

# THERMAL INVESTIGATION OF HIGH POWER OPTICAL DEVICES BY TRANSIENT TESTING

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## ABSTRACT

In case of opto-electronic devices the power applied on the device leaves in a parallel heat and light transport, the interpretation of  $R_{th}$  is not obvious. The paper shows results of a combined optical and thermal measurement for the characterisation of power LEDs. A model explaining  $R_{th}$  changes at different current levels is proposed.

## 1. INTRODUCTION

It started just like a routine  $R_{th,JC}$  measurement. We wanted to measure the junction-to-case thermal resistance of high power LEDs, using the well established structure function method.

Later we had to reconsider how we define thermal resistance, and still a lot of interesting questions remained open for discussion for people in semiconductor design and thermal analysis.

The problem originated when we measured the thermal behaviour of solid-state (LED) light sources. These devices have a sandwich-like heat-removal path of different materials ending in a copper cooling slug.

We captured the cooling transients after switching off from different power levels in the setup of Figure 1. Using current levels e.g. of 60 mA, 75 mA, 150 mA and 300 mA we gained cooling curves as in Figure 2.

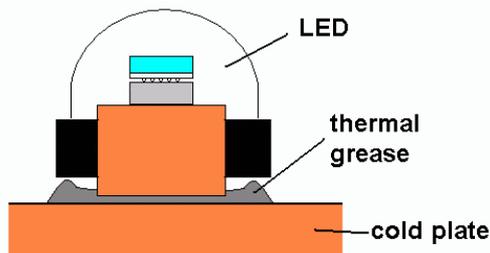


Figure 1 High power LED with cooling slug

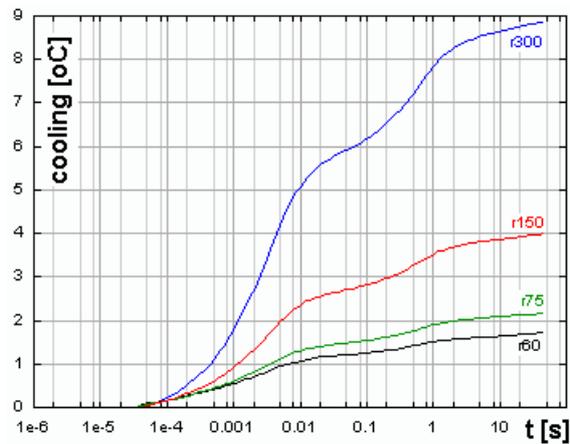


Figure 2 Cooling of a red LED from four different current levels

(With the usual reference direction elevating curves correspond to cooling.) The initial electric disturbances were removed by a correction discussed later.

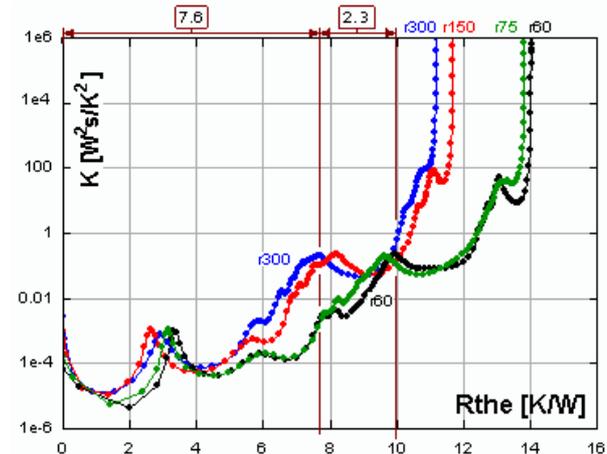


Figure 3 Differential structure functions calculated from the transients

For calculating junction-to-case thermal resistances we used the structure function approach ([2],[3], also [4] in this issue). An evaluation software converted the transients to structure functions like in Figure 3.

Reading the peak positions representing the  $R_{th\_JC}$  junction-to-case thermal resistance we get 7.6 K/W, 8.2 K/W, 9.6 K/W, 9.9 K/W for the four current levels on a red sample. For the  $R_{th\_JA}$  junction-to-“ambient” thermal resistance (interpreting the “ambient” as the end of the device + grease + cold-plate system) we can read 11.1 K/W, 11.6 K/W, 13.3 K/W, 14.0 K/W.

