Extraction of thermal resistance and its temperature dependence using DC methods

by

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Rth extraction using DC methods

Intro

- Rth extraction methods may be classified by different aspects:
  1. Used measurement principle: DC / pulsed
  2. Used Rth approach: \( Rth = \text{const.} \), \( Rth = f(T_A, P_D) \)
  3. Used temperature sensitive parameter (TSP): \( V_{BE}, I_B, B_N \)

<table>
<thead>
<tr>
<th>TSP: ( V_{BE} )</th>
<th>TSP: ( I_B )</th>
<th>TSP: ( B_N )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pfost 2003</td>
<td>Zweidinger 1996</td>
<td>Waldrop 1992</td>
</tr>
<tr>
<td>Intersection 2007</td>
<td>Williams 2002</td>
<td>Marsh 2000</td>
</tr>
</tbody>
</table>

- We propose here a DC extraction method, using forward Gummel measurements, which we call the Intersection method
- Results are compared with methods proposed by Rieh and Reisch
Gummel Plot $I_C = f(V_{be})$, $V_C = \text{Par. at } T_A = 25$

Gummel Plot $I_C = f(V_{be})$, $V_C = 1 \text{ V at } T_A = 50$
Rth extraction using the Intersection method

- At the intersection point we have $I_{C1} = I_{C2}$ and $V_{BE1} = V_{BE2}$
- Taking into account, that $q_2(T_J) \sim IS(T_J)$, and assuming VAF $\neq f(T_J)$ we may assume that the temperature dependence of $IS(T_J)$ and $q_B(T_J)$ is nearly cancelled
- The collector current is then a function of $V_{BE}$ and $T_J$ only
- We may conclude under these conditions, that the junction temperature $T_J$ is identical for both measurements at the intersection point

\[
IS(T) = C \cdot T^m \exp\left(-\frac{E_g}{kT_J}\right)
\]

\[
I_C(V_{BE}, T_J) = \frac{IS(T_J)}{q_B(T_J)} \exp\left[\frac{V_{BE}}{V_T(T_J)}\right]
\]

\[
V_T(T) = \frac{kT_J}{q}
\]
Rth extraction using the Intersection method

- Using the condition $T_{J1} = T_{J2}$, we may calculate $R_{th}$
- Making measurements for different ambient temperatures $T_{A1}$ and using a small temperature difference ($T_{A2} = T_{A1} + 10K$), we may extract the temperature dependence of the thermal resistance

$$V_{CE} = 1V \quad T_A = 25C$$

$$V_{CE} = 2V \quad T_A = 50C$$

$R_{th}$ equation

$$T_{J1} = T_{A1} + R_{th} \cdot P_{D1}$$

$$T_{J2} = T_{A2} + R_{th} \cdot P_{D2}$$

$$R_{th} = \frac{T_{A2} - T_{A1}}{P_{D1} - P_{D2}}$$

$$R_{th}(T) = R_{th\, ref} \left( \frac{T}{T_{ref}} \right)^{\alpha}$$
Rth extraction using the Intersection method
Measurement example (1)

- For a small device $R_{th} = 3700 \, \text{K/W}$ is extracted at $T_A = 273 \, \text{K}$
- The $R_{th}$ ambient temperature dependence was found by $\alpha = 0.76$

**Device:** npn, $Ae = 1.35 \, \mu\text{m}^2$

**Temperature condition:** $T_{A1} = 10$ to $80 \, \text{C}$, $T_{A2} = T_{A1} + 10\text{K}$

**Measurement condition:** $V_{C1} = 3 \, \text{V}$, $V_{C2} = 1\text{V}$

<table>
<thead>
<tr>
<th>TA 1</th>
<th>Tref</th>
<th>alpha</th>
<th>$R_{th_calc}$</th>
<th>$R_{th_meas}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>273</td>
<td>273</td>
<td>0.76</td>
<td>3734</td>
<td>3734</td>
</tr>
<tr>
<td>283</td>
<td>273</td>
<td>0.76</td>
<td>3838</td>
<td>3819</td>
</tr>
<tr>
<td>293</td>
<td>273</td>
<td>0.76</td>
<td>3941</td>
<td>3922</td>
</tr>
<tr>
<td>303</td>
<td>273</td>
<td>0.76</td>
<td>4042</td>
<td>4028</td>
</tr>
<tr>
<td>313</td>
<td>273</td>
<td>0.76</td>
<td>4143</td>
<td>4139</td>
</tr>
<tr>
<td>323</td>
<td>273</td>
<td>0.76</td>
<td>4244</td>
<td>4226</td>
</tr>
<tr>
<td>333</td>
<td>273</td>
<td>0.76</td>
<td>4343</td>
<td>4344</td>
</tr>
<tr>
<td>343</td>
<td>273</td>
<td>0.76</td>
<td>4442</td>
<td>4491</td>
</tr>
<tr>
<td>353</td>
<td>273</td>
<td>0.76</td>
<td>4540</td>
<td>4549</td>
</tr>
</tbody>
</table>
Rth extraction using the Intersection method
Measurement example (2)

