thermal model describes the dependence between internal temperature of the semiconductor device and power dissipated in it [5, 9, 14, 15, 21, 29, 30]. In case of the LED module, the simplest compact thermal model can make possible calculations for only one temperature of this module at the assumption that temperature distribution in the module is uniform. The model takes into account only self-heating phenomena due to thermal power dissipated in the module. Such a method has been presented in the literature [5, 9, 21].

Temperature distribution in the LED module is not uniform: structures of each diode can have different internal temperature considerably higher than temperature of the basis [17]. The waveform of internal temperature of every diode existing in the module results from self-heating phenomena in this diode and mutual thermal couplings between this diode and the other diodes contained in the module. For the diode of the number k, internal temperature can be described as follows [31]:

$$T_{jk}(t) = T_a + \sum_{i=1}^{M} \int_0^t Z'_{thik}(t) \cdot p_i(\tau)\, d\tau \qquad (1)$$

where T_a denotes ambient temperature, $Z'_{thik}(t)$ – time derivative of transient thermal impedance between i-th and k-th diode, $p_i(t)$ – power dissipated in i-th diode. If $i = k$, self-transient thermal impedance occurs, whereas if $i \neq k$ there is mutual transient thermal impedance.

The waveforms of self and mutual transient thermal impedances $Z_{th}(t)$ occurring in the considered model are described in the time domain using the formula in the form [31]:

$$Z_{th}(t) = R_{th}\left[1 - \sum_{i=1}^{n} a_i \cdot \exp\left(-\frac{t}{\tau_{thi}}\right)\right] \qquad (2)$$

where R_{th} denotes thermal resistance, a_i - the weight coefficient corresponding to i-th thermal time constant τ_{thi}, while N is the number of thermal time constant.

The network representation of equation 1 could have a form shown in Fig. 2. In this case, the number of thermally coupled devices is equal to 4, as in the IGBT module [17]:

In this model, current sources represent power dissipated in particular diodes included in the module. The networks visible on the left-hand side of the model represent self-heating phenomena in each diode with the use of RC Foster networks, whereas an increase in the device internal temperature caused by mutual thermal couplings is represented by the controlled voltage source. The output voltage of these sources is equal to the sum of voltages of the networks visible on the right-hand side. Each of these networks represents mutual transient thermal impedance between the considered diode and one of the diodes coupled thermally with it. Independent voltage sources represent ambient temperature.

As it is known from the literature [15, 32], a thermal model of semiconductor devices could be represented either by the Cauer network or the Foster network. The form of the Cauer network directly results from discretization of the heat conduction equation, whereas the Foster network does not have any physical justification [15, 33]. Yet, from the point of view of the node representing the device internal temperature these networks are fully equivalent [15]. An advantage of Foster network is that the values of RC elements existing in this network could be more easily estimated than elements of the Cauer network. This is a reason to use Foster network in modelling.

In the considered case (4 diodes mounted in the module) 4 self-transient thermal impedances and 12 mutual transient thermal impedances appear in its thermal model. Thermal capacitance and thermal resistance between each element of the heat flow path depend on the parameters of materials occurring in this path and their geometrical dimensions. Therefore, heat transfer between every pair of components of the module in both directions can be characterized by identical mutual transient thermal impedance. Since the heat transfer between each pair of semiconductor devices included in the considered module is characterized by the same mutual transient thermal impedance, only six (instead of 12) mutual transient thermal impedances are necessary in the model.

In turn, for the module including 16 diodes: 16 self-transient thermal impedances and 120 mutual transient thermal impedances are indispensable. These thermal parameters could be measured using a method described in the next section.

4. Measurement method

In order to measure self and mutual transient thermal impedances in the LED module and spatial distribution of temperature in the module the measurement set-up shown in Fig. 3 was used [5, 9, 14].

The considered measuring set-up contains the PC computer connected with an analogue-to-digital converter of the type USB-1608G by the Measurement Computing [34], the set of measuring-amplifiers fitting the suitable voltage for the input of the analogue-to-digital converter and a circuit polarizing diodes in the investigated LED module. The used A/D converter has 8 analogue inputs operating in the differential mode, which allows improving accuracy of measurements and isolation of each measuring channel. The block of measuring amplifiers allows obtaining large input resistance of the measuring track. The polarization circuit contains voltage sources E_H and E_M, resistors R_H and R_M limiting the current value and a switch S allowing realization of measurements of self and mutual courses of transient thermal impedance. Temperature distribution is measured with the use of an infrared camera of the type FLIR i5 [35].

