About Temperature of Shunt Resistors[1]

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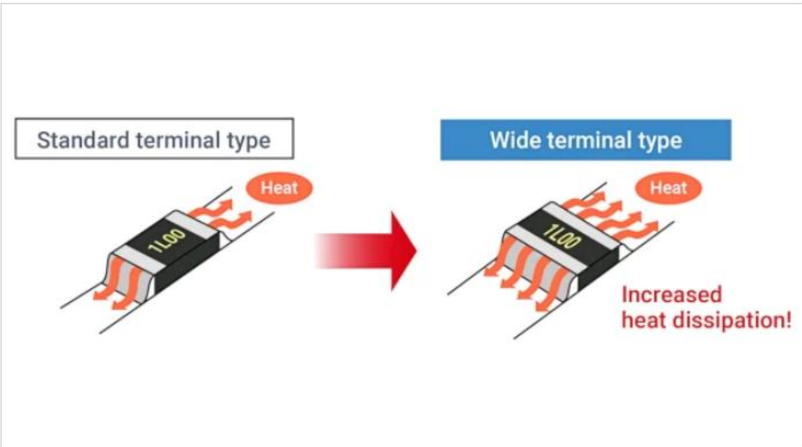
1. Introduction

In Bodo's Power Magazine, in an article by ROHM's Trevis Moench, I immediately noticed the picture, which I reproduce in Fig.1 [1]. How much does rotating the resistor really do for thermal management and what is the contribution of the trace? I want to investigate this in more detail in numerical experiments.



Wide terminal-style packages deliver improved thermal performance. Image used courtesy of Bodo's Power Systems [PDF]

Figure 1. Motivation [1]

The temperature of the resistor depends on a number of influences [2,3].

- Direct heat dissipation from the assembly side to the environment via convection and radiation
- Heat spreading (heat conduction) in the traces and within the circuit board into cooler areas (Fig.2)
- Heat dissipation from the opposite side of the component to the environment In addition, this is where things get interesting:
- Self-heating of the trace (so-called Joule heating)
- Temperature dependence of the electrical and thermal conductivity of copper.

In an assembly, depending on the layout, number of layers and the arrangement of other heat sources, one or the other mechanism can be suppressed and thus be ineffective. For example, there is no heat spreading if the assembly is equally heated everywhere due to many of the same components. On the

[1] Translated in parts with Microsoft® Translator

other hand, heat spreading could be intensified by a GND layer directly below the main heat source absorbing the heat and transporting it away to cooler peripheral areas.

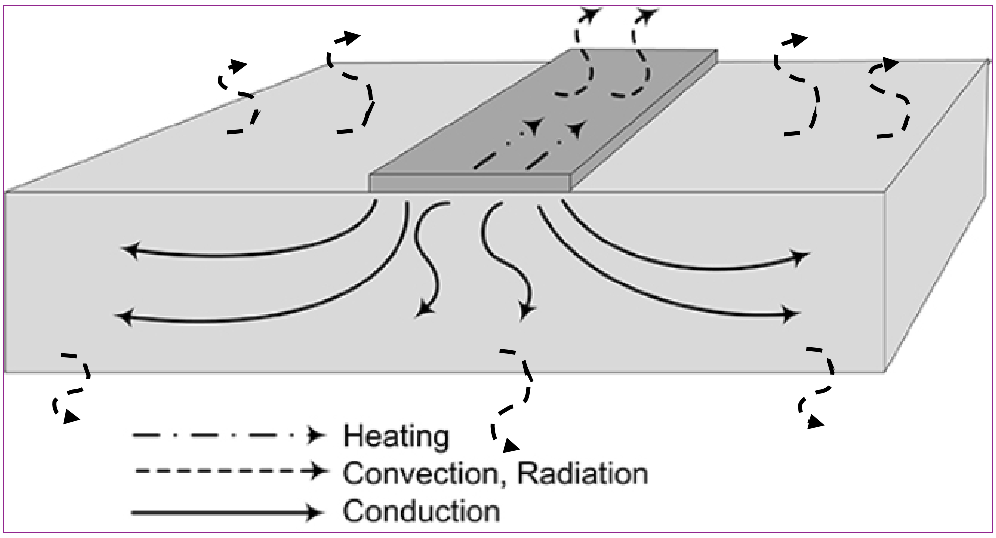


Figure 2: Heat dissipation from a trace [2]

There is no routed design available for this study that could have been modified accordingly. Therefore, a 4-layer PCB is assumed, consisting of 2 full-surface copper inner layers GND and VCC and the signal layer with the resistor on top. My tool for the following investigations is numerical calculation of the temperature field by using the **TRM** software from ADAM-Research. TRM combines layers and layout into a three-dimensional calculation model [4]. You don't need CAD for the "layout" required here. The traces can be generated from extruded rectangles within the software.

2. Model parameters

The layer structure is chosen in a "typical" way. The thermal conductivity ($k_{x,y}$=0.54 , k_z= 0.3 W/(m·K)) of "the FR4" is taken from IPC-2152. The traces in Top layer are made of copper with a temperature coefficient. The resistor is a simple block with a predetermined resistance without a temperature coefficient. Current is set in such a way that the resistor heats at room temperature with 1 Watt. DC is applied with a positive and a negative pole and flows through the component.

