

Extraction of thermal resistance and its temperature dependence using DC methods

by
Jörg Berkner
Infineon Technologies AG
Munich, Germany

Rth extraction using DC methods

Intro

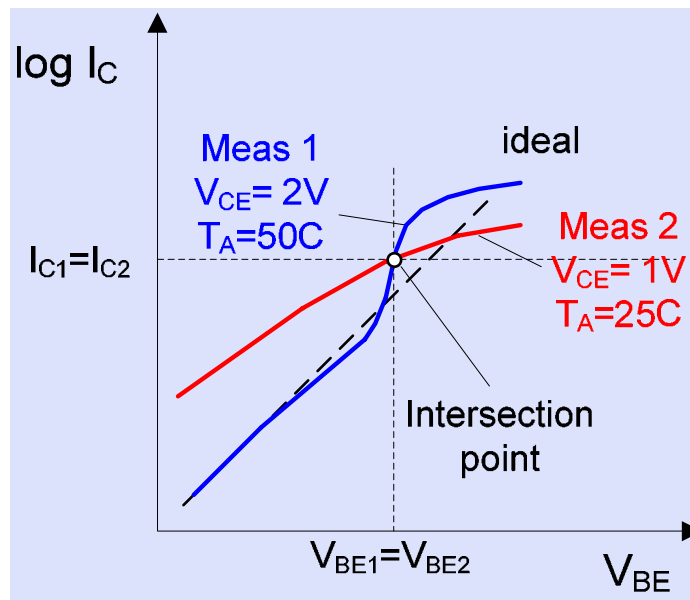
- Rth extraction methods may be classified by different aspects:
 1. Used measurement principle: DC / pulsed
 2. Used Rth approach: $R_{th} = \text{const.}$, $R_{th} = f(T_A, P_D)$
 3. Used temperature sensitive parameter (TSP): V_{BE} , I_B , B_N

TSP: V_{BE}	TSP: I_B	TSP: B_N
Rieh 2001	Reisch 1992	Dawson 1992
Pfost 2003	Zweidinger 1996	Waldrop 1992
Intersection 2007	Williams 2002	Marsh 2000

- 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

Rth extraction using the Intersection method Principle

- 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



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

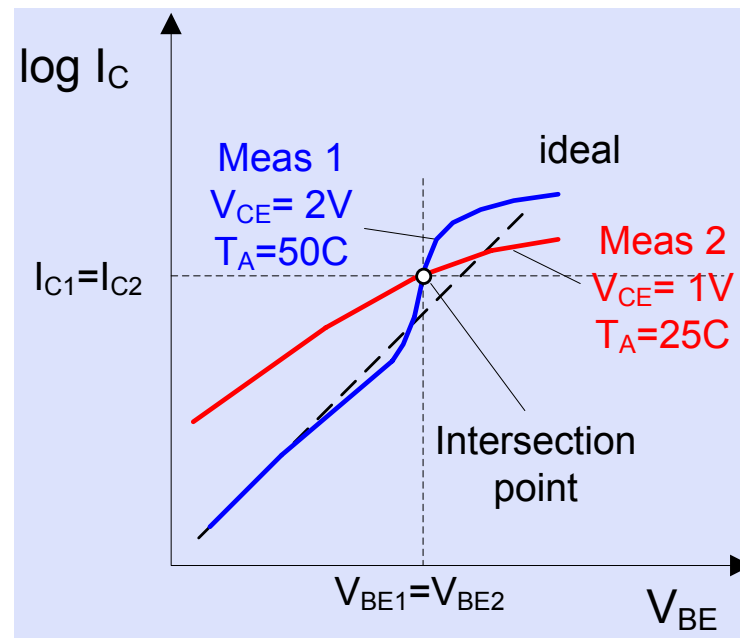
$$I_C(V_{BE}, T_J) = \frac{IS(T_J)}{q_B(T_J)} \exp\left[\frac{V_{BE}}{V_T(T_J)}\right]$$

$$V_T(T) = \frac{kT_J}{q}$$

Rth extraction using the Intersection method

Rth equation

- Using the condition $T_{J1} = T_{J2}$, we may calculate Rth
- 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