The used method of measuring self and mutual transient thermal impedances belongs to the group of indirect electrical methods making use of cooling conditions, whose conception is described in the literature [17, 36]. This method is realized in some steps. At first, thermometric characteristics $v_D(T)$ of each tested diode are measured when switch S is opened. There are dependences of forward diode voltage on temperature at the fixed value of forward current I_M. The slope of these

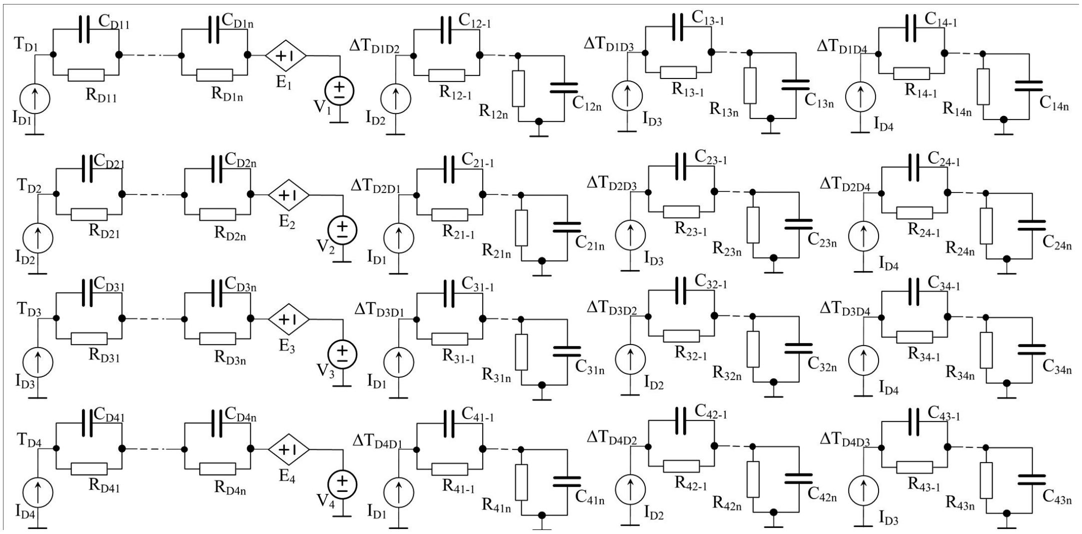


Fig. 2. Network representation of the thermal model of the LED module with 4 coupled devices.

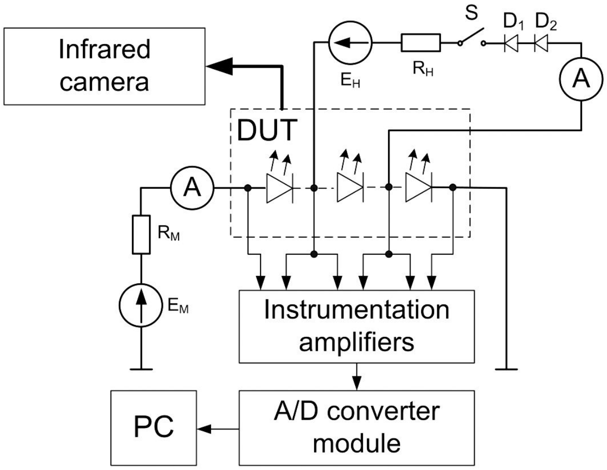


Fig. 3. Set-up to measure self and mutual transient thermal impedances in the LED module and temperature distribution in this module.

characteristics is denoted as F. Next, switch S is closed and the diode, which plays a role of a heater, is supplied from the voltage source E_H until the thermally steady state is obtained. Then, the forward voltage of this diode V_{DjH} and forward current I_H are measured and temperature distribution of the tested module is registered using the infrared camera. Next, at time $t = 0$ switch S is opened. Then, the measuring current I_M flows through the diodes connected in series and the waveforms of forward voltages $v_{Di}(t)$ of all the diodes playing the role of heaters and sensors are registered until the steady state is obtained. Waveforms of self and mutual transient thermal impedances are calculated using the classical formula of the form:

$$Z_{thij}(t) = \frac{v_{Di}(t=0) - v_{Di}(t)}{F \cdot V_{DjH} \cdot I_H} \tag{3}$$

If $i = j$, the obtained with equation 3 waveforms of self-transient thermal impedance $Z_{thii}(t)$ are calculated, whereas for $i \neq j$ – waveforms of mutual transient thermal impedance $Z_{thij}(t)$ are evaluated. Finally, for all the measured waveforms of self and mutual transient thermal impedances, values of parameters R_{th}, a_i, τ_{thi} existing in equation 2 are estimated using the software ESTYM described in the literature [37].

The analysis of uncertainty of the performed measurements can be carried out on the basis of considerations presented in the paper [38]. The value of a relative uncertainty of measurements of the considered transient thermal impedances at the steady state does not exceed 10 %, whereas the uncertainty of temperature measurements performed using the infrared camera does not exceed 2 K [35].