This drastic shift in  $R_{th\_JC}$  at less than 9 °C temperature elevation needs clarification. We attempt to give this in the subsequent sections.

## 2. CONSIDERATIONS

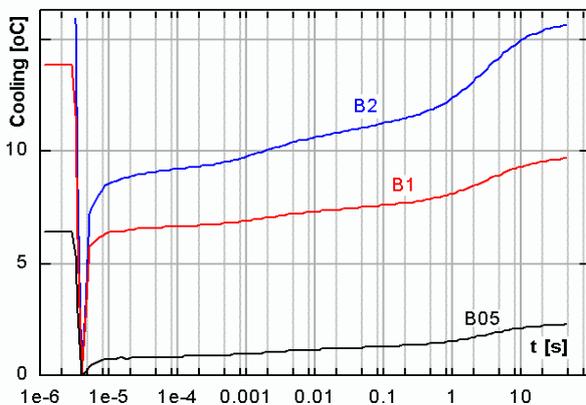
We are accustomed to the use of a single  $R_{th}$  value for calculating junction temperature at all powering levels. For most silicon devices  $R_{th}$  differs only at very high temperature change due to the nonlinearity of material parameters and heat irradiation [7]. Other descriptive functions ( $Z_{th}$ , structure functions) are also very much alike regardless the power level applied.

Figure 4 shows the raw transients of a silicon power diode at 0.5 A, 1 A and 2 A forward current.

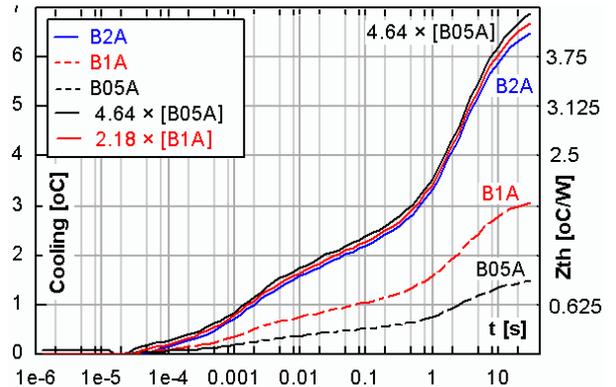
Figure 5 shows the “smooth” cooling curves. The removal of the initial transients is unambiguous, because steep electric transients end in a flat temperature change. The figure also shows curves normalised to the highest applied power upon Table 1. Real curves can be read in temperature on the left y-axis, normalised curves can be read in  $Z_{th}$  (i.e. multiplied by 1/P) on the right axis.

*Table 1 Power values of the measured Si diode*

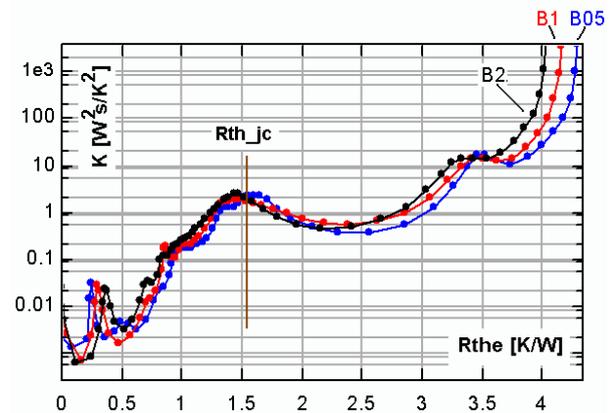
<b>I<sub>F</sub> [A]</b>	0.5	1	2
<b>P [W]</b>	0.345	0.735	1.6
<b>1/P</b>	2.89	1.36	0.625
<b>P<sub>max</sub>/P</b>	4.64	2.18	1



*Figure 4 Captured transients of a silicon power diode at 0.5A, 1 A and 2A*



*Figure 5 Cooling curves of a silicon power diode at 0.5A, 1 A and 2A*



*Figure 6 Differential structure functions of a silicon power diode at 0.5A, 1 A and 2A*

In Figure 6 we find the differential structure functions, the device has 1.5 °C/W junction-to-case thermal resistance at all power levels.

In LED devices there are several specific effects influencing thermal behaviour, like:

- Parallel energy transfer from the junction to the ambience as heat and light
- Materials of low  $\lambda$  thermal conductivity, large part of the heat conductance path lies in the die
- Thin epitaxial layers are grown on insulating substrate, causing high lateral resistance ([9])
- The diffusion charge in the junction can be changed by a lateral current flow only resulting in slower transients.