$$T_{J1} = T_{A1} + R_{TH} * P_{D1}$$

$$T_{J2} = T_{A2} + R_{TH} * P_{D2}$$



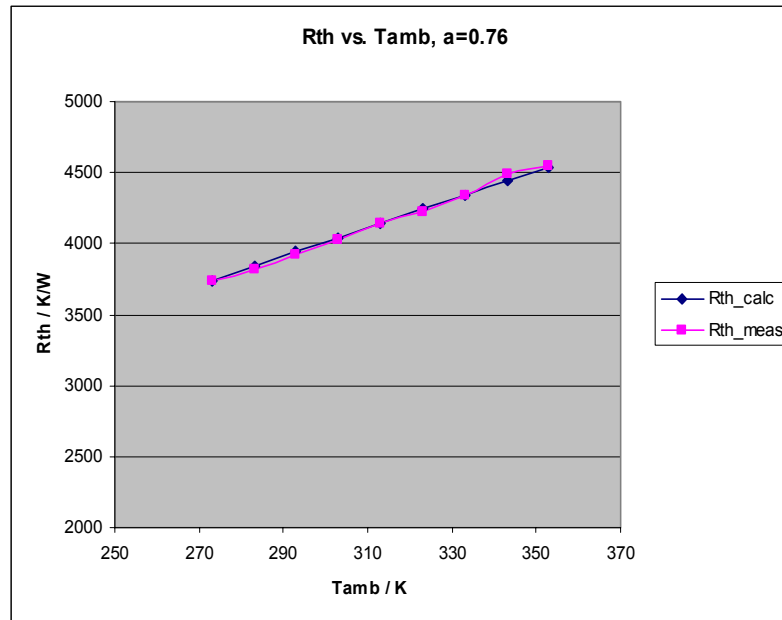
$$R_{TH} = \frac{T_{A2} - T_{A1}}{P_{D1} - P_{D2}}$$

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

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 $\alpha = 0.76$

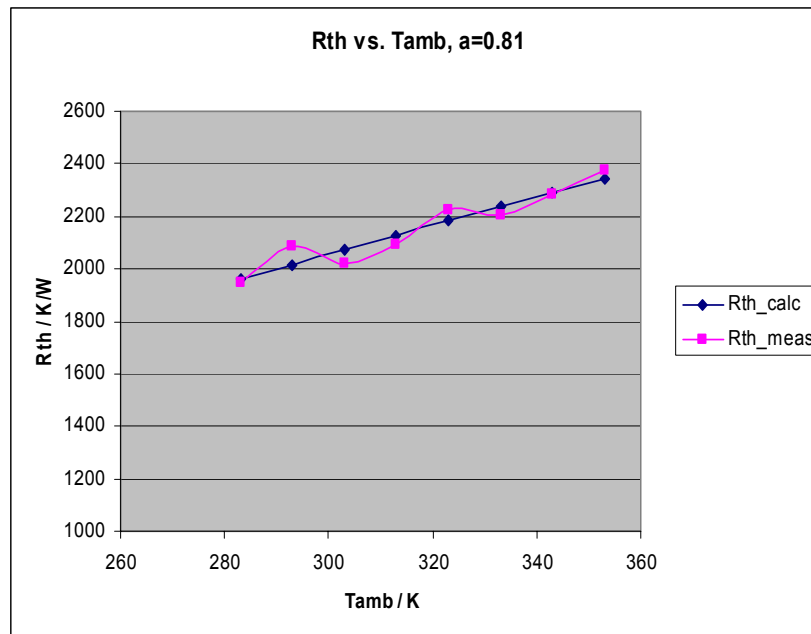


TA 1	Tref	alpha	Rth_calc	Rth_meas
273	273	0.76	3734	3734
283	273	0.76	3838	3819
293	273	0.76	3941	3922
303	273	0.76	4042	4028
313	273	0.76	4143	4139
323	273	0.76	4244	4226
333	273	0.76	4343	4344
343	273	0.76	4442	4491
353	273	0.76	4540	4549

- Device: npn, $A_e = 1.35 \mu\text{m}^2$
- Temperature condition: $T_{A1} = 10 \text{ to } 80 \text{ C}$, $T_{A2} = T_{A1} + 10\text{K}$
- Measurement condition: $V_{C1} = 3 \text{ V}$, $V_{C2} = 1\text{V}$

Rth extraction using the Intersection method Measurement example (2)