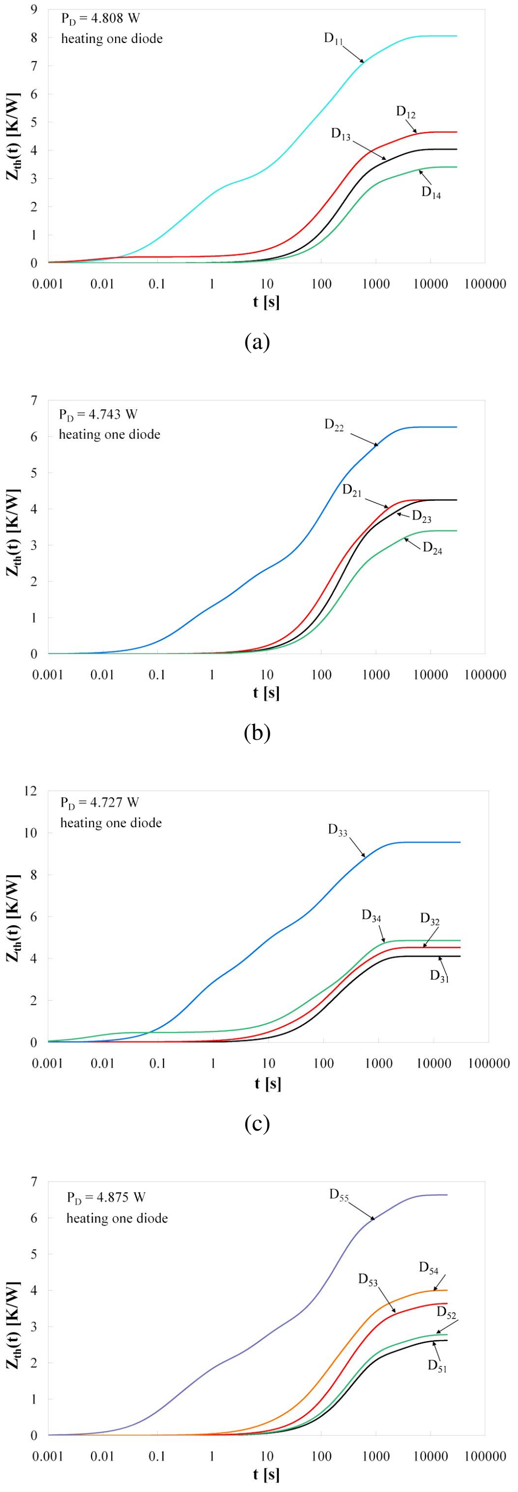
5. Investigation results

For the examined LED modules, measurements of self and mutual transient thermal impedances were performed. The tested modules were specially prepared and soldering pads of the tested diode were made without a solder mask. Self-transient thermal impedances of 5 diodes marked in Fig. 1 as D_1, D_2, D_3, D_4 and D_5, respectively, were measured. On the basis of the obtained results of measurements, the values of parameters existing in equation 2 were estimated. For example, in Fig. 4, the calculated with equation 2 waveforms of self and mutual transient thermal impedances are shown when heating power is dissipated only in one selected diode included in the module.

During the measurements, the heating power was dissipated only in one diode. While heating, the forward current flowing through this diode was equal to 1.5 A, therefore, the power dissipated in the diode was equal to about 4.8 W.

It is easy to observe that in each case self-transient thermal impedance is higher than mutual transient thermal impedances. Values of mutual transient thermal impedances are the biggest for diodes situated closest to the heater. The value of mutual transient thermal impedance at the steady state decreases as the distance between the heater and the sensor increases. It is also worth noticing that the heating process of the heater starts practically immediately after switching on the heating power, whereas this process for sensors starts after 2 s to 20 s after switching on this power. This delay increases when the distance between the heater and the sensor increases. Comparing the results of measurements obtained for different locations of the heater one can see the same differences between the measured waveforms of self-transient thermal impedances. These differences are even equal to 20 %.

In order to obtain values of the parameters existing in the thermal model of the considered module, the estimation algorithm given in the paper [37] was used. Using this algorithm the following values of the parameters existing in equation 2 were obtained. For example, in Table 1 values of thermal parameters describing self-heating in diodes



(a)

(b)

(c)

(d)

Fig. 4. Waveforms of self and mutual transient thermal impedances in the considered module when heating power is dissipated only in one diode D_1 (a), D_2 (b), D_3 (c) and D_5 (d), calculated with equation 2.

Table 1. Parameters values of the thermal model of selected diodes included in the LED module.

