Thermal Resistance of Power Modules

Webinar: Everything Power Electronics
Applications Manager

- Based in Hudson, New Hampshire at SEMIKRON Inc.
- BSc Electrical Engineering Rochester Institute of Technology
- 2003 - 2006: AC Technology/Lenze
- 2007 - 2014: Design Engineer Solutions Group, SEMIKRON
- 2014 - present: Applications Manager SEMIKRON
## Agenda

1. Definitions
2. Measurement methods
3. Thermal coupling
4. Derivation of values
5. Datasheets
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1. Definitions
2. Measurement methods
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Reference Points for $R_{th}$-Measurement

Cross section through a module at a heatsink:

- $T_J$ – Junction temperature
- $T_C$ – Case temperature in the centre of the chip positions(s)
- $T_S$ – Heatsink temperature in a drill hole 2mm below the heatsink surface
- $T_A$ – Inlet temperature of cooling medium

Module with baseplate

Module without baseplate
Definition of $R_{th}$ for Baseplateless Modules

"Heatsink rated devices"
- Specification of a $R_{th(j-s)}$ including thermal grease layer
- “Typical value” because TIM layer and mounting conditions are application (customer) specific
- Datasheet should specify grease type used (thermal conductivity is given)

**SKiiP 24AC12T7V1**

<table>
<thead>
<tr>
<th>$R_{th(j-s)}$</th>
<th>per IGBT, $\lambda_{paste}=0.8\ W/(mK)$</th>
<th>1.12</th>
<th>K/W</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{th(j-s)}$</td>
<td>per IGBT, $\lambda_{paste}=2.5\ W/(mK)$</td>
<td>0.93</td>
<td>K/W</td>
</tr>
</tbody>
</table>

- Wacker-Chemie P12
- SEMIKRON HPTP
**“Case rated devices”**

- Specification of a $R_{th(j-c)}$ “Maximum value” including deviation of products

**Temperature sensor**

- Path via sensor ($T_r$) is not a parallel heat path in the equivalent circuit! It is **one** thermal path with a different description.
- The sensor has ideally no power dissipation, that means it has the same temperature as the layer below (case or heatsink)
- Sensor behaviour is influenced by heatsink so no $R_{th(j-r)}$ is given on datasheets → see AN 20-001

\[
R_{th(j-c)} + R_{th(c-s)} + R_{th(s-a)} = R_{th(j-r)} + R_{th(r-a)}
\]
### Measurement Point for Modules with Baseplate

#### Method 1

<table>
<thead>
<tr>
<th>Heatsink Point</th>
<th>$\Delta T_{(c-s)}$/$R_{th(c-s)}$</th>
<th>$\Delta T_{(s-a)}$/$R_{th(s-a)}$</th>
<th>Advantage</th>
<th>Disadvantage</th>
<th>Used by SEMIKRON</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{s1}$</td>
<td>higher</td>
<td>lower</td>
<td>accessible measuring point, one measurement</td>
<td>strong heatsink dependency</td>
<td>for case rated modules with release date before 2014, SEMIPACK</td>
</tr>
</tbody>
</table>

#### Method 2

<table>
<thead>
<tr>
<th>Heatsink Point</th>
<th>$\Delta T_{(s-a)}$/$R_{th(s-a)}$</th>
<th>Advantage</th>
<th>Disadvantage</th>
<th>Used for</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{s2n}$</td>
<td>lower</td>
<td>higher</td>
<td>low heatsink dependency</td>
<td>special prepared heatsink, two measurements</td>
</tr>
</tbody>
</table>
Agenda

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Methods for Measuring Junction Temperature

Thermocouples (TC)

Infrared Camera

\[ V_{CE} = f(T_j) \]

SEMIKRON preferred method
- Generation of losses and heating with direct current in a switch X: $P_X = V_X \cdot I_{DC}$
- Turning off the load current and measure the forward voltage at measurement current
- Deriving of the junction temperature from the calibration curve: $T_{jX}(av) = f(V_{X0})$
- Measurement of temperatures of ambient, heatsink and baseplate with thermocouples
- Calculation of the thermal resistances by: $R_{th(x-y)} = \Delta T_{(x-y)}/P_X$
Case and Heatsink Temperature Measurement (Multichip)

- Junction temperature measurement result is an average of the area of all chips in parallel.
- Baseplate and heatsink temperatures are position related.

**Consequence:** thermal resistance is position dependent.

Paradox: Measurement at the hot spot below the hottest chips results in the lowest $R_{th}$.