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

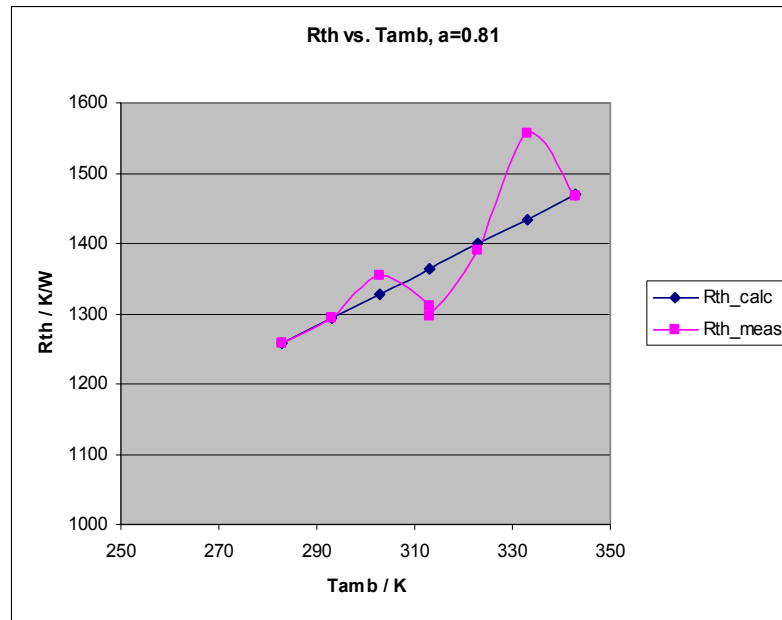


TA 1	Tref	alpha	Rth_calc	Rth_meas
283	283	0.81	1960	1950
293	283	0.81	2016	2086
303	283	0.81	2072	2020
313	283	0.81	2128	2093
323	283	0.81	2183	2227
333	283	0.81	2238	2206
343	283	0.81	2292	2286
353	283	0.81	2346	2374

- Device: npn, $A_e = 3.0 \mu\text{m}^2$
- Temperature condition: $T_{A1} = 10 \text{ to } 80 \text{ C}$, $T_{A2} = T_{A1} + 10\text{K}$
- Measurement condition: $V_{C1} = 3 \text{ V}$, $V_{C2} = 1 \text{ V}$

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 $\alpha = 0.81$



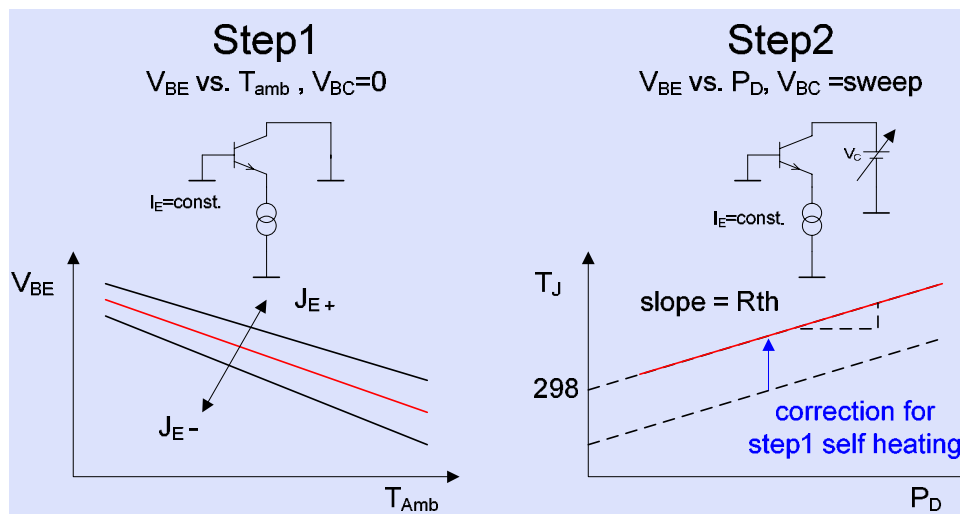
TA1	T0_K	alpha	Rth_calc	Rth_meas
283	283	0.81	1257	1257
293	283	0.81	1293	1294
303	283	0.81	1328	1353
313	283	0.81	1364	1310
313	283	0.81	1364	1297
323	283	0.81	1399	1390
333	283	0.81	1434	1557
343	283	0.81	1469	1469