	Z_{th11} (t)	Z_{th12} (t)	Z_{th13} (t)	Z_{th14} (t)
R_{th} [K/W]	8.06	4.64	4.04	3.41
a_1	0.157	0.189	0.241	0.206
a_2	0.302	0.596	0.752	0.705
a_3	0.209	0.169	0.007	0.089
a_4	0.220	0.046	–	–
a_5	0.099	–	–	–
a_6	0.013	–	–	–
τ_{th1} [s]	1427	2201.9	1893.7	3042
τ_{th2} [s]	198.6	230.2	233.6	321.7
τ_{th3} [s]	24.79	48.9	4×10^{-5}	4×10^{-5}
τ_{th4} [s]	0.575	4×10^{-5}	–	–
τ_{th5} [s]	0.08406	–	–	–
τ_{th6} [s]	0.01926	–	–	–
	Z_{th31} (t)	Z_{th32} (t)	Z_{th33} (t)	Z_{th34} (t)
R_{th} [K/W]	4.11	4.53	9.55	4.86
a_1	0.535	0.427	0.256	0.618
a_2	0.465	0.463	0.228	0.286
a_3	–	0.105	0.233	0.096
a_4	–	0.005	0.263	–
a_5	–	–	0.02	–
τ_{th1} [s]	497.1	556.2	489.3	400.1
τ_{th2} [s]	100.4	118.3	83.13	31.57
τ_{th3} [s]	–	12.276	5.108	0.00694
τ_{th4} [s]	–	0.00004	0.36267	–
τ_{th5} [s]	–	–	1.31967	–

D_1 and D_3 and mutual thermal couplings between these diode and diodes D_2 and D_4 are collected.

As it can be noticed, differences in the values of self-thermal resistances are visible and they attain even 22 %. This is due to location of each of the investigated LEDs at a different distance from the edge of the basis. In turn, the values of mutual thermal resistances are smaller even by 57 % in case, when diode D_3 is heated. The thermal steady state in most cases is obtained about 3000 s after switching-on the power supplying this diode. The longest time constant was obtained for diode D_4 in case, when only diode D_1 was supplied and it was even 3000 s. This difference can result from the distance between each diode operating on the common basis, and in turn, this results from different heat flow paths between the semiconductor structure and the environment.

The number of thermal time constants indispensable to proper describing the measured waveforms of self and mutual transient thermal impedances was calculated by the used ESTYM algorithm automatically. This number depends on properties of the heat flow path, especially on the distance between the heater and the sensor. When this distance is smaller, the indispensable number of thermal time constants is lower.

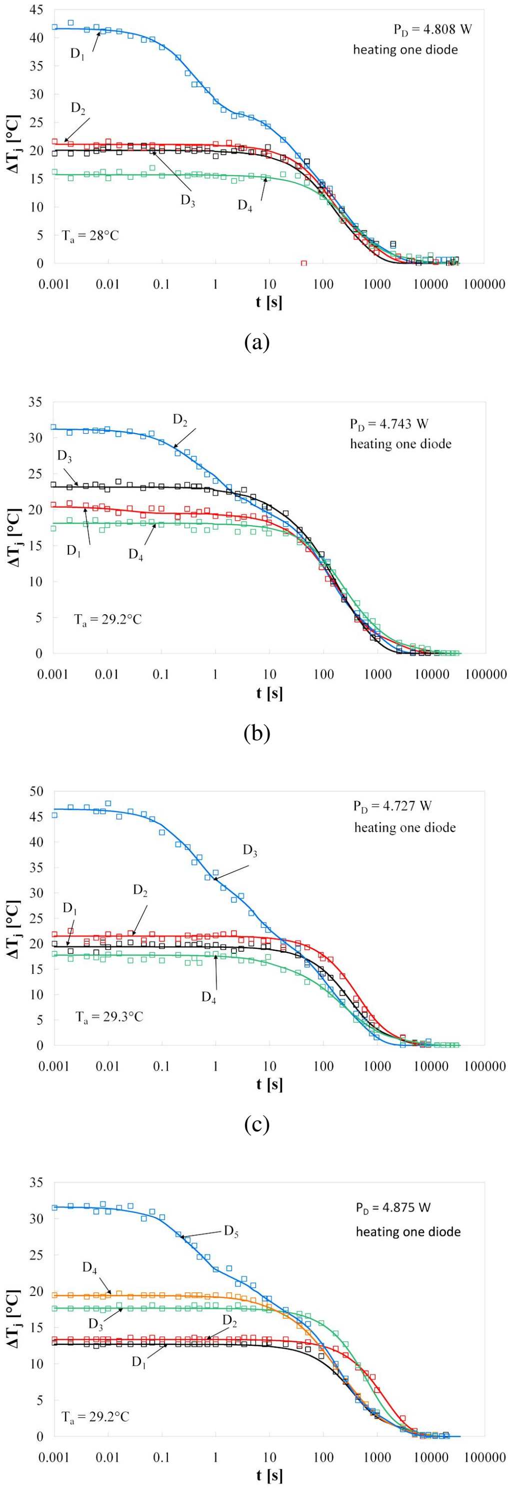
Analyzing the considered module with the use of its thermal model, it can be noticed that for one of the diodes from this module some waveforms show an excess ΔT_j of internal temperature over ambient temperature while cooling of the module is simulated. The obtained results of calculations were compared with the results of measurements. The measurements were carried out by the indirect electrical method described in the authors' previous papers [6, 19]. Calculations and measurements were performed for different manners of power dissipation in the module. The results of these measurements are shown in Fig. 6 to Fig. 9. Before the cooling process starts in the module, the thermally steady state occurs. In these figures, the points denote the results of measurements, whereas the lines are the results of calculations.

