Measurements of thermal resistance of power LEDs

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Abstract

Purpose – The purpose of this paper is to present a new method of measuring thermal resistance of power light-emitting diodes (LEDs). Properties of power LEDs strongly depend on their internal temperature. The value of this temperature depends on the cooling conditions characterized by thermal resistance.

Design/methodology/approach – The new method of measuring the value of this parameter belongs to the group of electric methods. In this method, the problem of estimating the value of electrical power converted into light is solved. By comparing the values of the case temperature obtained for the LED operating in the forward mode and the reverse-breakdown mode, the thermal power is estimated. On the basis of the measured value of the thermally sensitive parameter (the LED forward voltage) and the estimated value of the thermal power, thermal resistance is calculated.

Findings – The elaborated method was used to measure thermal resistance of the selected types of power LEDs operating at different cooling conditions. The correctness of the elaborated measurement method was proved by comparing the results of measurements obtained with the use of the new method and the infrared method.

Research limitations/implications – On the basis of the obtained results of measurements and the catalog data of the tested diodes, the dependence of the measurement error of thermal resistance of the LED on its luminous efficiency is discussed.

Originality/value – The new measurement method is easy to use and more accurate than the classical method of thermal resistance measurement of the diode.

Keywords Measurements, Power LEDs, Thermal resistance, Solid state lighting, Self-heating, Thermal parameters

Paper type Research paper

Introduction

Nowadays, power light-emitting diodes (LEDs) are more and more frequently used, e.g. in lighting applications (Mroziewicz, 2010; Weir, 2012). The development of these devices is supported by the law regulations, e.g. in the European Union and in Australia (Weir, 2012; Uddin *et al.*, 2012). In many papers devoted to power LEDs, (Weir, 2012; Wiśniewski, 2009; Górecki and Zarębski, 2008; Krejcar and Frischer, 2013; Bianco and Parra, 2010; Qu *et al.*, 2011; Chen and Chung, 2011; Qin *et al.*, 2009), the problems connected with the use of these semiconductor devices for lighting are described (Górecki and Górecka, 2011; Górecki, 2013a, 2013b). To these problems belong the removal of heat generated in the considered devices (> 80 per cent of the energy received from the power source is exchanged into heat) (Weir, 2012; Cheng and Cheng, 2006), the fall of the luminous flux at the temperature increase (Qin *et al.*, 2009; Górecki and Górecka, 2011; Górecki, 2012a) and during the operation and the exponential decrease of life time with temperature (Górecki and Zarębski, 2008; Krames, 2003; Narendran and Gu, 2005).

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[DOI 10.1108/MI-11-2013-0069]

The properties of semiconductor devices, e.g. power LEDs, strongly depend on their internal temperature (Górecki and Górecka, 2011; Górecki, 2012a; Schubert, 2006). Temperature affects both the characteristics and parameters of semiconductor devices (Schubert, 2006; Amerasekera *et al.*, 1993; Zarębski, 1996; Janke, 1992; Rashid, 2007) and their reliability (Castellazzi *et al.*, 2006; Parry *et al.*, 2001; Ciappa *et al.*, 2002; Castellazzi *et al.*, 2002; Coquery *et al.*, 2001). The value of this temperature is equal to the sum of the ambient temperature and the excess of the temperature resulting from the self-heating phenomenon (Zarębski, 1996; Janke, 1992; Zarębski and Górecki, 2010; Masana, 2006; Rencz *et al.*, 2000). The thermal resistance is the parameter characterizing the ability of the semiconductor device to dissipate the heat generated in this device and the influence of the dissipated power on the internal temperature of this device (Zarębski, 1996; Janke, 1992; Masana, 2006; Rencz *et al.*, 2000; Oettinger and Blackburn, 1990; Górecki and Zarębski, 2003; Zarębski and Górecki, 2007a, 2007b, 2007c).

According to the classical definition, given, for example in Oettinger and Blackburn, 1990; Rubin and Oettinger, 1979; Blackburn, 2004, the thermal resistance R_{th} of the semiconductor device is equal to the quotient of the excess of the junction temperature T_j of this device over the temperature of the reference point T_0 through the thermal power P_{th} dissipated in the device which caused this excess:

$$R_{th} = \frac{T_j - T_a}{P_{th}} \tag{1}$$

The values of the ambient temperature and the dissipated power can be measured in a simple manner. The value of the temperature T_j must be measured at the steady state.