- Device: npn, $A_e = 5.2 \mu\text{m}^2$
- Temperature condition: $T_{A1} = 10 \text{ to } 70 \text{ C}$, $T_{A2} = T_{A1} + 10\text{K}$
- 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
- Step1: Calibration measurement
 V_{BE} is measured vs. temperature at $V_{BC} = 0$ for different $I_E = \text{const.}$,
 D_T is calculated for each curve
- Step 2: Power dissipation measurement
 V_{BE} measured at $T = 298$ 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



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



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

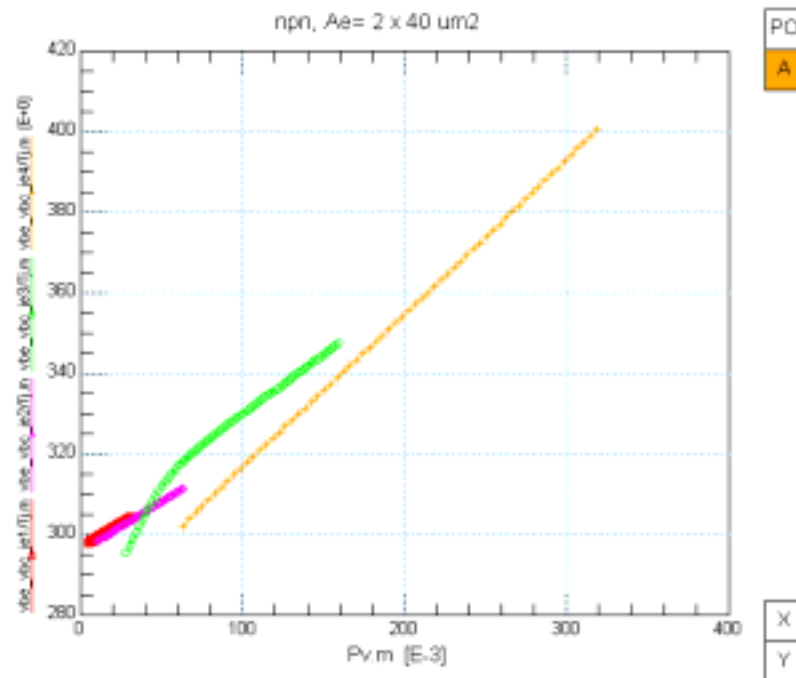


$$T_J(P_D) = T_A + R_{TH} * P_D$$

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



Je mA/ μ m ²	Rth K/W
0.1	242
0.2	248
0.5	295
1	380

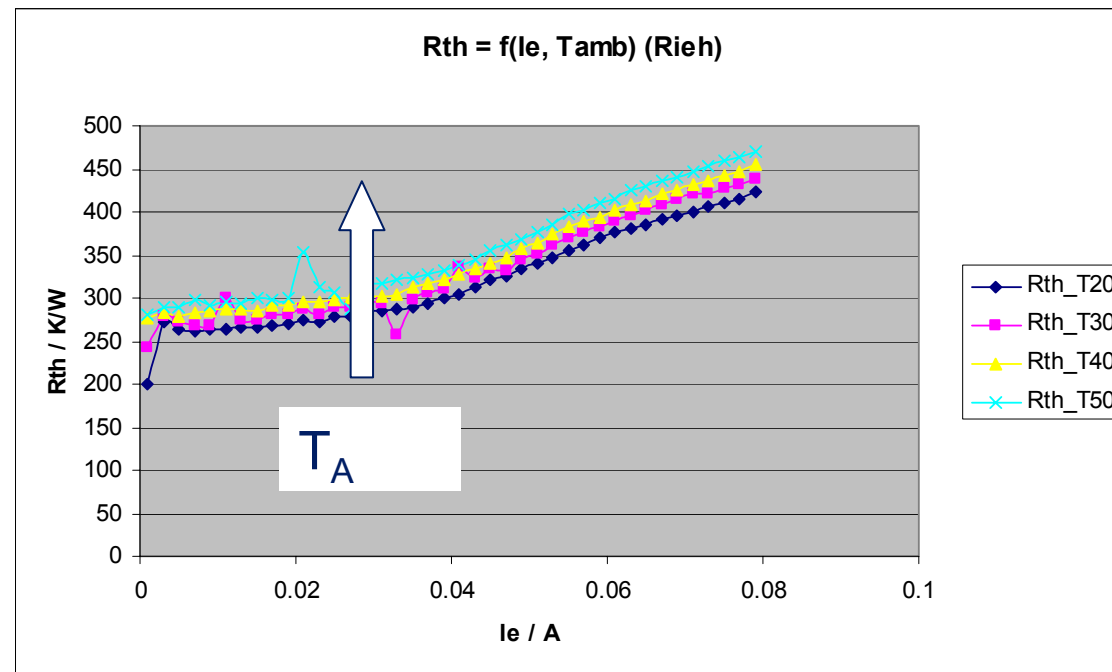
- Device: npn, $A_e = 2 \times 40 \mu\text{m}^2$
- Measurement condition: $V_C = -0.2 \dots 3 \text{ V}$, $J_e = 0.1, 0.2, 0.5, 1 \text{ mA} / \mu\text{m}^2$
- Temperature condition: $T_A = 20 \text{ C}$