As it is visible in Fig. 5, in case when only one diode (heater) is heated by a forward current of the maximum admissible value, at the steady state, the internal temperature of the heater is higher than the internal temperature of other diodes (sensors) included in the tested module even by 20 °C, as could be expected. At this state, the internal temperature of the sensors situated further from the heater is lower than the internal temperature of the sensors situated closest to the heater. While cooling, the internal temperature of the sensors starts to decrease, whereas the internal temperature of the heater is equal to the internal temperature of the considered sensors.

Fig. 6 shows the measured and calculated waveforms of internal temperatures of selected diodes included in the tested module during its cooling. Before cooling, the thermally steady state was observed in the module and heating current flowed through four (Fig. 6a) or five (Fig. 6b) diodes. In this case, forward current of these diodes was equal to 1.5 A.

As one can see, in spite of the fact that the power dissipated in each diode is nearly the same, visible differences between internal temperatures of the considered diodes are observed. These differences are higher in case when 5 diodes are fed, and they exceed even 30 °C. The highest value of this temperature is observed for diode D_3, which is characterized by the highest value of thermal resistance, whereas the lowest value of this temperature was obtained for diode D_1.

Fig. 7 shows the measured waveforms of internal temperature of selected diodes included in the considered module when the current flows through



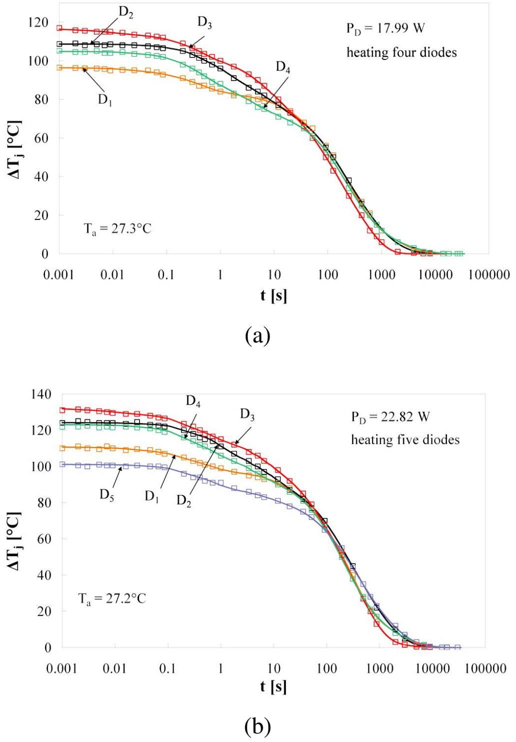
(a)

(b)

(c)

(d)

Fig. 5. Measured (points) and calculated (lines) waveforms of a temperature excess of diodes over ambient temperature when power is dissipated in one diode only.



(a)

(b)

Fig. 6. Measured (points) and calculated (lines) waveforms of a temperature excess of diodes over ambient temperature when power is dissipated in four (a) or five (b) diodes.

all the diodes. In the considered case, the forward current of all the diodes is equal to 750 mA. As it is visible, in spite of the fact that the power dissipated in the module is higher than in the event presented in Fig. 6, differences between temperature values of the diodes included in the module are smaller. They do not exceed 10 K. This results from smaller values of power dissipated in each diode.

Fig. 8 presents the waveforms of an internal temperature excess of diode D_5 over ambient temperature when the power of the value equal to about 3.5 W is dissipated only in diode D_5 (blue curve) or simultaneously in 4 diodes (red line). As one can notice, a manner of power dissipation in the module indeed influences the obtained waveforms ΔTj(t). Particularly, the value of the considered excess of temperature at the steady-state and at dissipation of power only in diode D_5 amounts to 41 K, and at dissipation of such power in 4 diodes - only just 15 K. The thermally steady state appears in the module after about one hour from the moment of power-off of the diodes. It testifies the high thermal capacitance of the considered LED module. The results of calculations obtained with the use of the model described by equation 1 are convergent with the results of measurements.

The obtained results show that every diode contained in the module will influence an increase in internal temperature of the other diodes from this module. In case when through all the diodes flows the current of the same value, an increase of internal temperature of a given diode will influence mutual thermal coupling between the diodes more strongly than self-heating phenomena. Temperature distribution on the surface of the tested module at a steady state for different conditions of power dissipation is shown in Fig. 9.