## 3. MODELLING

As a first attempt to explain changing  $R_{th}$  values at different powering let us make a very simple model for the LED (Figure 7).

Suppose the basic effect can be modelled as an ideal diode having the usual  $U_D = mU_T \cdot (\ln(I/I_0))$  characteristics. The total electric power fed into this internal device is  $P_D = U_D \cdot I$ . Suppose our device has a constant  $\eta_0$  efficiency and

it emits  $P_{opt} = \eta_0 \cdot P_D$  optical power regardless the power level. Electric losses can be considered in the simplest case as a resistor in series. We do not count optical losses now.

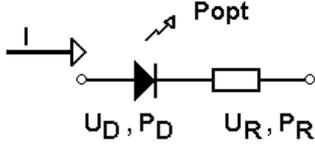


Figure 7 Simple LED model

Before going further we have to define more precisely what the  $R_{th}$  value the x-axis is scaled in is in previous figures.

If  $P_{el}$  is the electric input power,  $P_{opt}$  is the emitted optical power and  $P_{heat}$  remains as heat in the structure we can define

$$R_{the} = \Delta T / P_{el} \quad (1)$$

as *effective* thermal resistance for calculating the thermal stress on the actual packaged device at a certain powering, and

$$R_{thr} = \Delta T / P_{heat} = \Delta T / (P_{el} - P_{opt}) \quad (2)$$

as *reduced* or *residual* thermal resistance for characterising package quality, not influenced by the actual type (colour, etc.) of the packaged LED. The structure functions of Figure 3 are obviously scaled in  $R_{the}$ .

Due to the serial resistor we measure an  $\eta_1$  actual efficiency lower than  $\eta_0$  at higher current levels:

$$h_1 = P_{opt} / P_{el} = h_0 \cdot P_D / (P_D + P_R) \quad (3)$$

We have to note that the location of electric losses in the physical structure influences the thermal behaviour. If the effect represented by the serial resistance is in a material section near to the junction and thermally strongly coupled to it, we can say:

$$P_{heat} = P_D + P_R - h_0 \cdot P_D \quad (5)$$

$$\Delta T = P_{heat} R_{thr} = [(1 - h_0) \cdot P_D + P_R] \cdot R_{thr} \quad (6)$$

$R_{thr}$  corresponds to the thermal characteristics of the package, so it can be treated as a constant value, independent of the powering level. We can express  $R_{the}$  as

$$\begin{aligned} R_{the} &= \Delta T / P_{el} = \frac{[(1 - h_0) \cdot P_D + P_R]}{P_D + P_R} R_{thr} \\ &= R_{thr} - h_0 \frac{P_D}{P_D + P_R} R_{thr} = (1 - h_1) \cdot R_{thr} \end{aligned} \quad (7)$$

(7) means that we measure expanding  $R_{the}$  curves with growing power levels.

If the effect represented by the resistor is in a material section far from the junction and thermally strongly coupled to the case (well cooled),  $P_R$  does not cause much heating and we get

$$P_{heat} = P_D - h_0 \cdot P_D \quad (8)$$

$$\Delta T = P_{heat} R_{thr} = (1 - h_0) \cdot P_D \cdot R_{thr} \quad (9)$$

$$R_{the} = \Delta T / P_{el} = \frac{[(1 - h_0) \cdot P_D]}{P_D + P_R} R_{thr} \quad (10)$$

$$\begin{aligned} R_{the} &= \frac{P_D + P_R - P_R - h_0 \cdot P_D}{P_D + P_R} R_{thr} \\ &= R_{thr} - \left( h_0 \frac{P_D}{P_D + P_R} + \frac{P_R}{P_D + P_R} \right) R_{thr} \\ &= \left( 1 - h_1 - \frac{P_R}{P_D + P_R} \right) \cdot R_{thr} \end{aligned} \quad (11)$$

Different forms of (11) suggest that with this model we shall experience both shrinking and expanding effects on  $R_{the}$  curves with changing power levels.

For normal devices with no parallel energy transport we can use (7) and (11) with  $\eta_1=0$ . We really see a slight shift of the peaks towards the junction in Figure 6 that can mean that a part of the serial resistance is in a “cooler” material section.