With regard to the manner by which the value of the temperature T_j is obtained, one can distinguish two kinds of methods measuring the device thermal resistance. The first are optical (infrared) methods (Zarębski, 1996; Janke, 1992; Rubin and Oettinger, 1979), in which the value of the device inner temperature is obtained by measuring infrared radiation energy emitted by the investigated device (Górecki and Zarębski, 2003). The others are electrical methods, in which the information about the device internal temperature results from the measurements of the device temperature-sensitive parameter of the known temperature dependence. The advantage of the electrical methods is the ability to estimate the thermal resistance of both capsulated and uncapsulated devices.

As seen in the study by Blackburn, 2004, the optical methods are dedicated mainly to uncapsulated devices, yet they can also be used to measure thermal resistance of the capsulated device, provided that the investigated device operates without any heat sink. In such operation conditions of the device, the difference between the case and the inner device temperature is negligibly small compared with the difference between the device internal temperature and the ambient temperature (Zarębski and Górecki, 2007a, 2007b, 2007c; Zarębski and Górecki, 2008).

In the group of electrical methods of measuring the device thermal resistance, the pulse methods are commonly used. In these methods, the investigated device is excited by the power rectangular pulses train, and the values of the thermo-sensitive parameter are measured during the break of the pulse excitation (Zarębski, 1996; Rencz *et al.*, 2000; Zarębski and Górecki, 2007a, 2007b, 2007c; Oettinger and Blackburn, 1990).

In electrical methods, the electrical parameter of the well-known and one-for-one dependence on temperature is used as a thermally sensitive parameter. In these methods, only one value of the averaged internal temperature of the device is measured. The big advantage of these methods is not their destructive character. As the thermally sensitive parameter, the voltage on the forward biased p–n junction is used.

In the literature, one can find many methods of measuring thermal resistance for the diode (e.g. Zarębski and Górecki, 2007a, 2007b, 2007c; Górecki and Zarębski, 2008). Unfortunately, the classical methods of measuring this parameter, used for other types of diodes, cannot be used for LEDs.

In semiconductor devices different than LEDs, the thermal power P_{th} is equal to the total power P dissipated in this device. On the contrary, in LEDs, some part of the electrical energy is transformed into light (the power P_L), and some part into heat (Poppe and Lasance, 2009; Górecki, 2012a, 2012b; Poppe *et al.*, 2006). Therefore, the thermal power can be calculated using the following equation (Górecki and Górecka, 2011; Poppe and Lasance, 2009; Górecki, 2012a, 2012b):

$$P_{th} = P - P_L \tag{2}$$

The omission of light radiation in energy balance causes the understating of the value of thermal parameters. The participation of light in energy balance increases with the development of the LED technology and with an increase in the obtained values of luminous efficiency (Górecki, 2013a, 2013b). The total power is equal to the product of the current and the voltage. In turn, the lighting power can be estimated in three ways:

1. the measurement of the power of optical radiation in the photometric sphere;
2. the measurement of the spectral characteristics and the emission angle and the integration of the spectral characteristic; and
3. the measurement of the lighting power demands special instrumentation.

In the paper (Górecki, 2013a, 2013b), two solutions of the described problem are proposed. The first consists in measuring thermal resistance of the investigated LED operating in the reverse-breakdown range. The other solution consists in estimating the power of the emitted light with the use of equations presented in this paper and the data given by the producers. The presented results of measurements prove that both the mentioned manners ensure obtaining the results of close values.

In this paper, which is an extended version of the paper published by Górecki, 2013a, 2013b, a new method of measuring thermal resistance of power LEDs is proposed. In this method, the energy emitted in the form of heat is obtained after the comparison of characteristics of the investigated LED measured in the forward mode and the breakdown mode.

In next sections, the idea of the measurement method and the measuring set realizing this method are described. Some results of measurements of the selected types of the power LEDs illustrating the correctness of the worked out method and the analysis of the measurement error are presented.

Description of the method

The new method belongs to the group of electrical methods. The temperature-sensitive parameter is the voltage on the forward biased LED at the small value of the forward current. The thermal power is estimated by comparing the device case temperature during its operation in the forward mode and in the reverse-breakdown region. The difference between the total power dissipated in the LED in both the modes of its operation at the same value of the case temperature is equal to the optical power.