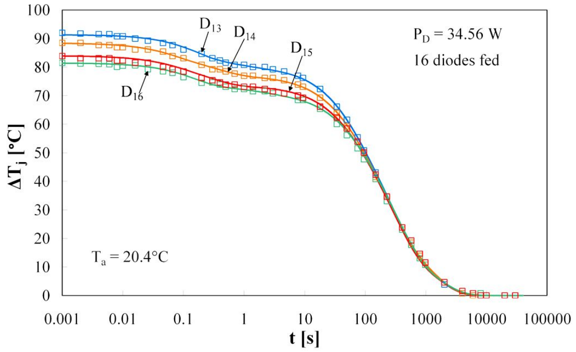


Fig. 7. Measured waveforms of a temperature excess of diodes over ambient temperature when power is dissipated in all the diodes included in the LED module.

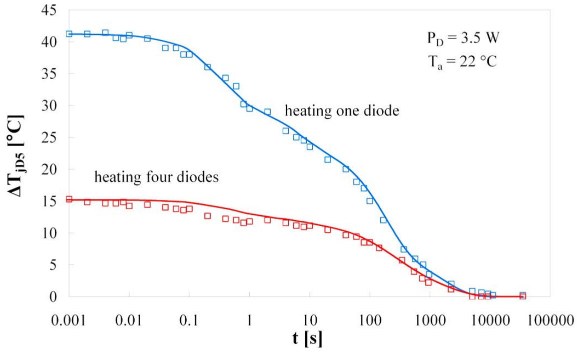
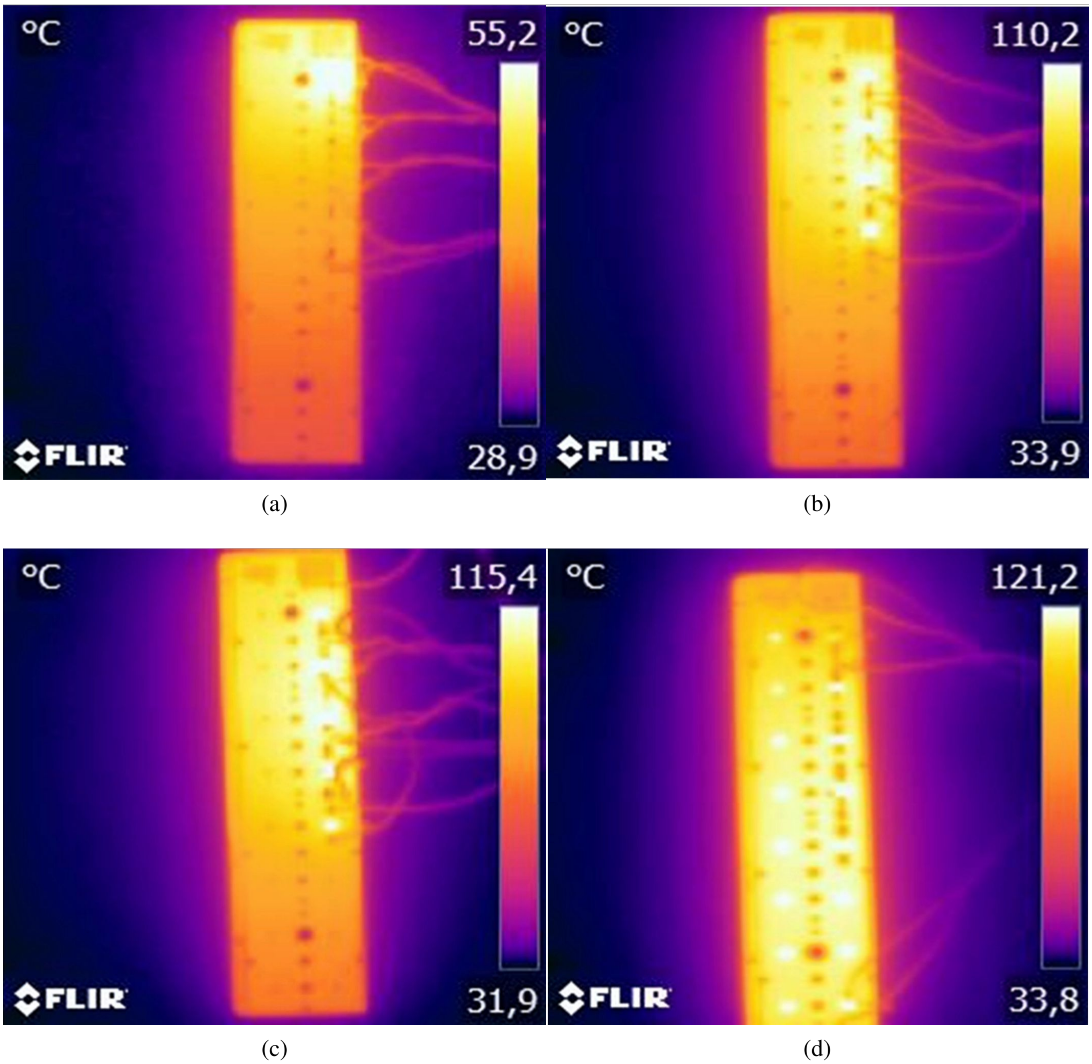


Fig. 8. Waveforms of a temperature excess ΔTj of diode D_5 at different conditions of power dissipation.