The shunt resistance, which is the subject of [1], is not particularly large at 2 mm x 1.25 mm. This is rather unfavorable for heat dissipation. There are 2 classes of resistors with same shape: one with high resistance "LTR" and one with very small resistance "PML". That makes things even more interesting.

Table 1. The major parameters and assumptions about the thermal PCB models.

<table>
<tr><td>Layer stack</td><td>
<table>
<tr><th>Name</th><th>Type</th><th>File</th><th>View</th><th>FR4 white</th><th>Thick (um)</th><th>Conductor</th><th>Dielectric</th><th>Expo:</th><th>Color</th></tr>
<tr><td>Top</td><td></td><td></td><td>View</td><td>☑</td><td>50</td><td>Cu$TRM</td><td>FR4-1A$TRM</td><td></td><td></td></tr>
<tr><td>pre1</td><td>pre</td><td></td><td>View</td><td>☑</td><td>250</td><td></td><td>FR4-1A$TRM</td><td></td><td></td></tr>
<tr><td>inner1</td><td>met</td><td></td><td>View</td><td>☑</td><td>35</td><td>Cu$TRM</td><td></td><td></td><td></td></tr>
<tr><td>core</td><td>pre</td><td></td><td>View</td><td>☑</td><td>900</td><td></td><td>FR4-1A$TRM</td><td></td><td></td></tr>
<tr><td>inner2</td><td>met</td><td></td><td>View</td><td>☑</td><td>35</td><td>Cu$TRM</td><td></td><td></td><td></td></tr>
<tr><td>pre3</td><td>pre</td><td></td><td>View</td><td>☑</td><td>250</td><td></td><td>FR4-1A$TRM</td><td></td><td></td></tr>
<tr><td>Bottom</td><td>pre</td><td></td><td>View</td><td>☑</td><td>50</td><td></td><td>FR4-1A$TRM</td><td></td><td></td></tr>
</table>
</td></tr>
<tr><td>Size of board</td><td>100 mm x 100 mm</td></tr>
<tr><td>Traces</td><td>Right and left side each 40 mm long</td></tr>
<tr><td>Copper</td><td>Specific electric resistance: $\rho_{el}(T) = 0.0175 \cdot 10^{-6} \cdot (1+0.00395 \cdot (T-20°C))$ Ω m²/m</td></tr>
</table>

Components	LTR10L Data sheet 1: R = 200 mΩ (assumed). PML10 Data sheet 2: R = 2 mΩ (assumed).
Power loss	LTR10L Data sheet 1: P = 1 W (rated power) PML10 Data sheet 2: P = 0.66 W (rated power)
Current	Data sheet 1: P=1 W -> I_{DC} = 2.23 A. Voltage drop at component ΔU=R·I=0.45 V Data sheet 2: P=0.66 W -> I_{DC} = 18 A (!!)
Ambient	20 °C, „still air“. Lab conditions

Data sheet 1

ltr-low-e.pdf

ROHM SEMICONDUCTOR

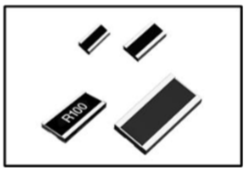
High Power Thick Film Shunt Resistors / Wide terminal type

LTR/LTRL series

Datasheet

●Features

1) Chip Resistors for current detection : 10mΩ ~
2) High joint reliability with long side terminations.
3) Improvement of rated power enables to displace smaller size of resistors, and it contributes space savings in your set.
4) ROHM resistors have obtained ISO9001 / IATF16949 certification.
5) Corresponds to AEC-Q200.



Part No.	(mm)	(inch)	L	W	t
LTR10L	1220	0508	1.25±0.15	2.0±0.15	0.55±0.10

●Products list

Part No.	Type code (mm)	Type code (inch)	Rated power (W)	Rated ambient temperature (°C)	Rated terminal temperature (°C)	Resistance tolerance	Temperature coefficient (ppm /°C)	Resistance rang (Ω)
New LTR10L	1220	0508	1.0	70	125	D(±0.5%)	0~150	100m≦R<200m (E2 seri
							0~100	200m≦R≦910m (E24 seri
						F(±1%) J(±5%)	0~150	33m≦R<100m (E24 seri
							0~150	100m≦R≦200m (E24 seri
							0~100	200m≦R≦910m (E24 seri

Data sheet 2

pml-e-3.pdf

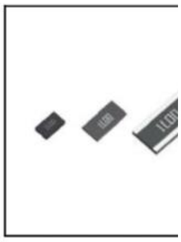
ROHM SEMICONDUCTOR

Ultra-low ohmic chip resistors for current detection <Wide terminal t

PML series

●Features

1) Ultra low-ohmic resistance range.
2) Wide terminal configuration for high joint reliability.
3) Improved current detection accuracy by trimming-less structure.
4) ROHM resistors have obtained ISO9001 / IATF16949 certification.
5) Corresponds to AEC-Q200