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



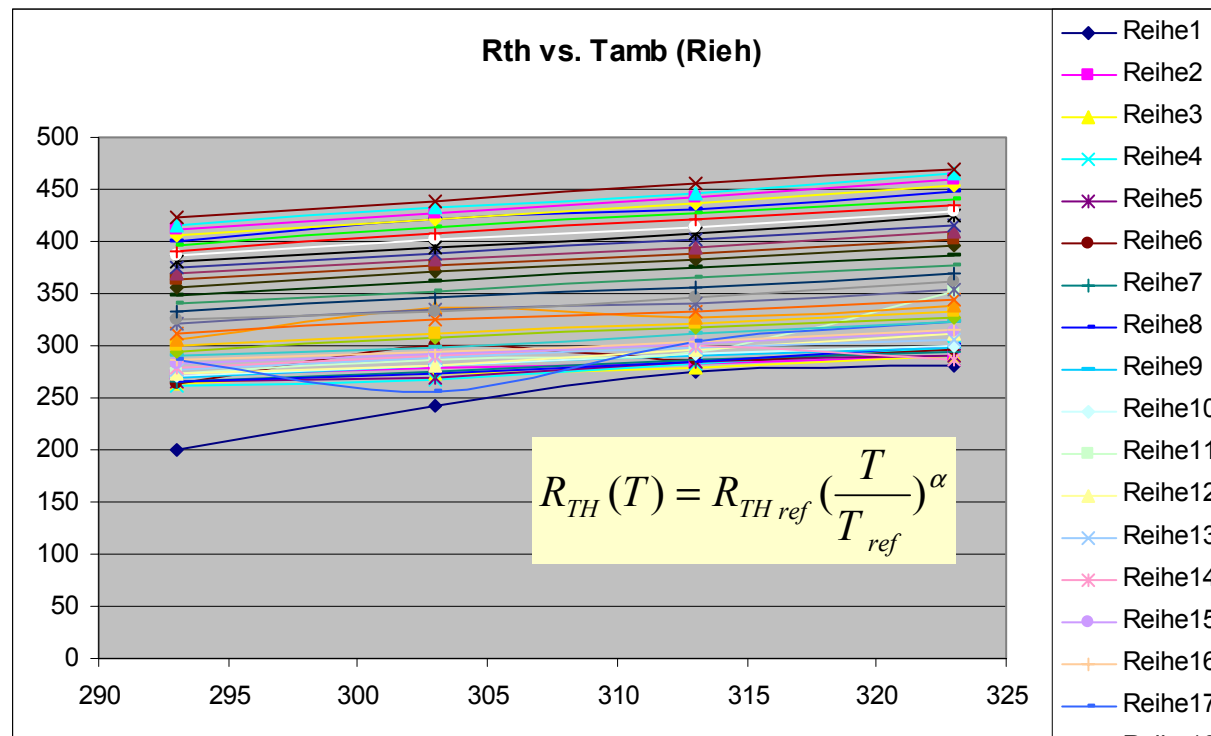
- Device: npn, $A_e = 2 \times 40 \mu m^2$
- $T_A = 20, 30, 40, 50 \text{ C}$

Measurements for this method made by J. Fester [1]

Rth extraction according to Rieh (2001)

Measurement example (3)