(a) (b) (c) (d)

Fig. 9. Measured temperature distribution on the surface of the tested module at different conditions of power dissipation: (a) diode D_1 fed only, (b) diodes D_1-D_4 fed, (c) diodes D_1-D_5 fed, (d) diodes D_1-D_{16} fed.

Thermographic measurements were performed with the use of an infrared camera of the type i5 by FLIR Systems. In Fig. 9a a thermogram of the tested module when only one diode D_1 is supplied with the current equal to 1.5 A is shown. In turn, Fig. 9b and Fig. 9c illustrate temperature distribution in the tested module when 4 or 5 diodes connected in series with forward current equal to 1.5 A are supplied. In these cases we obtain two different values of power dissipated equal to 18 W (4 diodes) and 22.82 W (5 diodes), respectively. Fig. 9d presents a thermogram for 16 LEDs connected in series, through which the forward current equal to 750 mA flows and power dissipated in the module is equal to 33.86 W.

As it is visible, in all the considered cases, diodes in which power is dissipated have the highest temperature in the module. Differences between the highest and the lowest temperature on the surface of the module can exceed even 48 °C when 5 diodes connected in series from D_1 to D_5 are supplied with the highest values of forward current (Fig. 9c). In turn, the smallest difference of the surface temperature of the LED module equal to about 14 °C is observed in case, when all the 16 LEDs are supplied by the current equal to 750 mA, which is shown in Fig. 9d. In this case through diodes connected in series much lower current flows, which reduces the influence of self-heating phenomena and results in bigger influence of mutual thermal couplings between the diodes situated in the same module.

6. Conclusions

In the paper, selected findings concerning thermal proprieties of the large LED module have been presented. The thermal model of this module was proposed in the form of RC network and it enabled easy estimation of the parameters values existing in this model. The model was verified experimentally for many cases of heat dissipation in this module. Essential influence on the increase in internal temperature of every diode was caused by mutual thermal couplings between the diodes contained in the module. It was shown that the results of calculations fit well the results of measurements both at the transient state and at the steady state.

It was shown that a strong non-uniform distribution of temperature occurred in the LED module. Differences between the values of internal temperature of each diode increased together with an increase in forward current. For the largest value of the considered current, temperature of each diode contained in the module differed between each other even by 48 K. It is advisable to take into account the system of cooling for this module at the stage of its designing.

The experiments were performed for the modules with different soldering manners. It was shown that the manner could visibly influence the values of self-thermal resistance of the diodes included in the considered model. An obvious influence of a soldering manner on mutual transient thermal impedances between the considered pairs of diodes was not observed, but one can see that mutual thermal resistance between the diodes changes when the distance between the diodes changes, as well.

Acknowledgements

Project financed in the framework of the program by the Ministry of Science and Higher Education called the „Regionalna Inicjatywa Doskonałości" in the years of 2019 and 2022, Project No. 006/RID/2018/19, the sum of financing 11 870 000 PLN.

References

[1] FARKAS G., BEIN M.C., GAAL L., *Multi domain modelling of power LEDs based on measured isothermal and transient I-V-L characteristics,* in PERRY J. (Ed.), *Proceedings of 22nd International Workshop on Thermal Investigations of ICs and Systems (THERMINIC)*, Budapest, 2016, p. 181.

[2] POPPE A., *Microelectron. J.*, 46 (2015), 1138.

[3] CHANG M.-H., DAS D., VARDE P.V., PECHT M., *Microelectron. Reliab.*, 52 (2012), 762.

[4] SONG B.-M., HAN B., LEE J.-H., *Microelectron. Reliab.*, 53 (2013), 435.

[5] GÓRECKI K., PTAK P., *Microelectron. Reliab.*, 79 (2017), 440.

[6] GÓRECKI K., DZIURDZIA B., PTAK P., *Solder. Surf. Mt. Tech.*, 30 (2) (2018), 81.

[7] DZIURDZIA B., SOBOLEWSKI M., MIKOŁAJEK J., *Solder. Surf. Mt. Tech.*, 30 (2) (2018), 87.

[8] UDDIN S., SHAREEF H., MOHAMED A., HANNAN M.A., *Przegląd Elektrotechniczny*, 88 (11) (2011), 266.

[9] GÓRECKI K., PTAK P., *Microelectron. Int.*, 32 (3) (2015), 152.

[10] WEIR B., *IEEE Spectrum*, 49 (3) (2012), 42.