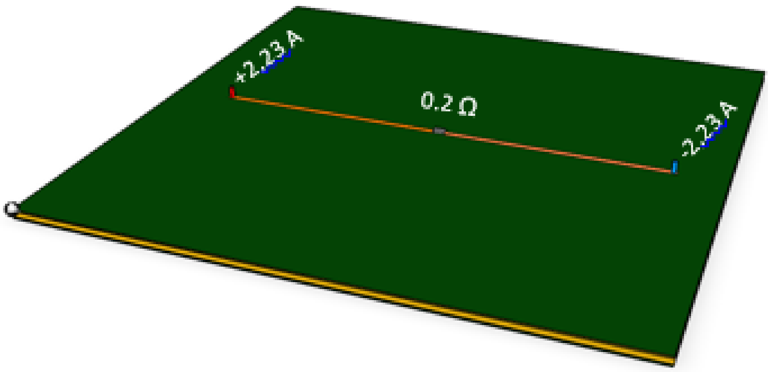


●Products List

Part No.	Size (mm)	Size (inch)	Rated power (70°C) (W)	Temperature coefficient (ppm / °C)	Resistance tolerance (%)	Resistance range (mΩ)	Operating temperatur range (°C)
PML10	1220	0508	0.66	±200	G (±2%) J (±5%)	1.0,1.5,2.0,2.5	-55 ~ +15

3. High-power thick film shunt resistor *LTR10L*

This and all the calculation models described below consist of a spatial grid with a resolution of 0.1 mm. In addition, there is material allocation at the nodes and 2 cable ends where power is applied in and out.



The algorithms in TRM calculate the DC potential field for the electrical nodes, the local heat generation and finally the temperature field in the entire assembly. As explained in Brooks, the heat flux splits into conduction, convection and radiant components [3].

The result of the calculations for the two situations in Fig. 1 is shown in Fig. 3 and with numerical values the Table 2. It is indeed as claimed in [1]: with a wide connector it gets cooler.

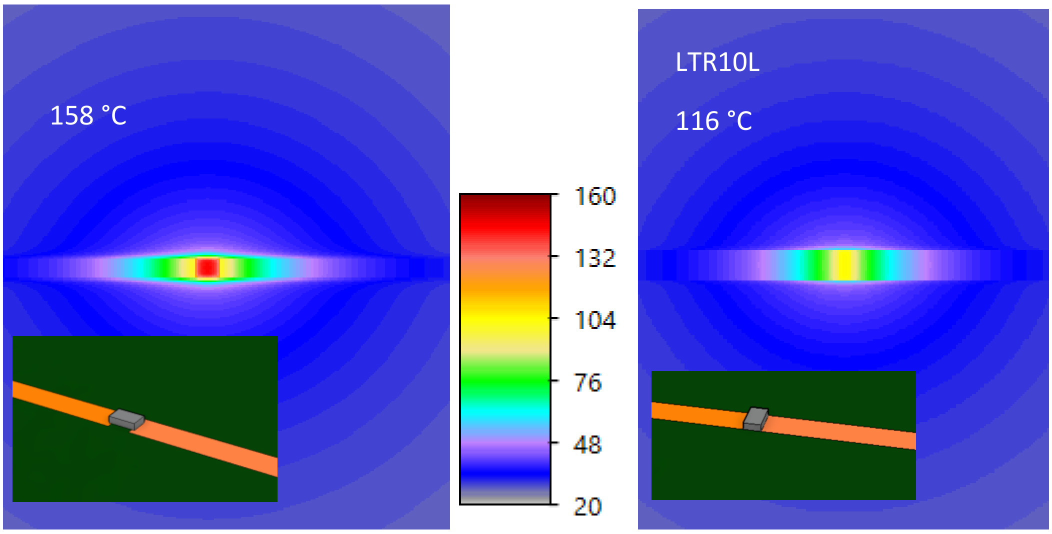
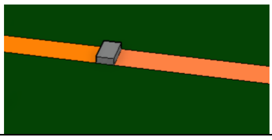
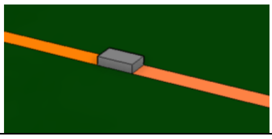
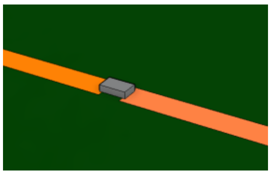


Figure 3: In fact! The wide-side installation with the wider trace (right) is thermally more advantageous than short-side with the narrow trace (left).

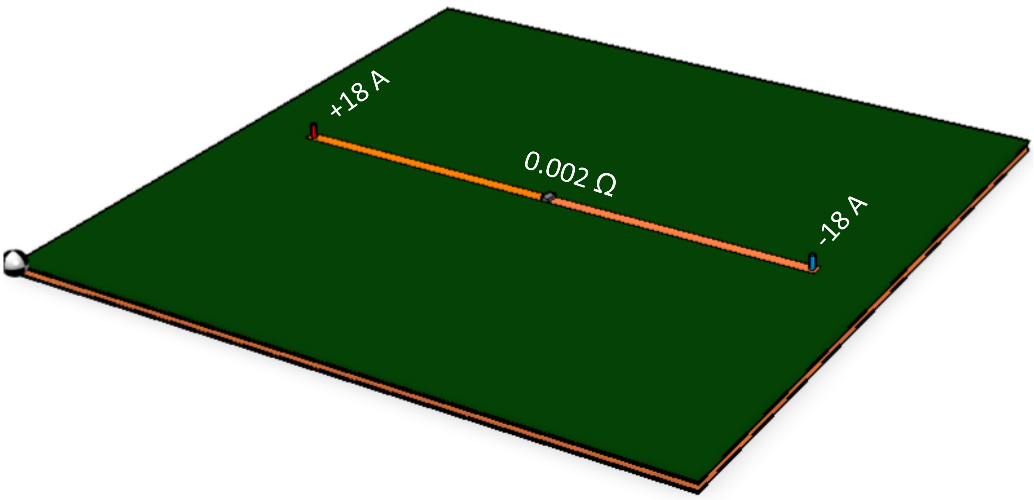
Table 2: Comparison of some computational results on LTR10L. Lines 1 and 2 are shown in Fig.3.