It is necessary to measure $T_c$ and $T_s$ below each chip and calculate an average value.
Case and Heatsink Temperature Measurement (Multichip)

<table>
<thead>
<tr>
<th></th>
<th>P [W]</th>
<th>Rth(c-s) [K/W]</th>
<th>Rth(c-s) Switch [K/W]</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOP IGBT1</td>
<td>108,7</td>
<td>0,0487</td>
<td></td>
</tr>
<tr>
<td>TOP IGBT2</td>
<td>108,7</td>
<td>0,0322</td>
<td></td>
</tr>
<tr>
<td>TOP IGBT3</td>
<td>108,7</td>
<td>0,0349</td>
<td>0,0386</td>
</tr>
<tr>
<td>BOT IGBT1</td>
<td>128,6</td>
<td>0,0396</td>
<td></td>
</tr>
<tr>
<td>BOT IGBT2</td>
<td>128,6</td>
<td>0,0303</td>
<td></td>
</tr>
<tr>
<td>BOT IGBT3</td>
<td>128,6</td>
<td>0,0459</td>
<td>0,0386</td>
</tr>
<tr>
<td>TOP Diode1</td>
<td>114,8</td>
<td>0,0366</td>
<td></td>
</tr>
<tr>
<td>TOP Diode2</td>
<td>114,8</td>
<td>0,0349</td>
<td></td>
</tr>
<tr>
<td>TOP Diode3</td>
<td>114,8</td>
<td>0,0532</td>
<td>0,0415</td>
</tr>
<tr>
<td>BOT Diode1</td>
<td>116,4</td>
<td>0,0516</td>
<td></td>
</tr>
<tr>
<td>BOT Diode2</td>
<td>116,4</td>
<td>0,0344</td>
<td></td>
</tr>
<tr>
<td>BOT Diode3</td>
<td>116,4</td>
<td>0,0421</td>
<td>0,0427</td>
</tr>
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Heat Spreading/Thermal Coupling

**Measurement 1**
(IGBT only)

**Measurement 2**
(diode only)

**In Operation**
(e.g. inverter)

Thermal coupling
Datasheet Statement with $R_{th(c-s)M}$ per Module

![Diagram of power module with thermal resistances $R_{th(j-c)I}$, $R_{th(j-c)D}$, $R_{th(j-c)s}$, and $R_{th(c-s)M}$.

Legend:
- IGBT TOP
- IGBT BOT
- D TOP
- D BOT

Graph showing $R_{th(c-s)M}$ for SEMiX3 as a function of operation point.

Key:
- Full coupling
- No coupling

Values for $R_{th(c-s)M}$:
- 0.000
- 0.005
- 0.010
- 0.015
- 0.020
- 0.025
- 0.030
- 0.035
- 0.040
- 0.045
- 0.050

Operation Points:
- 1x IGBT
- 2x IGBT
- All
- 2x D
- 1x D

Legend:
- No coupling
- Full coupling
- No coupling

Note: The diagram and graph represent the thermal resistance values for different configurations of the power module.
# Examples for Operation Points in Half-Bridge Module

<table>
<thead>
<tr>
<th>#</th>
<th>Example circuit</th>
<th>Power losses per IGBT and diode</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Example circuit</td>
<td>T TOP</td>
</tr>
<tr>
<td>1</td>
<td>Brake chopper</td>
<td>100%</td>
</tr>
<tr>
<td>2</td>
<td>Inverter operation power factor 1</td>
<td>100%</td>
</tr>
<tr>
<td>3</td>
<td>Inverter operation power factor = -0.8....+0.8</td>
<td>50%</td>
</tr>
<tr>
<td>4</td>
<td>Inverter operation power factor = -1</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>Boost converter at max. voltage</td>
<td>0</td>
</tr>
</tbody>
</table>
Datasheet Statement with $R_{th(c-s)X}$ per Switch

![Diagram showing the thermal resistance components and operation points for various configurations of IGBTs and Diodes.]

Datasheet values!
Datasheet Statement with $R_{th(c-s)}X$ per Switch

$$R_{th(c-s)M\_theoretical} = \left( \frac{2}{R_{th(c-s)I}} + \frac{2}{R_{th(c-s)D}} \right)^{-1}$$

Datasheet value!
Agenda

<p>| | |</p>
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<td>5.</td>
<td>Datasheets</td>
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</table>
Determination of “Coupled” $R_{th(c-s)M}$ with Finite Element Method (FEM) Simulation + Measurement

SEMIX3 $R_{th(c-s)2}$

Rth [K/W]

0,06

0,05

0,04

0,03

0,02

0,01

0,00

1 2 3 4 5

Operation points

= Measured points → Validation of FEM model
Operation Point 3

- 50Hz current source sufficient for case and heatsink temperature measurement
- Disadvantage: ratio of losses IGBT:diode not controllable