[11] MARTIN P.S., *High power white LED technology for Solid State Lighting*, Lumileds, 2005.

[12] KRAMES M., *Progress and future direction of LED technology*. 2003, [Online], available at: `http://www.netl.doe.gov/ssl/PDF's/Krames.pdf`.

[13] SCHUBERT E.F., *Light emitting diodes. Second edition,* Cambridge University Press, New York, 2008.

[14] GÓRECKI K., *Microelectron. Reliab.*, 55 (2) (2015), 389.

[15] BAGNOLI P.E., CASAROSA C., CIAMPI M., DALLAGO E., *IEEE T. Power Electr.*, 13 (6) (1998), 1208.

[16] GÓRECKI K., PTAK P., *The influence of the mounting manner of the power LEDs on its thermal and optical parameters,* in: NAPIERALSKI A. (Ed.), *Proceedings of the 21st International Conference Mixed Design of Integrated Circuits and Systems MIXDES*, Lublin, 2014, 303.

[17] GÓRECKI P., GÓRECKI K., ZARĘBSKI J., *IOP Conf. Ser.*, 1033 (2018), 1.

[18] LASANCE C.J.M., POPPE A., *Thermal management for LED applications,* Springer Science+Business Media, New York, 2014.

[19] GÓRECKI K., PTAK P., JANICKI M., TORZEWICZ T., *Influence of cooling conditions of power LEDs on their electrical, thermal and optical parameters* in: NAPIERALSKI A. (Ed.), *Proceedings of 25th International Conference Mixed Design of Integrated Circuits and Systems MIXDES 2018*, Gdynia, 2018, 237.

[20] TORZEWICZ T., PTAK P., GÓRECKI K., JANICKI M., *Influence of LED Operating Point and Cooling Conditions on Compact Thermal Model Element Values,* in PERRY J. (Ed.), *Proceedings of the 24th International Workshop on Thermal Investigations of ICs and Systems*, Stockholm, 2018.

[21] GÓRECKI K., PTAK P., *Modelling LED Lamps with Thermal Phenomena Taken into Account*, in PERRY J. (Ed.), *Proceedings of 22nd International Workshop on Thermal Investigations of ICs and Systems (THERMINIC)*, Budapest, (2016), 202.

[22] `http://fideltronik.com/pl/` accessed on 2018.09.28.

[23] *Datasheet XP-G2 diode*, `https://www.cree.com/led-components/media/documents/XLampXPG2.pdf`, accessed on 2018.09.28.

[24] ILLES B., SKWAREK A., GECZY A., KRAMMER O., BUSEK D., *Int. J. Heat Mass Tran.*, 114 (2017), 613.

[25] LIVOVSKY L., PIETRIKOVA A., *Solder. Surf. Mt. Tech.*, 29 (1) (2017), 42.

[26] SYNKIEWICZ B., SKWAREK A., WITEK K., *Solder. Surf. Mt. Tech.*, 26 (1) (2014), 8.

[27] ULZHÖFER CH., *SMT*, 4 (2012), 1.

[28] *Data Sheet "ALPHA OM340 Solder paste"*, `https://alphaassembly.com/Products/Solder-Paste/OM-340` (2018), accessed on 2018.09.28.

[29] CASTELLAZZI A., GERSTENMAIER Y.C., KRAUS R., WACHUTKA G.K.M., *IEEE T. Power Electr.*, 21 (3) (2006), 603.

[30] GÓRECKI K., ZARĘBSKI J., *IEEE T. Comp. Pack. Man. Tech.*, 4 (3) (2014), 421.

[31] ZARĘBSKI J., GÓRECKI K., *Appl. Math. Model.*, 31 (8) (2007), 1489.

[32] ZARĘBSKI J., GÓRECKI K., *IEE Proc. Cicuits Dev. Sys.*, 153 (1) (2006), 46.

[33] RAYPAH M.E., DEVARAJAN M., AHMED A.A., SULAIMAN F., *J. Appl. Phys.*, 123 (10) (2018), 105703.

[34] *Datasheet A/D Converter USB-1608G,* `https://www.mccdaq.com/pdfs/manuals/usb-1608g-series.pdf`, accessed on 2018.09.28.

[35] *Datasheet of infrared camera Flir i5*, `http://www.amc-magazin.ro/PRODUSE-DOC/FLIR/FLIR%20i5.pdf`, accessed on 2018.09.28.

[36] OETTINGER F.F., BLACKBURN D.L., RUBIN S., *IEEE T. Electron Dev.*, 23 (8) (1976), 831.

[37] GÓRECKI K., ROGALSKA M., ZARĘBSKI J., *Microelectron. Reliab.*, 54 (5) (2014), 978.

[38] GÓRECKI K., PTAK P., *IEEE T. Instrum. Meas.*, (2019) in press, doi: 10.1109/TIM.2019.2894043

Received 2018-12-31
Accepted 2019-04-23