	Installation LTR10L	Trace width	Shunt temperature[2]	ΔU Traces	P_{Joule} Left+right trace	R Left+right trace
1		2 mm	116 °C	0.032 V	0.07 W	0.014 Ω
2		1.2 mm	158 °C	0.054 V	0.12 W	0.024 Ω
3		2 mm	141 °C			

- The Joule Heating power of the traces is small compared to the 1 W of the resistor.
- Therefore, it makes little difference that the electrical conductivity of the copper decreases in the vicinity of the component due to the heat input from the component (see Fig. 7).
- Far from the resistance, the trace is cool, indicating low self-heating.
- The "main work" of cooling is done by the two inner layers.
- The heat dissipation into the conductor tracks makes an additional substantial contribution.

4. Ultra-low ohmic chip resistor *PML10*

The current that leads to 0.66 W component heating with 0.002 Ω is about 18 A. Would that melt the trace? The simulation shows that, surprisingly, this does not happen. Fig. 4 shows that the inner layers massively distribute the heat in the inner layers and make it available for cooling into the environment.



[2] Accuracy about +- 5%, since the real thermal properties of the resistor are unknown.

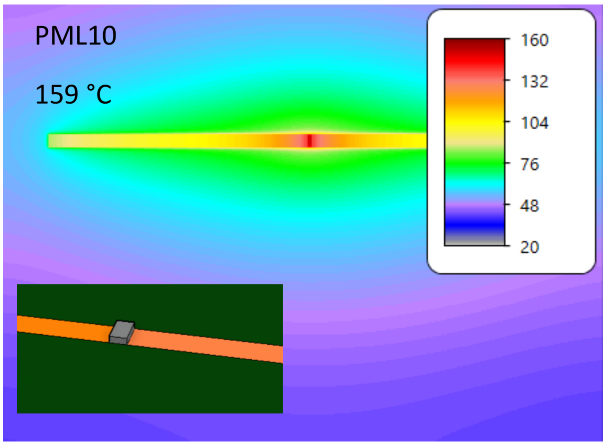
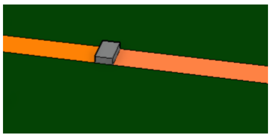
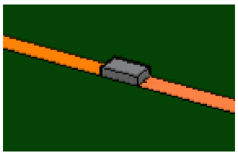


Figure 4. Astonishing! Even 18 A on traces and total loss of 6.3 W don't lead to melting

Table 3: Computational results on PML10.

	Installation PML10	Trace width	Shunt temperature[3]	ΔU Traces	P_{Joule} Left+right trace	R Left+right trace
1		2 mm	160 °C	0.32 V	5.7 W	0.017 Ω
2		1.2 mm	280 °C	0.74 V	13 W	0.04 Ω

In this case, too, some portion of the heat does flow from the component into the traces because the latter are cooler. The correct parameter for temperature is not the power dissipation Watts, instead is the power per footprint area q", i.e. W/mm². Large components keep cooler than small ones at same power dissipation. Now let's compare the calculated power by area of the two trace parts with the input values of the shunt[4]:

Shunt: P=0.66 W A=2 mm x 1.2 mm q"=P/A=0.27 W/mm²
Traces: P=5.7 W A=2 mm x 2x40 mm q"=P/A=0.035 W/mm²

If the situation were reversed, then it would really be a problem.

Assuming that the power dissipation of the shunt alone on a given PCB produces a reasonable temperature and if we don't take into account the temperature coefficient of copper, we can even *eliminate power, current and conductor length* in the following ways

Shunt: $q''_{shunt} = I^2 \cdot R_{shunt}/A_{shunt}$

Trace [3]: $q''_{trace} = [I^2 \cdot \rho_{el} \cdot L/(w \cdot t)] / (L \cdot w)$ length L, width w, thickness t. In meters

So if $q''_{trace} < q''_{shunt}$, then the trace can absorb heat. How much, that depends on circumstances.

[3] Accuracy about +- 5%, since the real thermal properties of the resistor are unknown.
[4] q" is the common terminology for power/area in the literature

$q''_{\text{trace}} < q''_{\text{shunt}}$: $\frac{\rho_{el}}{w^2 \cdot t} < \frac{R_{\text{shunt}}}{A_{\text{shunt}}}$

For the set of geometries in this paper (shunt+traces), the criterion almost always applies and can only be violated with great effort. For our shunts in side-wise installation (w=0.002 m) the numbers are:

LTR10L: 85 < 80000
PML10 : 85 < 830

References

[1] Moench, T.: „High-Power, Low-Ohmic Current Sense Resistors“. Bodo's Power Systems® (Issue Jan 2023, pp. 40-41). Also in https://eepower.com/technical-articles/high-power-low-ohmic-current-sense-resistor/

[2] Brooks D., Adam, J.: "The Dynamics of PCB Trace Heating and Cooling, and a Call to Action". Printed Circuit Design & Fab. July (2016) https://www.pcdandf.com/pcdesign/index.php/magazine/10931-conductor-temperatures-1607