The proposed method is realized in four steps. To use the considered thermally sensitive parameter, the previous calibration of the thermometric characteristic u(T) of the investigated diode at the chosen value of the forward current is indispensable. This calibration is the first step of the measurement. The considered characteristic is nearly linear (Oettinger and Blackburn, 1990; Blackburn, 2004; Górecki and Zarębski, 2001), its slope is F = du/dT and the value of this voltage in the temperature T_a is equal to u_A.

In the second step of the measurement, the investigated diode is forward biased, and the current of the diode has a shape of the rectangular pulses train. The high level of the diode current I_H should be chosen, so that the increase in the

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junction temperature of the diode due to a flow of this current is significant, whereas the low level of this current I_L is equal to the values of this current during the calibration. The frequency of the current of the investigated diode should be low (near some hertz), and the duty of the time course of this current should be close to 1. In this step of the measurement, the values of the forward voltage in the end of the high level of the current course and u_L immediately after switching to the low level of this current are measured. This stage is continued until a steady state is obtained. On the basis of the value of the voltage u_L, the value of the junction temperature T_j is read from the thermometric characteristic (measured in the first step). Additionally, at the steady state, the value of the temperature of the metal part of the diode case T_{CF} by means of the pyrometer or thermoresistor is measured.

In the third step of the measurement, the investigated diode operates in the reverse-breakdown mode. In this step, the voltage on the diode u_{BR} and the case temperature T_{CB} are measured. The value of the breakdown current I_{BR} should be chosen in such a manner that the steady-state value of the temperature T_{CB} is equal to the temperature T_{CF} obtained at the end of the second step.

In the fourth step, the values of the thermal resistance of the LED are calculated from the equation:

$$R_{th} = \frac{u_L - u_A}{F \cdot (I_{BR} \cdot u_{BR})} \tag{3}$$

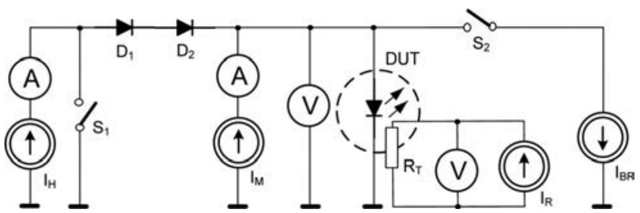
Measurement set

The measuring method described in the previous section can be realized in the measuring set, the block scheme of which is shown in Figure 1.

In this set, the thermoresistor R_T is situated in the case of the investigated LED (DUT). The thermoresistor R_T is supplied by the current source I_R, and the voltage on this thermoresistor is measured by the voltmeter calibrated in units of temperature. The value of the current I_R is very small. Therefore, the power dissipated in the thermoresistor is negligibly small compared to the power dissipated in the DUT. The current source I_M extorts the current of the investigated LED during the calibration and at the low level of the current during the second step of the measurement.

The high level of the current in the second step of the measurement determines the current source I_H. In turn, the investigated diode in the third step of the measurement is supplied by the current source I_{BR}. The switch S_1 is opened during the calibration and in the third step of the measurement, whereas in the second step of the measurement, it is periodically closed in time indispensible for measuring the voltage on the investigated LED at the current I_M.

Figure 1 The block diagram of the measuring set



Diodes D_1 and D_2 protect the current source I_M against the short-circuit with the switch S_1. The switch S_2 is opened in the first and in the second step of the measurement and closed in the third step of the measurement.

Results of measurements

Using the measuring method described in the second section and the measuring set described in the third section, the thermal resistance of the selected power LEDs is measured. In Figures 2 and 3, the results of measurements of the LED of the type OF-HPW-5EL by Optoflash of the power dissipated equal to 5 W are shown. The luminous efficiency of this diode is equal to 42 lm/W. Two cases are considered: in the first, the diode is situated on the aluminium heat sink of the dimensions $75 \times 100 \times 2$ mm^3, and in the second, the diode operates without any heat sink.

In Figure 2, the measured dependences of the case temperature of the LED on the power dissipated in this diode operating in the forward mode (the solid line) and in the breakdown range (the dashed line) are shown.