#### 4. MEASUREMENTS

We repeated the thermal transient measurements on the high power LEDs with a photodiode attached to the fixture to measure the (relative) light emission of the LED. The photocurrent was recorded on another channel of the transient tester ([6], Figure 8).

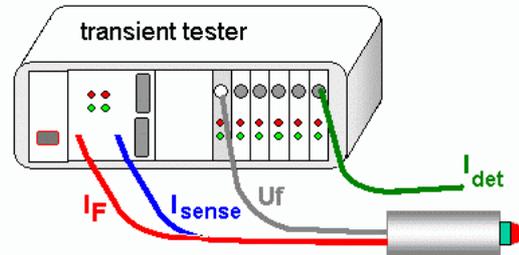


Figure 8 Electric side of a combined measurement: Powering the LED for the optical measurement, capturing the thermal transient after switching off

In some cases we also measured absolute emission in a CIE standard [5] optical measurement (Figure 9).

We selected current values of 60 mA, 75 mA, 150 mA and 300 mA again for the powering and 10 mA sensing current for the cooling. Besides the 60 s long transients we also measured more steady-state points for having the static characteristics of the LED.

Table 2 contains measured and calculated data for a few selected operating points.  $R_S$  grows at higher current, which is a known effect.  $P_{el}$  differs a bit from  $P_D + P_R$  because we used a constant  $R_S$  value of 1.9  $\Omega$  for simplicity.

Figure 10 (and for a few points the first three columns of

Table 2 Measured and calculated data for selected operating points

I mA	U <sub>f<sub>h</sub></sub> V	U <sub>f<sub>c</sub></sub> V	P <sub>el</sub> mW	P <sub>opt</sub> mW	h <sub>l</sub>	P <sub>heat</sub> W	R <sub>s</sub> W	P <sub>D</sub> mW	P <sub>R</sub> mW	P <sub>D+P<sub>R</sub></sub> mW
	hot	cold						at R <sub>S</sub> = 1.9Ω		
2	1.719		3.4					3.44	0.01	3.45
10	1.822		18.2					18.3	0.20	18.5
20	1.882		37.6					37.5	0.78	38.2
60	2.030	2.033	122	45.1	0.37	76.7		117	7.0	124
75	2.078	2.082	156	54.5	0.35	101	1.59	147	11	158
150	2.280	2.287	342	106	0.31	236	1.84	301	44	344
300	2.634	2.650	790	205	0.26	584	1.95	615	175	791

Table 2) show the forward voltage versus the forward current. The upper U<sub>f<sub>h</sub></sub> curve is the “hot” plot, which was measured waiting until steady state in each operating point, the lower U<sub>f<sub>c</sub></sub> is the characteristics of the “cold” diode, measured by pulse technique. Heating transients occur as the tiny voltage change between the two curves along a steady current. Cooling cannot be directly interpreted in this plot.

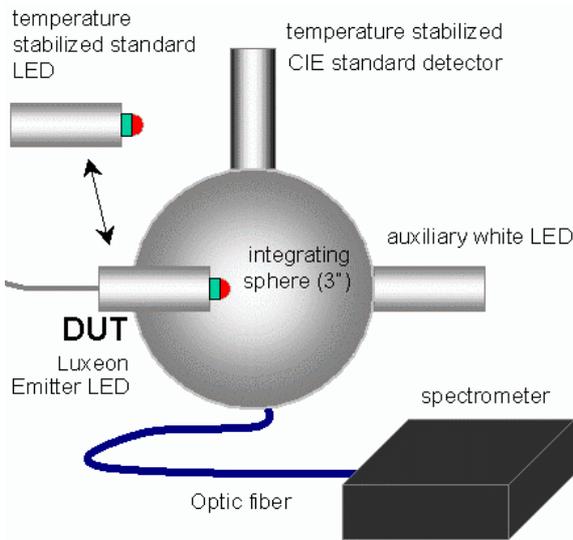


Figure 9 Optical side of a combined measurement: measuring the total light output and spectral power distribution of the LED