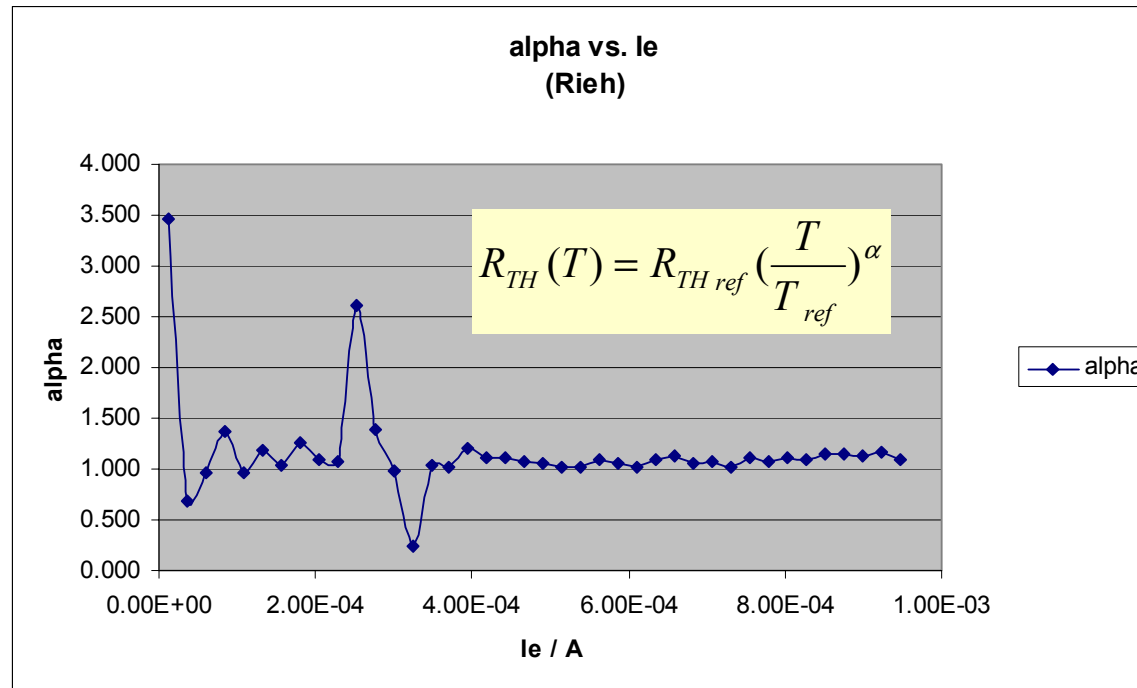
- Rth increases with T_A
- Using an exponential approach, we may extract an coefficient alpha for each curve



- Device: npn, $A_e = 2 \times 40 \mu\text{m}^2$
- $T_A = 20, 30, 40, 50 \text{ C}$

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
- Literature: alpha = 4/3 (Paasschens, BCTM 2004)