As it can be seen, at the same value of the power dissipated in the diode, the higher (even by several degree celsius) values of the case temperature of the device operating in the breakdown range are obtained. This is due to the fact that in the breakdown range, all the dissipated power in the diode is exchanged into heat, whereas in the forward mode, some part

Figure 2 The measured dependences of the case temperature on the dissipated power

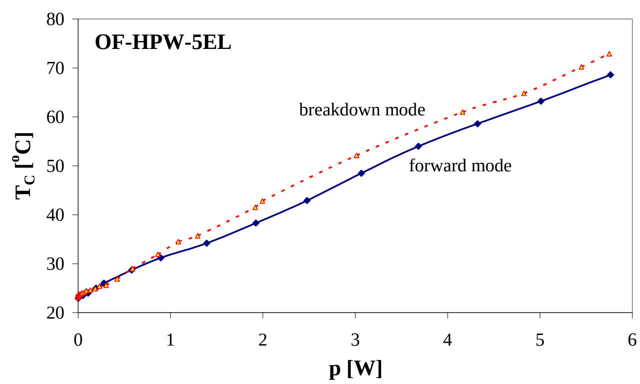
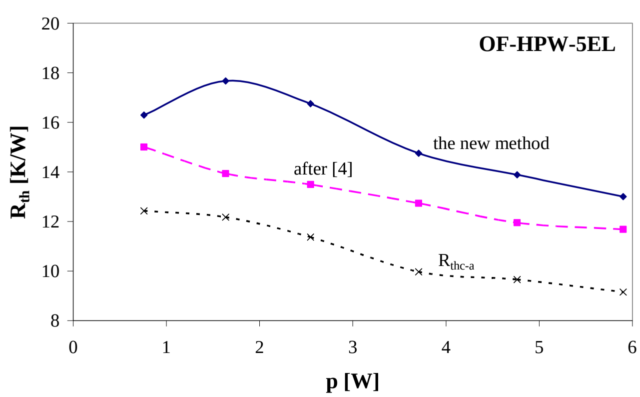


Figure 3 The measured dependences of thermal resistance on the dissipated power



of electrical energy is exchanged into light, and the other part into heat. Analyzing the obtained course $T_C(p)$, one can notice that the identical values of the case temperature of the investigated diode operating in the breakdown range and in the forward mode are obtained when the dissipated power in the diode operating in the breakdown range is about 0.5 W higher than the power dissipated in the breakdown range. This means that a dozen or so per cent of the energy received from the power source is exchanged into heat. It is worth noticing that the difference between the considered courses $T_C(p)$ is the highest when the power is <3 W. It is convergent with the results of measurements of dependences of intensity of the emitted radiation on the forward current presented in previous papers (Górecki and Górecka, 2011; Rubin and Oettinger, 1979).

The calibration of the thermometric characteristics u(T) of the considered diode in the range of temperatures from 20-120°C is performed. The linear dependences u(T) are obtained, and their slope in a wide range of forward currents is equal to −1.5 mV/K.

In Figure 3, the measured dependences of the thermal resistance R_{th} of the considered diode on the dissipated power are presented. In this figure, the solid lines denote the results of measurements obtained by means of the method proposed in the present paper, the dashed lines denote the results obtained by means of the classical impulse method (Oettinger and Blackburn, 1990) and the dotted lines denote the results of measurements of thermal resistance between the case and the surrounding R_{thc-a} obtained with the method from the paper (Górecki, 2012a, 2012b).

As it can be noticed, thermal resistance is a decreasing function of power. The omission of the exchange of some part of electrical energy into light results in understating the value of thermal resistance even by about 20 per cent. In turn, thermal resistance between the case and the surrounding R_{thc-a} is even about 30 per cent smaller than the thermal resistance junction-to-ambient R_{thj-a}.

In Figures 4 and 5, the measured dependences of thermal resistance on the dissipated power for two diodes of different values of the admissible power, operating at different cooling conditions, are presented. In these figures, the solid lines mark the results of measurements obtained by omitting the power of the emitted light ($P_{th} = P_0$), while the dashed lines mark the results obtained while taking into account this component of the power ($P_{th} = P_0 - P_L$). The values of luminous efficiency η_L are calculated on the basis of the catalog data of the investigated diodes, and the following values of this parameter are obtained: 16.7 lm/W for the diode LXHL-BW03 and 40 lm/W for the diode OF-HPW5-3EL.

Figure 4 illustrates the influence of cooling conditions of the diode LXHL-BW03 on the dependence of thermal resistance of this diode on the dissipated power. The measurements are performed both for the diode operating without any heat sink and for the diode situated on heat sinks of different dimensions.