- For a medium device $R_{th} = 1950 \, K/W$ is extracted at $T_A = 273 \, K$
- The $R_{th}$ ambient temperature dependence was found by $\alpha = 0.81$

- Device: npn, $A_e = 3.0 \, \mu m^2$
- Temperature condition: $T_{A1} = 10$ to $80 \, C$, $T_{A2} = T_{A1} + 10K$
- Measurement condition: $V_{C1} = 3 \, V$, $V_{C2} = 1 \, V$
Rth extraction using the Intersection method
Measurement example (3)

- For a long device $R_{th} = 1250 \text{ K/W}$ is extracted at $T_A = 273 \text{ K}$
- The $R_{th}$ ambient temperature dependence was found by $\alpha = 0.81$

### Device:
- npn, $A_e = 5.2 \ \mu\text{m}^2$

### Temperature condition:
- $T_{A1} = 10$ to $70 \text{ C}$, $T_{A2} = T_{A1} + 10\text{K}$

### Measurement condition:
- $V_{C1} = 3 \text{ V}$, $V_{C2} = 1 \text{ V}$
Rth extraction according to Rieh (2001)

Principle: TSP = \( V_{BE} \)

- Rieh [7] proposed a two step approach, using \( V_{BE} \) as thermometer
- Step 1: Calibration measurement
  \( V_{BE} \) is measured vs. temperature at \( V_{BC} = 0 \) for different \( I_E = \text{const.} \), 
  \( DT \) is calculated for each curve
- Step 2: Power dissipation measurement
  \( V_{BE} \) measured at \( T = 298 \text{ K} \) and at the same \( I_E = \text{const.} \), as in step 1. 
  \( V_{BC} \) is swept from –0.2 to 3V, in this way the dissipated power is varied
- \( R_{th} \) is calculated from the slope of the characteristic \( T_J \) vs. \( P_D \)

\[
V_{BE}(T_J) = V_{BE0} + D_T \cdot T_J
\]

\[
T_J(P_D) = \frac{V_{BE\text{meas}} - V_{BE0}}{D_T}
\]

\[
T_J(P_D) = T_A + R_{TH} \cdot P_D
\]
Rth extraction according to Rieh (2001)

Measurement example (1)

- $T_J$ vs. $P_D$ is shown here for different $I_E$, $R_{th}$ increases with $I_E$
- Reason: $P_D$ increases the junction temperature $T_J$ and thus $R_{th}$
- Physical reason for the effect is the temperature dependence of the thermal conductivity

Device: npn, $A_e = 2 \times 40 \, \mu m^2$

Measurement condition: $V_C = -0.2 \ldots 3 \, V$, $J_e = 0.1, 0.2, 0.5, 1 \, mA / \mu m^2$

Temperature condition: $T_A = 20 \, ^\circ C$

<table>
<thead>
<tr>
<th>$J_e$ (mA/µm²)</th>
<th>$R_{th}$ (K/W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>242</td>
</tr>
<tr>
<td>0.2</td>
<td>248</td>
</tr>
<tr>
<td>0.5</td>
<td>295</td>
</tr>
<tr>
<td>1</td>
<td>380</td>
</tr>
</tbody>
</table>

Measurements for this method made by J. Fester [1]
Rth extraction according to Rieh (2001)
Measurement example (2)

- Extracted Rth values shown here vs. \( I_E \) with \( T_A \) as parameter
- Rth increases with \( I_E \), as shown before. Additional, Rth increases with \( T_A \)
- Reason for the effect is again the temperature dependence of the thermal conductivity

\[
Rth = f(Ie, Tamb) \quad (\text{Rieh})
\]

- Device: npn, \( A_e = 2 \times 40 \ \mu m^2 \)
- \( T_A = 20, 30, 40, 50 \ C \)

Measurements for this method made by J. Fester [1]
Rth extraction according to Rieh (2001)
Measurement example (3)

- Rth increases with $T_A$
- Using an exponential approach, we may extract an coefficient alpha for each curve

$$R_{TH}(T) = R_{TH\text{ ref}} \left(\frac{T}{T_{ref}}\right)^{\alpha}$$

- Device: npn, $Ae = 2 \times 40 \, \mu m^2$
- $T_A = 20, 30, 40, 50 \, ^\circ C$
Rth extraction according to Rieh (2001)
Measurement example (4)