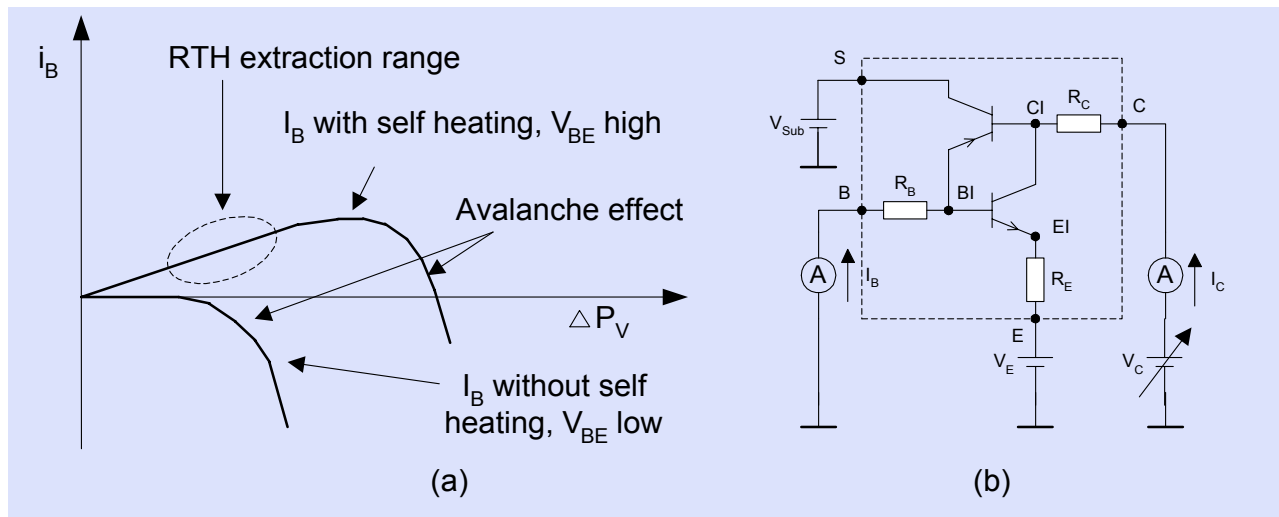


- Device: npn, A_e = 2 x 40 μm²
- T_A = 20, 30, 40, 50 C

Rth extraction according Reisch (1992)

Principle: TSP = IB

- Reisch [6] proposed 1992 to use $\Delta I_B / I_B$ vs. ΔP_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. ΔP_D may be used for Rth extraction



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

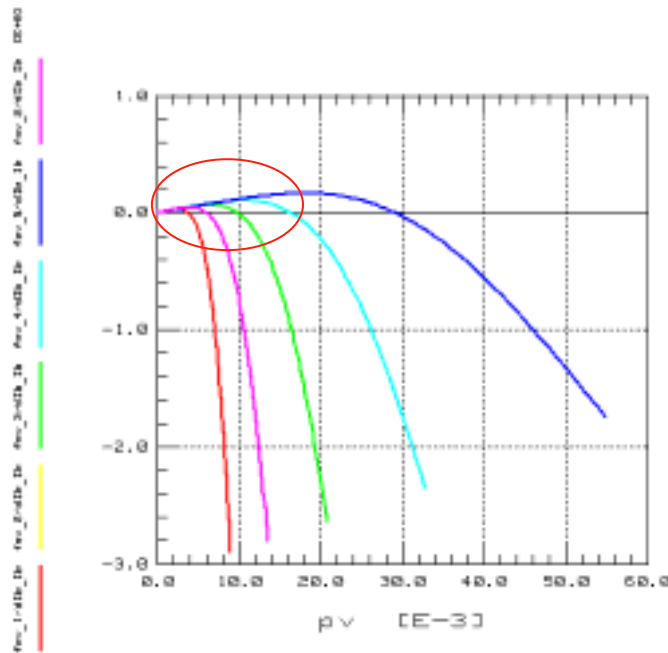


$$R_{TH} = \left(\frac{k \cdot T_J^2}{E_g - qV_{B'E'}} \right) \left(\frac{i_B}{\Delta P_D} \right)$$

Rth extraction according Reisch (1992)

Measurement example (1)

- $\Delta I_B / I_B$ vs. P_D is shown
- Extracted R_{th} 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

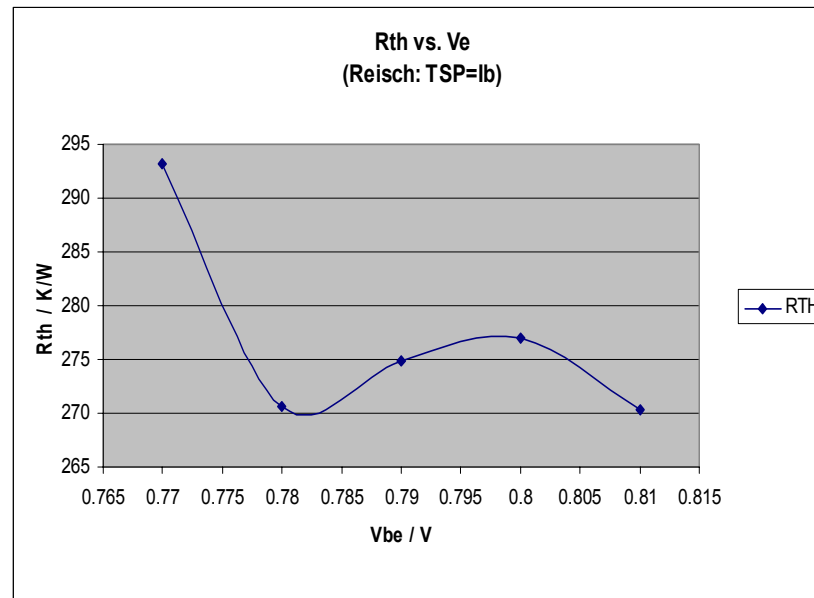


- Device: npn, $A_e = 2 \times 40 \mu\text{m}^2$
- $V_C = \text{sweep, start} = 0, \text{stop} = 5 \text{ V}$
- $V_{BE} = 0.77, 0.78, .79, 0.80, 0.81 \text{ V}$
- $T_A = 25 \text{ C}$