More effort but with controllable power-ratio: module in horizontal branch of a H-bridge circuit
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SEMIKRON Datasheets for Baseplate ("Case rated") Modules

Per Switch Model

\[ R_{th(j-c)I} \]
\[ R_{th(c-s)I} \]

\[ R_{th(j-c)D} \]
\[ R_{th(c-s)D} \]

Relevant for:
- Chopper operation
- 0Hz inverter operation

Per Module Model

\[ R_{th(j-c)I} \]
\[ R_{th(j-c)D} \]
\[ R_{th(c-s)M} \]

Relevant for:
- Typical inverter operation with IGBT losses = 40…80% of the total module losses
**SEMIKRON Datasheets for Baseplate ("Case rated") Modules**

**$R_{th(c-s)}$ per Switch (IGBT or diode) from single switch measurements**

**$R_{th(c-s)}$ per Module including thermal coupling**
- Based on the $R_{th(c-s)_I}$ per IGBT and $R_{th(c-s)_D}$ per diode from single switch measurements and a finite element simulation or AC measurement

**$R_{th(c-s)}$ per Module without thermal coupling (theoretical value)**
- Based on the $R_{th(c-s)_I}$ per IGBT and $R_{th(c-s)_D}$ per diode from single switch measurements and the number of switches $n$ per module

\[
R_{th(c-s)M(\text{theor})} = \left( \frac{n}{R_{th(c-s)_I}} + \frac{n}{R_{th(c-s)_D}} \right)^{-1} \quad | \quad n = \text{number of switches}
\]
- Theoretical value only valid for comparison to other manufacturers datasheets, not for actual thermal calculations
## Example Datasheet SEMiX press-fit (>2015)

### SEMiX453GB12E4p

**R\(_{th}\) per single IGBT switch:**

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>(R_{th(c-c)}) per IGBT</td>
<td>0.066</td>
<td>K/W</td>
</tr>
<tr>
<td>(R_{th(c-s)}) per IGBT ((\lambda_{grease}=0.81\ \text{W/(m*K)}))</td>
<td>0.03</td>
<td>K/W</td>
</tr>
<tr>
<td>(R_{th(c-o)}) per IGBT, pre-applied phase change material</td>
<td>0.021</td>
<td>K/W</td>
</tr>
</tbody>
</table>

**R\(_{th}\) per single diode switch:**

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>(R_{th(c-c)}) per diode</td>
<td>0.1</td>
<td>K/W</td>
</tr>
<tr>
<td>(R_{th(c-s)}) per diode ((\lambda_{grease}=0.81\ \text{W/(m*K)}))</td>
<td>0.045</td>
<td>K/W</td>
</tr>
<tr>
<td>(R_{th(c-o)}) per diode, pre-applied phase change material</td>
<td>0.036</td>
<td>K/W</td>
</tr>
</tbody>
</table>

**R\(_{th}\) per module:**

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>(R_{th(c-c)}) calculated without thermal coupling</td>
<td>0.009</td>
<td>K/W</td>
</tr>
<tr>
<td>(R_{th(c-s)}) including thermal coupling, Ts underneath module ((\lambda_{grease}=0.81\ \text{W/(m*K)}))</td>
<td>0.014</td>
<td>K/W</td>
</tr>
<tr>
<td>(R_{th(c-o)}) including thermal coupling, Ts underneath module, pre-applied phase change material</td>
<td>0.011</td>
<td>K/W</td>
</tr>
</tbody>
</table>

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For comparison purposes only.
Considerations When Examining a Datasheet

**Where is $T_{\text{sink}}$ measured?**
- Next to the module or underneath the module?

**What type of thermal interface material has been used to derive the $R_{\text{th(c-s)}}$ values?**

**How is $R_{\text{th(c-s)}}M$ derived?**
- From measurements considering thermal coupling or as a theoretical value derived from individual $R_{\text{th(c-s)}}I$ and $R_{\text{th(c-s)}}D$ in parallel?

**For SEMIKRON datasheets:**
- Check Technical Explanations for product line to confirm measurement location
- Check if it is an “old” (<2015) datasheet
Application References Available for Download

**Application Manual:**
- Available in [English](#) and [German](#)

**Application Notes:**
- AN-1404: Thermal resistances of IGBT Modules
- AN 20-001: Calculating Junction Temperature using a Module Temperature Sensor

Application Notes Available
Presented by Paul Drexhage

(Original presentation by Dr. Arendt Wintrich)

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