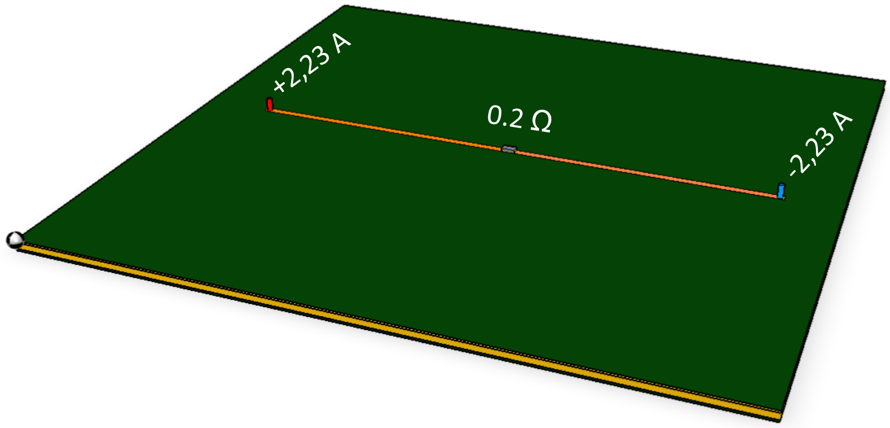
[3] Brooks D.: *PCB Design Guide to Via and Trace Currents and Temperatures.* Artech House, Boston (2021) https://us.artechhouse.com/PCB-Design-Guide-to-Via-and-Trace-Currents-and-Temperatures-P2191.aspx

[4] TRM3. https://www.adam-research.de/en/software/ and https://www.youtube.com/@adamresearch-thermalriskma7955/videos

Appendix. Picture Gallery

LTR10L. Short-side connection

Trace width is 1.2 mm.



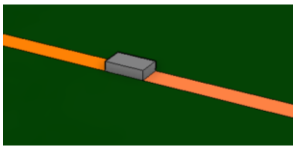


Figure 5: Assembly model with short side connection

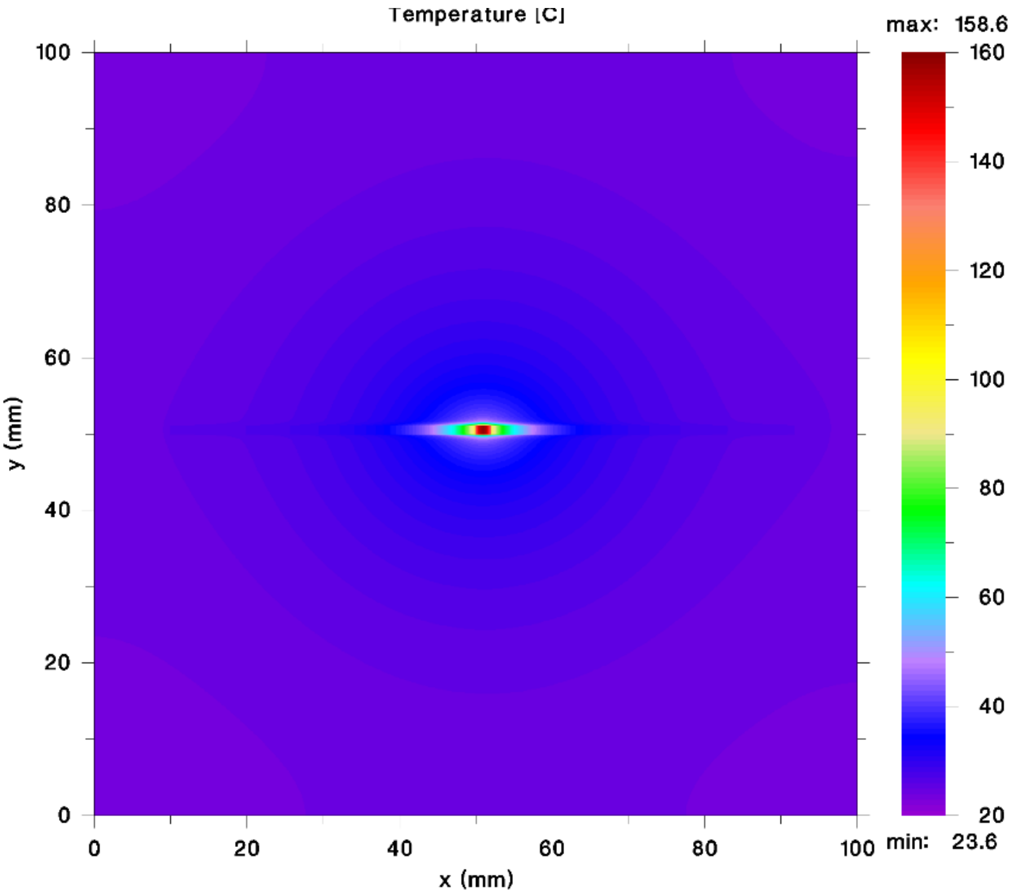


Figure 6: Temperature on Top. Shunt ≈161 °C with short side connection

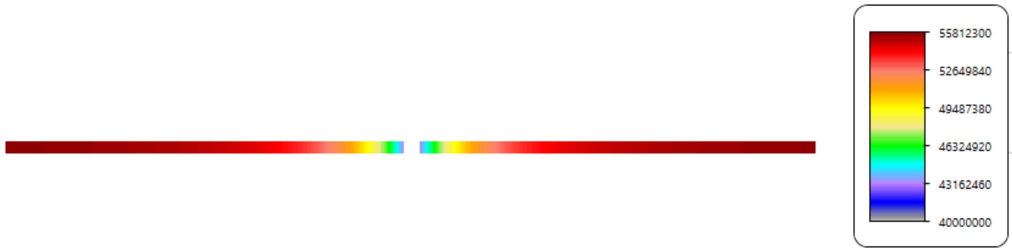


Figure 7: Decrease in electrical conductivity (S/m) in the hot zone with short-side connection