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



Ve	le(Vbc=0)	Rth
0.77	0.0015	293
0.78	0.0022	271
0.79	0.0032	275
0.80	0.0044	277
0.81	0.0061	270

- Device: npn, $A_e = 2 \times 40 \mu\text{m}^2$
- Vc = sweep, start = 0, stop = 5 V
- Vbe = 0.77, 0.78, .79, 0.80, 0.81 V (Parameter)
- $T_A = 25$ C

Rth extraction using Gummel Plot measurements

Summary and comparison

	Intersection	Rieh	Reisch
TSP	V_{BE}	V_{BE}	I_B
Measurement effort for Rth @ RT	fg @ RT: 1 fg @ RT+ ΔT : 1	Cal. meas: 12 PD meas.: 1	fwd output meas. @ RT: 1
Speed	fast	time consuming	very fast
Contact resistance sensitivity	high	low	high
Applicable	only in high current range	wide I_E range	only in low current range
Rth (K/W) for npn Ae=2x40	315 at $I_C=80\text{mA}$; $T_{A1}=25$, $T_{A2}=75$	264 at $I_E=5\text{mA}$; $T_A=20\text{ C}$ 290 $I_E=5\text{mA}$; $T_A = 50\text{ C}$	270 at $I_E=6\text{mA}$; $T_A=25\text{ C}$
Rth (T_A)	alpha = 0.8	alpha = 1.1	n.a.

Rth extraction using DC measurements

Literature

- [1] Fester, Jacek: "Investigation and Comparison of different Methods for the Extraction of the Thermal Resistance of Bipolar Transistors in SiGe-Technologies", Diploma Thesis, Wroclaw University of Technology (Faculty of Electronics), Wroclaw, 2005
- [2] Dawson, D.E., Aydiyta, Gupta, Salib, M.L.: „CW Measurement of HBT Thermal Resistance“, IEEE Transactions on Electron Devices, Vol.39 , No.10, October 1992, pp. 2235-2239
- [3] Marsh, S.P.: „Direct Extraction Technique to Derive the Junction Temperature of HBT's Under High Self-Heating Bias Conditions“, IEEE Transactions on Electron Devices, Vol. 47, No.2, February 2000, pp. 288 - 291
- [4] Paasschens, J.C.J., Harmsma, S., van der Toorn, R.: "Dependence of Thermal Resistance on Ambient and Actual Temperature", Proc. of the BCTM 2006, p.96 - 99
- [5] Pfof, M.; Kubrak, V.; Brenner, P.: "A Practical Method to Extract the Thermal Resistance for Heterojunction bipolar Transistors", ESSDERC 2003
- [6] Reisch, M.: "Self Heating in BJT Circuit Parameter Extraction". Solid State Electronics, Vol.35, No.5, 1992, pp.677 - 679
- [7] Rieh, J.S. et.al.: "Measurement and Modeling of Thermal Resistance of High Speed SiGe Heterojunction Bipolar Transistors", Topical Meeting on Silicon Monolithic Integrated Circuits in RF-Systems, Sept. 2001
- [8] Waldrop, J.R., Wang, K.C., Asbeck, P.M.: "Determination of Junction Temperature in AlGaAs/GaAs Heterojunction Bipolar Transistors by Electrical Measurement", IEEE Transactions on Electron Devices, Vol.39 , No.5, May 1992, pp. 1248-1250
- [9] Williams, David; Tasker, Paul: „Thermal Parameter Extraction Technique using DC I-V-Data for HBT Transistors“, 2000 High Frequency Postgraduate Student Colloquium, ISBN 0-7803-6590-9, Dublin, Ireland, 7-8 Sept. 2000
- [10] Zweidinger, D.T. et.al.: "Thermal Impedance Extraction for Bipolar Transistors", IEEE Transactions on Electron Devices, Vol.43 , No.2, 1996, pp. 342 - 346