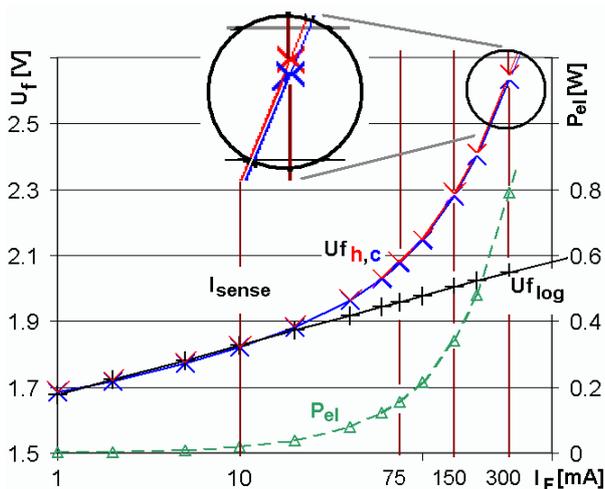


Figure 10 Forward voltage and power on the LED vs. forward current

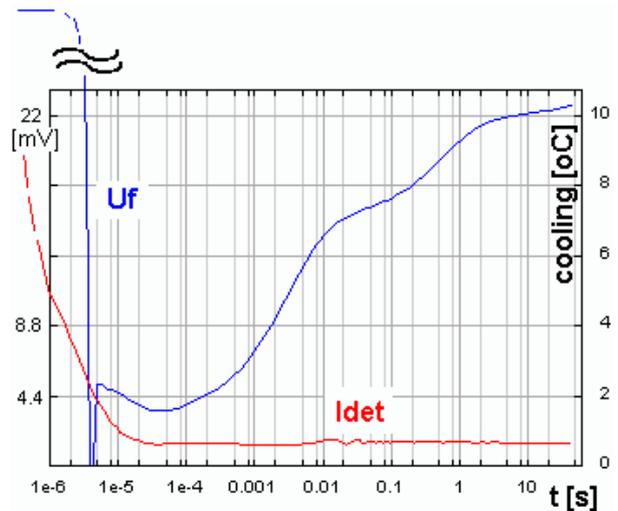


Figure 11 Voltage across the LED and photocurrent of the detector, I<sub>F</sub>=300 mA to 10 mA

Figure 10 also shows P<sub>el</sub> belonging to operating currents and the “ideal” logarithmic diode characteristics used to calculate the R<sub>S</sub> values of the model.

A recorded transient of a red LED is shown in Figure 11. It proves that the initial electric transient is largely the discharge of the diffusion capacitance. I<sub>det</sub> (proportional through the emitted light to the recombination and so to the charge in the junction) diminishes together with the forward voltage and stabilises afterwards at the level belonging to the sensor current.

In the total emitted light power measurement (Figure 9) we got first the F<sub>x</sub> light flow values calculated from the photocurrent of the calibrated detector.

For getting the emitted optical power we measured afterwards the relative spectral power distribution (rSPD) of the LED and calculated the emitted P<sub>opt</sub> power, using the known spectral sensitivity of the calibrated detector. The η<sub>1</sub> light emission can be gained from P<sub>el</sub> and P<sub>opt</sub> (Table 3).

Table 3 Measured values of a red LED in the total luminous flux measuring geometry

	R60	R75	R150	R300
$I_F$ [mA]	60	75	150	300
$I_{det}$ [ $\mu$ A]	16.38	20.03	38.15	72.71
$F_x$ flux [lm]	7.77	9.50	18.09	34.48
$P_{opt}$ [mW]	45.1	54.5	106	205
$P_{el}$ [mW]	122	156	342	790
$h_J$	0.37	0.35	0.31	0.26

### 5. EVALUATION

Let us check now whether our model can be verified by the measurement results.

Figure 12 attempts to display different current dependent amounts in an intricate but condensed chart. Besides power values we see the ratio of the detected  $I_{det}$  photocurrent to  $I_F$ ,  $P_{el}$  and  $P_D$ . We displayed these efficiency values, and also  $R_{th\_JC}$  values from Figure 3 relative to their value at 60 mA.