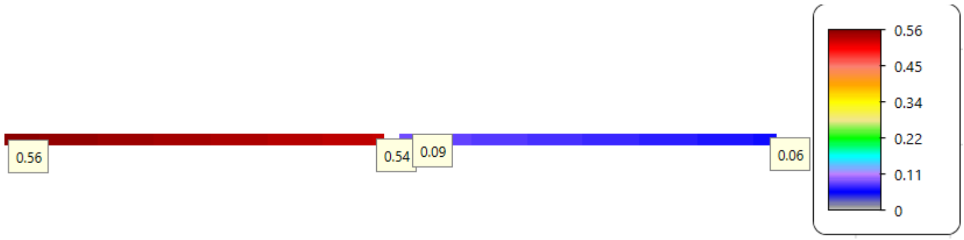


Figure 8: Voltage drop (V). On the component 0.45 V, in each trace part ≈ 0.025 V with short-side connection

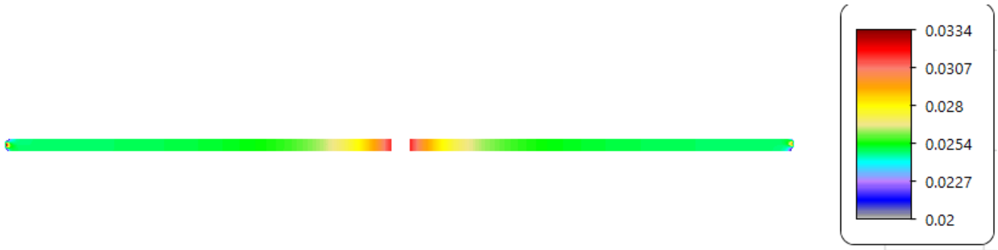


Figure 9: „Joule Heating" (mW/mm³) with short-side connection

LTR10L. Wide-side connection

Trace width is 2.0 mm.