As it can be noticed, for all the considered cooling conditions, the monotonically decreasing dependence $R_{th}(p)$ is obtained. Of course, an increase in sizes of the heat sink causes a decrease in thermal resistance by even several times. Big values of thermal resistance observed within the range of

Figure 4 The measured dependences of thermal resistance of the diode LXHL-BW03 on the dissipated power

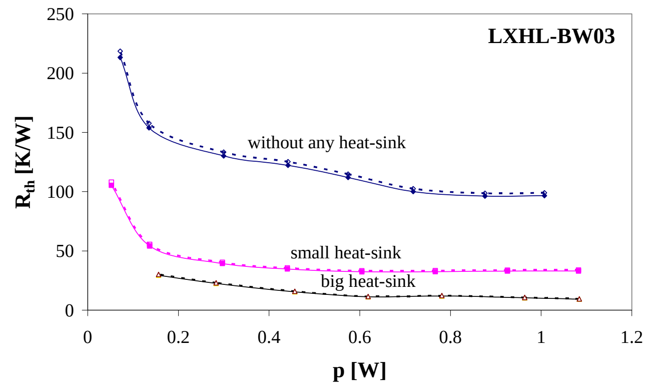
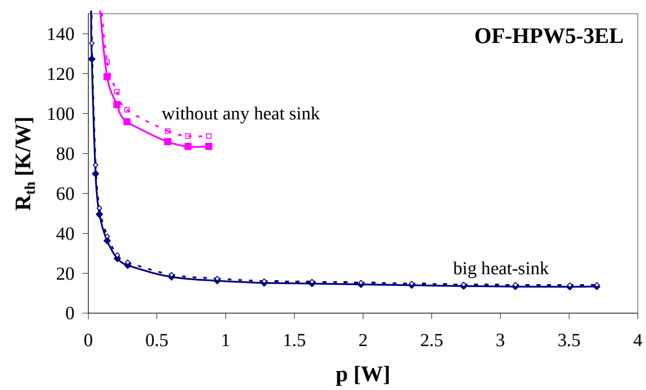


Figure 5 The measured dependences of thermal resistance of the diode OF-HPW5-3EL on the dissipated power



low values of the dissipated power are connected with the low efficiency of convection and radiation. In the case, when the power P_L is taken into account, the value of thermal resistance is higher than in the case when this part of the power is omitted. Yet, the difference between the values of thermal resistance obtained in both the considered cases is not large and does not exceed 3 per cent.

In turn, Figure 5 illustrates the influence of cooling conditions on the dependence of thermal resistance of the diode OF-HPW5-3EL on the dissipated power. As it can be observed, together with an increase in the value of the dissipated power, the fall in the value of thermal resistance occurs connected with an increase in the efficiency of the accompanying heat as a result of convection and radiation. The value of thermal resistance of the diode operating without any heat sink is so high that it causes limitation of the value of the power dissipated in the investigated diode to about 1 W, because exceeding this value could lead to a damage of the device. The use of the heat sink causes more than fivefold decrease in thermal resistance and operation of this diode at the nominal value of the forward current. For the considered diode, taking into account the power of the emitted light causes an increase in the value of thermal resistance even by about 6 per cent.

Comparing the results of measurements presented in Figures 3–5, it can be noticed that the shape of the obtained dependences $R_{th}(p)$ for different types of power LEDs is similar, but for the diode of the higher value of luminous efficiency, a greater influence of the power of the emitted light on the obtained value of thermal resistance is obtained.

The value of thermal resistance of the diode can be measured both in the forward mode and in the reverse-breakdown range. The essential advantage of measurements of this parameter in the reverse-breakdown range is elimination of the error due to the omission of the power of the emitted light, because, as it is commonly known, in the reverse-breakdown range, the LED does not emit light.

In Figure 6, the measured dependences of thermal resistance of the diode OF-HPW5-3EL on the power are shown, whereas the curve marks the results of measurements obtained at the forward mode of the investigated diode omitting the power of the emitted light, the curve b marks the results of measurements obtained in the forward mode of the investigated diode taking into account the power of the emitted light and the curve c marks the results of measurements obtained for the diode operating in the reverse-breakdown range.

As it can be observed, after taking into account the power of the emitted light, the values of thermal resistance obtained for the diode operating in the forward mode and in the reverse-breakdown range have the nearing values, whereas the omission of this power causes the values of thermal resistance obtained to be understated by about several per cent. Then, the estimation of the power of the emitted light makes it possible to obtain essential improvement in the accuracy of the measurement of thermal resistance.