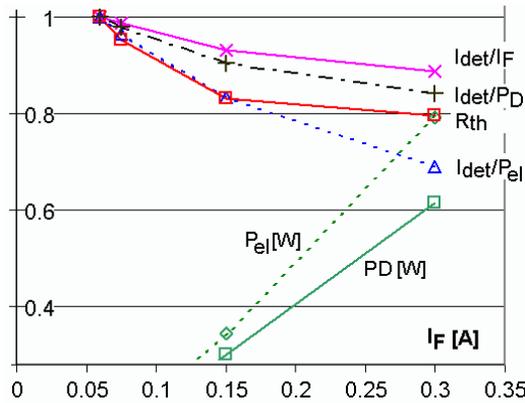


Figure 12 Thermal resistance, efficiency values and heating power vs. forward current of the LED

The chart shows that  $I_{det}/I_F$  and  $I_{det}/P_D$  slowly diminish at growing currents in this range,  $I_{det}/P_{el}$  sinks faster. (Other experiments have shown a maximum efficiency at 5 mA.) Our model with constant  $h_O$  (constant  $I_{det}/P_D$ ) is acceptable but the  $I_{det}/I_F$  curve suggests that a better model can be built assuming constant quantum efficiency.

For model evaluation we use the same technique as in Figure 5. In Table 4 we listed the  $P_{heat}$  values calculated from  $P_{el}$  with different assumptions of section 3, and also the normalisation factors related to the maximum power at 300 mA current. We can observe that  $(1-h_J)$  is monotonous (“hot resistor” model),  $Y=1-h_J-P_R/(P_D+P_R)$  has a maximum (“cool resistor” model).

Figure 13 shows the measured cooling curves of the LED. The base curve belonging to  $I_F=300$  mA remained unchanged, the y-axis of the chart is scaled in  $^{\circ}$ C for this curve. All other curves are multiplied by the ratio of their

Table 4 Power calculations for different models

Measured					
$I_F$	[mA]	60	75	150	300
$P_{el}$	[mW]	122	156	342	790
$P_{max}/P$		<b>6.48</b>	<b>5.06</b>	<b>2.31</b>	<b>1</b>
$h_J$		0.37	0.35	0.31	0.26
$1-h_J$		0.63	0.65	0.69	0.74
Hot resistor model					
$P_{heat}=P_{el}(1-h_J)$	[mW]	77	104	241	596
$P_{max}/P$		<b>7.75</b>	<b>5.72</b>	<b>2.47</b>	<b>1</b>
Cool resistor model					
$P_R/(P_D+P_R)$		0.057	0.069	0.127	0.222
$Y=1-h_J-P_R/(P_D+P_R)$		0.573	0.581	0.563	0.518
$P_{heat}=P_{el}*Y$	[mW]	70	91	192	409
$P_{max}/P$		<b>5.85</b>	<b>4.52</b>	<b>2.13</b>	<b>1.00</b>
"Best fit"					
$P_{max}/P, t_0=500$ ms		<b>6.12</b>	<b>4.95</b>	<b>2.36</b>	<b>1</b>
$P_{max}/P, t_0=10$ ms		<b>6.30</b>	<b>4.99</b>	<b>2.39</b>	<b>1</b>

actual  $P_{el}$  value related to that of the base curve. An arbitrary fitting point at  $t_0=500$   $\mu$ s was selected for all similar figures in this section.

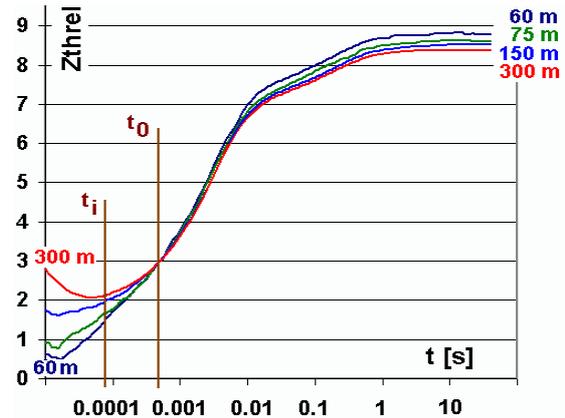


Figure 13 Normalised measured cooling curves

Figure 14 and Figure 15 are scaled using the “hot resistor” and the “cool resistor” model. These curves depict how the ideal “model LEDs” would behave if they produced the measured  $P_{el}$  and  $P_{opt}$  values.