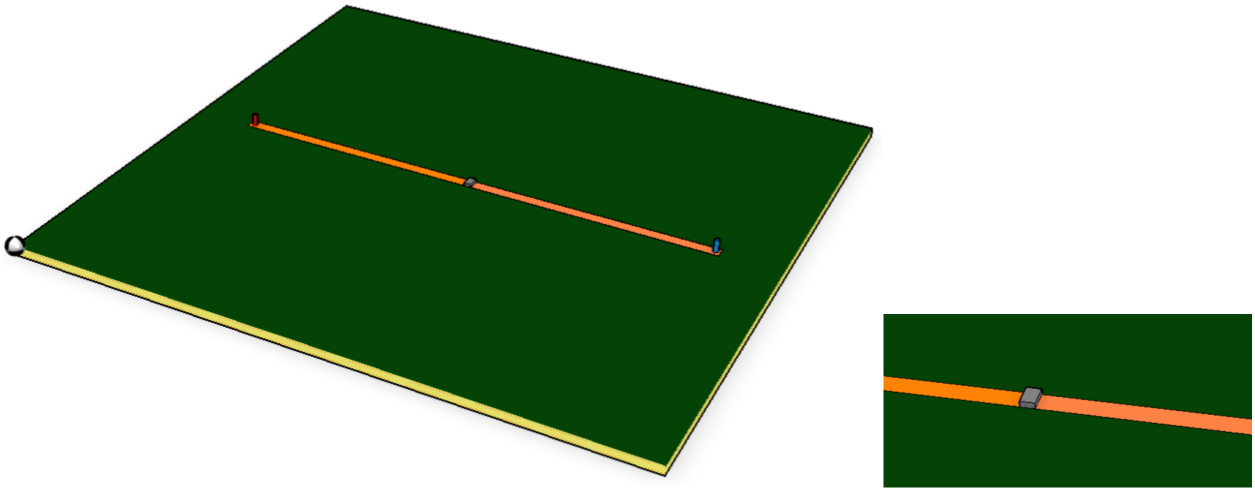


Figure 10: Assembly model with wide-side connection

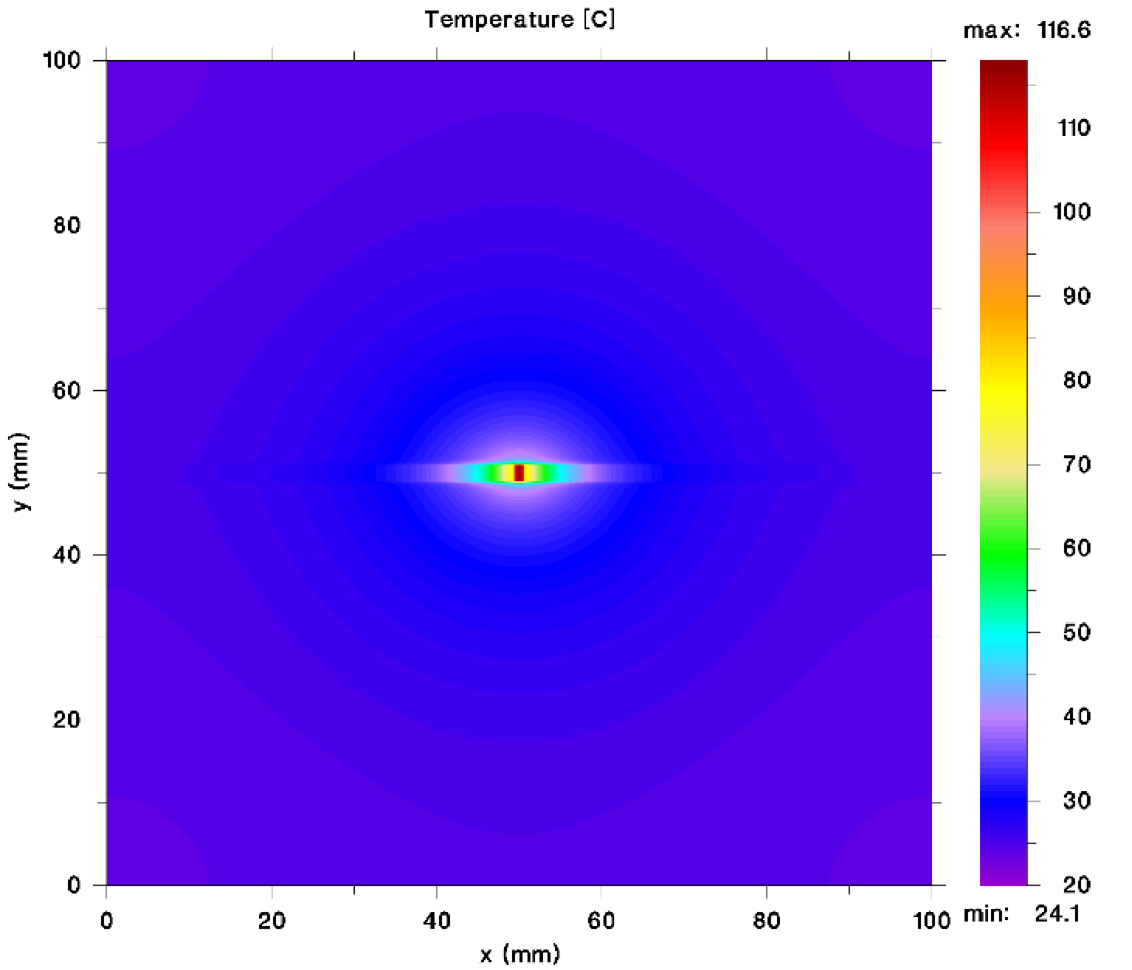


Figure 11: Temperature on Top. Shunt ≈109 °C with wide-side connection

LTR10L. Wide-side trace with short-side aligned component

How is the lower temperature actually achieved? Due to the wider temperature dissipation, as shown in Fig.1, or simply due to the wider trace and its lower current heating?

Trace width 2.0 mm.

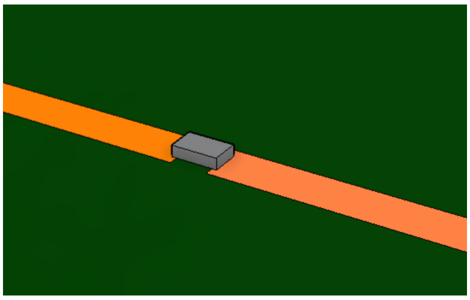


Figure 12: Narrow component on a wide conductor track: “wide-side connection with a short-side aligned component”