- Extracted alpha values are shown here for each operating point
- Neglecting the outliers we have a mean of alpha = 1.1

Device: npn, \( A_e = 2 \times 40 \ \mu m^2 \)

\[ R_{TH}(T) = R_{TH \ ref} \left( \frac{T}{T_{ref}} \right)^\alpha \]
Rth extraction according Reisch (1992)
Principle: TSP = IB

- Reisch [6] proposed 1992 to use $\Delta I_B / I_B$ vs. $\Delta P_D$ for Rth extraction
- For high $V_{BE}$ self heating is present, resulting in an increasing $\Delta I_B / I_B$
- The slope of $\Delta I_B / I_B$ vs. $\Delta P_D$ may be used for Rth extraction

$$i_B = \frac{\Delta I_B}{I_B} = \frac{I_B(V_{BE}, V_{CB}) - I_B(V_{BE}, V_{CB} = 0)}{I_B(V_{BE}, V_{CB} = 0)}$$

$$R_{TH} = \left( k \cdot T_J^2 \right) \left( \frac{i_B}{\Delta P_D} \right)$$
Rth extraction according Reisch (1992)
Measurement example (1)

- $\Delta I_B / I_B$ vs. $P_D$ is shown
- Extracted Rth value depends on the extraction range and selected curve
- Because of the approximation $T_J = T_A$, the method is restricted to low current densities, that is small junction temperature increase

- Device: npn, $Ae = 2 \times 40 \, \mu m^2$
- $V_C =$ sweep, start= 0, stop = 5 V
- $V_{BE} = 0.77, 0.78, .79, 0.80, 0.81 \, V$
- $T_A = 25 \, C$

Measurements for this method made by J. Fester [1]
Rth extraction according Reisch (1992) Measurement example (2)

- Rth = 270 K/W was extracted using the $V_{BE}=0.81$ V curve
- The Rth dependence on ambient temperature was not investigated using this method

![Graph showing Rth vs. Ve (Reisch: TSP=Ib)]

<table>
<thead>
<tr>
<th>Ve</th>
<th>$I_e(V_{bc}=0)$</th>
<th>Rth</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.77</td>
<td>0.0015</td>
<td>293</td>
</tr>
<tr>
<td>0.78</td>
<td>0.0022</td>
<td>271</td>
</tr>
<tr>
<td>0.79</td>
<td>0.0032</td>
<td>275</td>
</tr>
<tr>
<td>0.80</td>
<td>0.0044</td>
<td>277</td>
</tr>
<tr>
<td>0.81</td>
<td>0.0061</td>
<td>270</td>
</tr>
</tbody>
</table>

- Device: npn, $Ae = 2 \times 40 \mu m^2$
- $V_c = $ sweep, start = 0, stop = 5 V
- $V_{be} = 0.77, 0.78, .79, 0.80, 0.81$ V (Parameter)
- $T_A = 25$ C
### Rth extraction using Gummel Plot measurements

#### Summary and comparison

<table>
<thead>
<tr>
<th></th>
<th>Intersection</th>
<th>Rieh</th>
<th>Reisch</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>TSP</strong></td>
<td>$V_{BE}$</td>
<td>$V_{BE}$</td>
<td>$I_B$</td>
</tr>
<tr>
<td><strong>Measurement effort for Rth @ RT</strong></td>
<td>$fg @ RT$: 1</td>
<td>Cal. meas: 12</td>
<td>fwd output meas. @ RT: 1</td>
</tr>
<tr>
<td></td>
<td>$fg @ RT+\Delta T$: 1</td>
<td>PD meas.: 1</td>
<td></td>
</tr>
<tr>
<td><strong>Speed</strong></td>
<td>fast</td>
<td>time consuming</td>
<td>very fast</td>
</tr>
<tr>
<td><strong>Contact resistance sensitivity</strong></td>
<td>high</td>
<td>low</td>
<td>high</td>
</tr>
<tr>
<td><strong>Applicable</strong></td>
<td>only in high current range</td>
<td>wide $I_E$ range</td>
<td>only in low current range</td>
</tr>
<tr>
<td><strong>Rth (K/W) for npn $Ae=2\times40$</strong></td>
<td>315</td>
<td>at $I_C=80mA$; $T_A=25$, $T_A=75$</td>
<td>264</td>
</tr>
<tr>
<td></td>
<td>290</td>
<td>$I_E=5mA$; $T_A = 50$ C</td>
<td></td>
</tr>
<tr>
<td><strong>Rth ($T_A$)</strong></td>
<td>$\alpha = 0.8$</td>
<td>$\alpha = 1.1$</td>
<td>n.a.</td>
</tr>
</tbody>
</table>
Rth extraction using DC measurements

Literature