We can see that the curves related to  $R_{thr}$  shrink and expand like an accordion, the base curve belonging to 300 mA remains in the same position. In the high time range the curves belonging to low currents run above the base curve for the real LED and the “hot” model, they run below for the “cool” model. This implies that our structure has an equivalent serial resistor which is in a “rather hot than cool” position. We can also find a best fit for normalised cooling curves, fitting them to the base curve between  $t_0$  and the end of the cooling. Table 4 gives

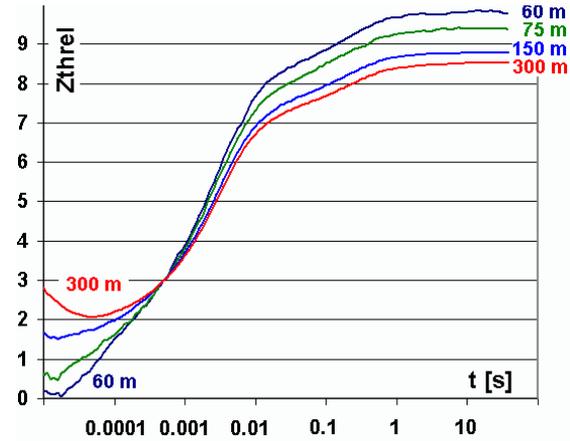


Figure 14 Normalised cooling curves, scaled to the "hot resistor" model

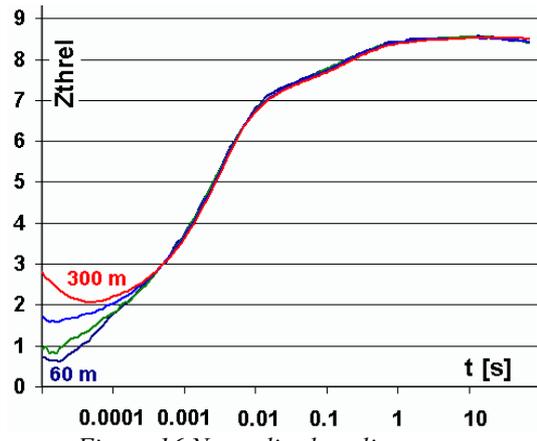


Figure 16 Normalised cooling curves, scaled to best fit above 500  $\mu$ s

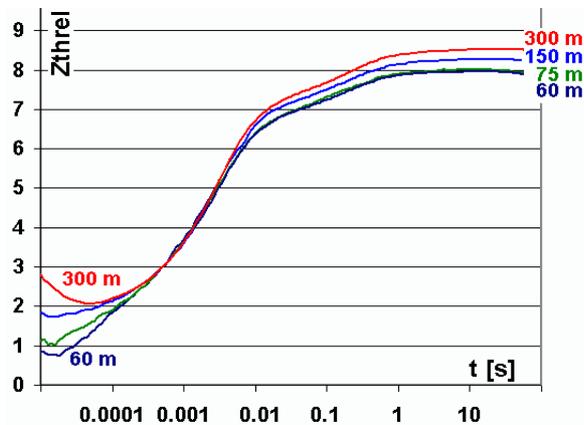


Figure 15 Normalised cooling curves, scaled to the "cool resistor" model

"best" normalisation factors for selecting 500  $\mu$ s and 10 ms as  $t_0$  point – the values are practically the same, because the threads are very near in this time range.

The curves prove that the junction-to-case thermal resistance really diminishes at higher currents, normalised transients of the real diode span a smaller temperature interval at high current. The difference between curves in the ms range and above belongs definitely to thermal effects and our LED model gives a possible explanation. The distance between threads below  $t_0$  belongs partly to this effect, partly to electric ones. An estimation on the magnitudes could be given comparing Figure 13 and Figure 16. The structure functions were calculated from transient curves between a  $t_i$  initial correction point (which was assumed to separate the "electric" and "thermal" portion of the transient) and the end of the cooling, so the effect is slightly overestimated in Figure 3.

We do now research on the correct interpretation of the  $\mu$ s time range, which has much more meaning than simply "electric perturbation". Results will be given in a subsequent paper.

## 6. CONCLUSIONS

Measuring power LEDs we found that their thermal behaviour depends on the applied power level. We defined for optical devices an *effective* thermal resistance for calculating the thermal stress and a *residual* thermal resistance for characterising package quality.

We set up a model, which reflects the behaviour of the device in mid to high time range. Results of research on short transients will be published in a subsequent paper.

## 7. ACKNOWLEDGEMENT

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