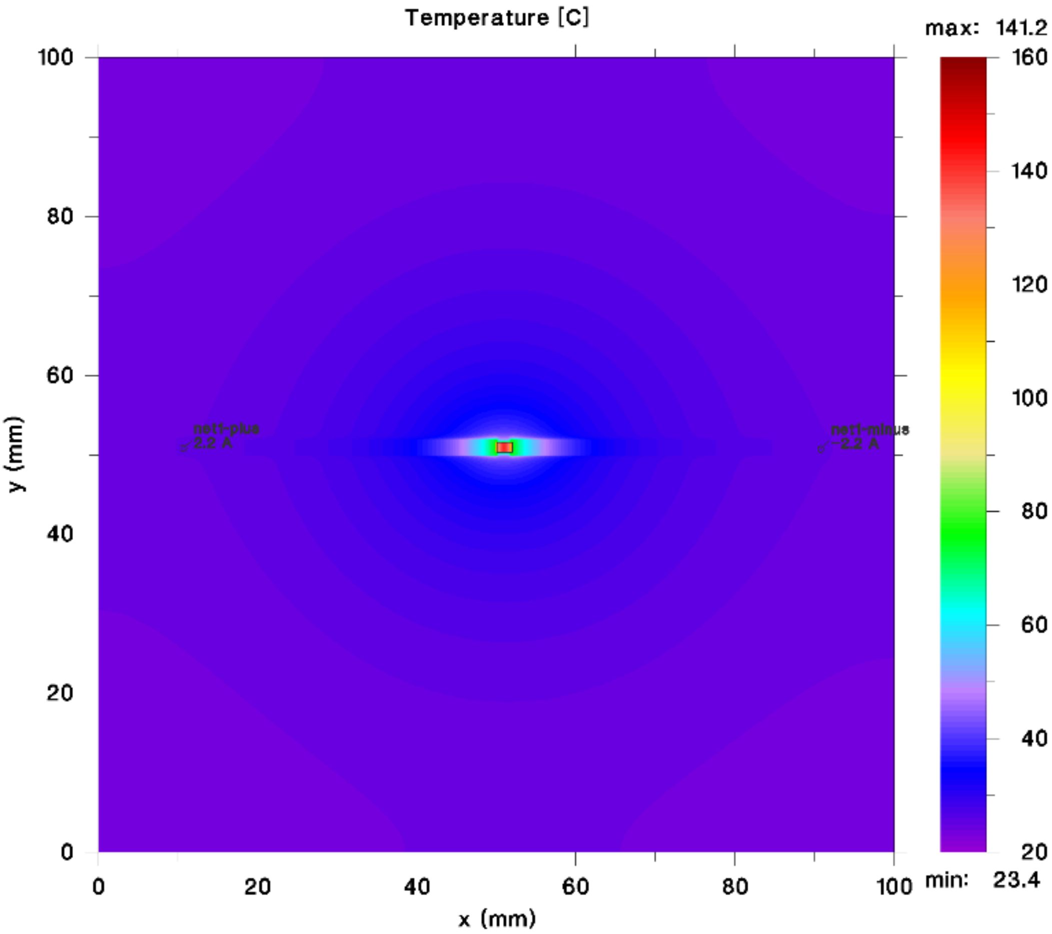
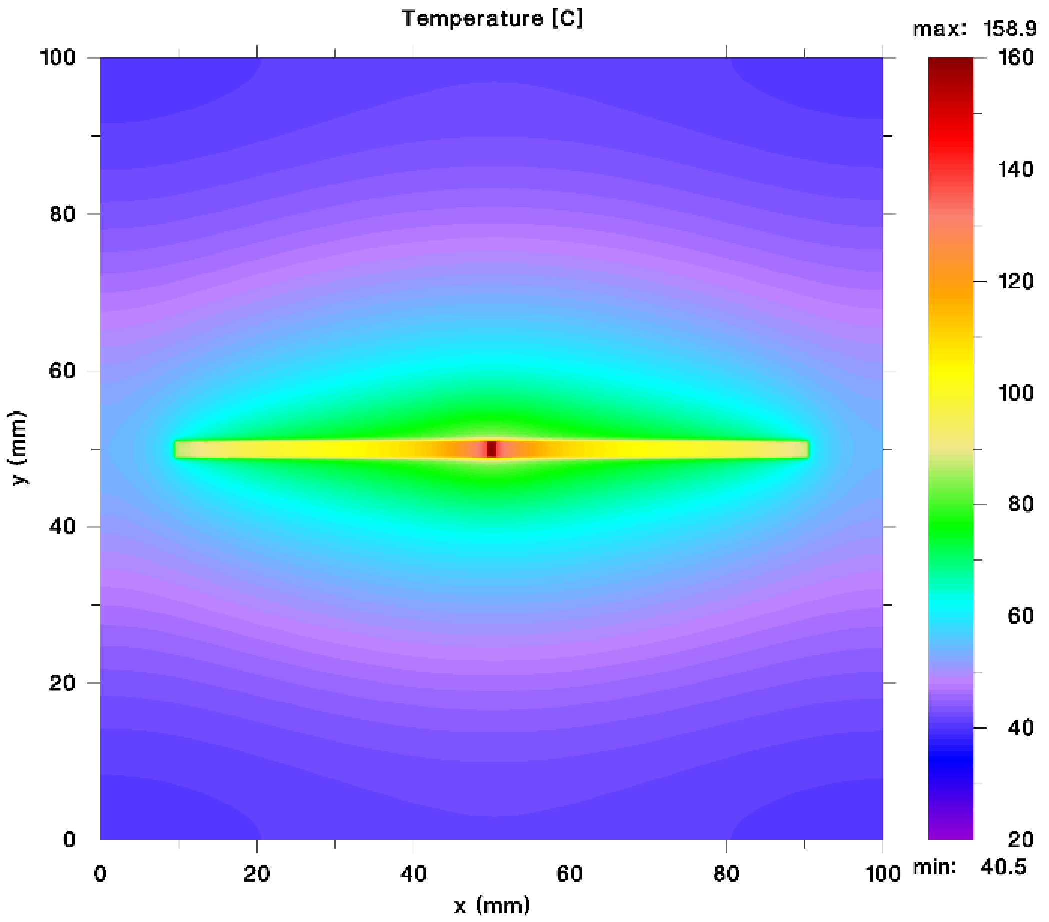


Figure 13: Temperature on top. Shunt ≈143 °C with wide-side connection with short-side aligned component

PML10. Wide-side connection

Trace width 2.0 mm. 18 Ampere, Total thermal losses 6.6 W!

The temperature level of the trace has increased, but the maximum temperature remains tolerable.



Contact

ADAM-Research

sales@adam-research.com
www.adam-research.com

https://www.youtube.com/@adamresearch-thermalriskma7955/videos

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2024-02-08