However, the considered diodes are characterized by not high value of luminous efficacy (to 40 lm/W). Meanwhile, as it appears in the literature (Mroziewicz, 2010; Narukawa *et al.*, 2010), in some laboratories already the power LEDs of luminous efficiency exceeding even 240 lm/W are worked out, and, according to the forecasts of USA DOE in the year 2020, such luminous efficacy should reach the commercially accessible light sources LED (*LED Magazine*, 2010).

In Figure 7, the dependence of the relative error of measurements of thermal resistance of LED resulting from the omission of the power of the emitted light on luminous efficiency of the investigated diode is illustrated. The presented results are calculated using the equation from Górecki, 2012a, 2012b.

Figure 6 Dependence of thermal resistance of LED on the dissipated power

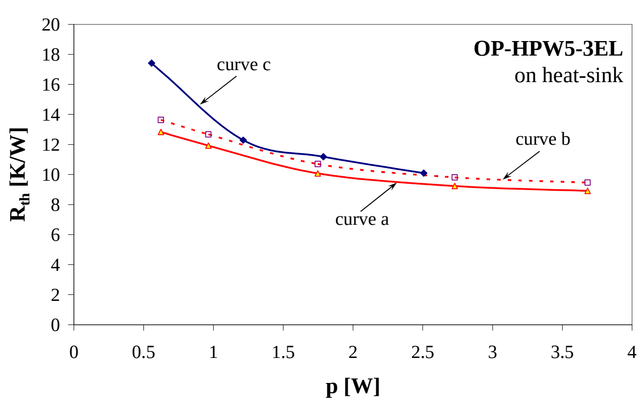
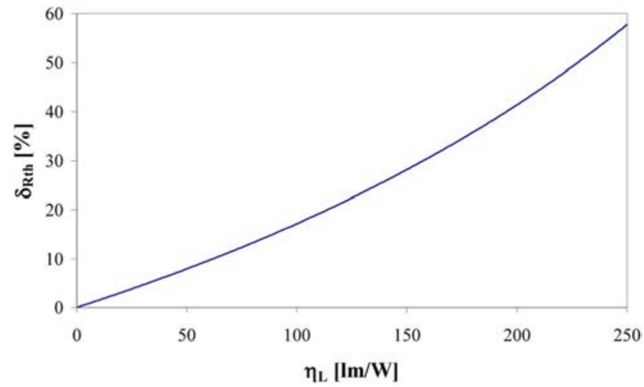


Figure 7 The calculated dependence of the measurement error of the LEDs thermal resistance on its luminous efficiency



As it can be observed, together with an increase in the luminous efficiency of the LED, the measuring error of the thermal resistance of this device resulting from the omission of the power of the emitted light increases too. The value of this error is not high for LEDs of the older type of low luminous efficacy. However, luminous efficiency of the value equal to 60 lm/W causes that the considered error attains 10 per cent, and at the luminous efficiency exceeding 200 lm/W, this error exceeds even 40 per cent.

Conclusions

In the paper, the new method of measuring thermal resistance of power LEDs is proposed. This method is based on the electric impulse method, and additionally, it takes into account the fact of the exchange of the part of electrical energy into light. The obtained results of measurements confirm that the use of the classical method of the thermal resistance measurement of the diode for power LEDs can result in understating the value of thermal resistance even by about 15 per cent.

It results from the obtained measurements that for the old-style power LEDs, characterized by the low value of luminous efficiency, the omission of the power of the emitted light does not cause a large measuring error. On the other hand, together with the development of technology of power LEDs, which results in an increase of luminous efficiency, the problem of taking into account the power of the emitted light in the measurements of thermal resistance is more and more significant. Assuming the present dynamics of the development of technology of solid-state light sources, in this decade, they will probably reach the value of $\eta >240$ lm/W. At such a value of η, the omission of the power of the emitted light will cause the measuring error of thermal resistance of LEDs to exceed even 40 per cent, which is not an acceptable value.

The accuracy of the described method depends on the measuring error of the voltage on the forward biased diode and the measuring error of the case temperature of the diode operating in the forward mode and in the breakdown range. One should notice that this measurement should be performed at the steady state, which for the diode situated on the heat sink can be observed even after 1 hour.

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