Extraction of thermal resistance and its temperature dependence using DC methods

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HICUM Workshop
18./19.6.2007
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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 = const. , Rth = 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

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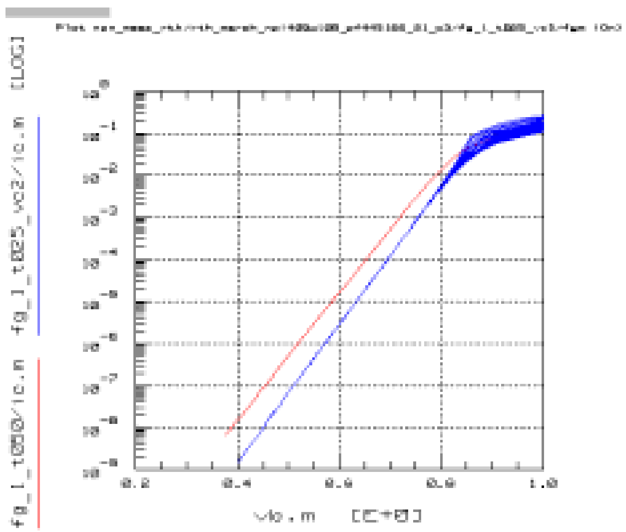
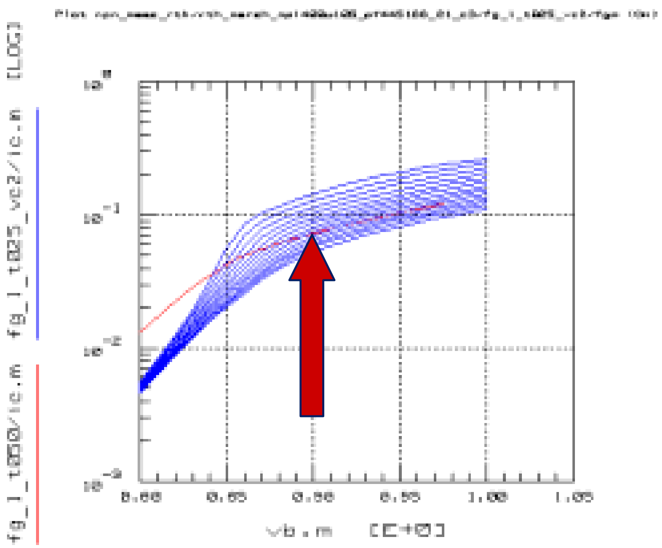
Rth extraction using the Intersection method
Principle (1)

- For SiGe and SiGeC transistors we observe an typical Ic increase at high currents, created by self heating
- Using two Gummel Plots, measured at two different ambient temperatures, we get intersection points
- The intersection points are useful for Rth extraction





- Gummel Plot Ic = f(Vbe), Vc = Par. at T_A = 25
- Gummel Plot Ic = f(Vbe), Vc = 1 V at T_A = 50

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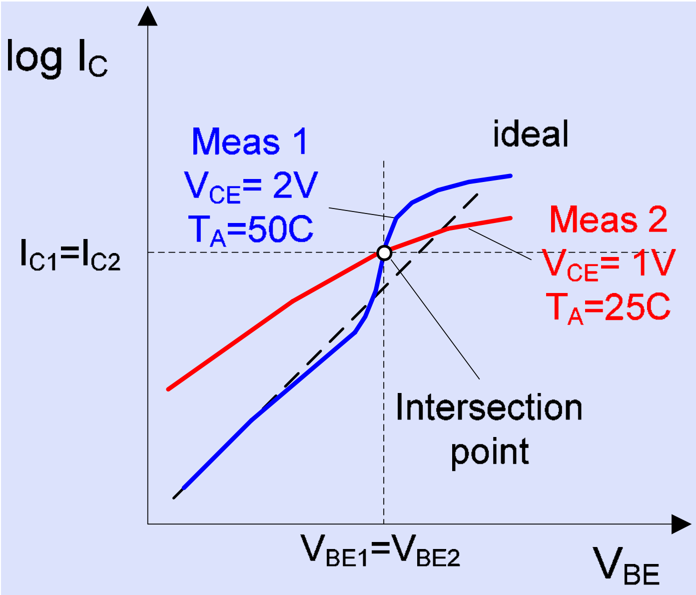
Rth extraction using the Intersection method
Principle

- 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 ≠ $f(T_J)$ 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



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

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

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

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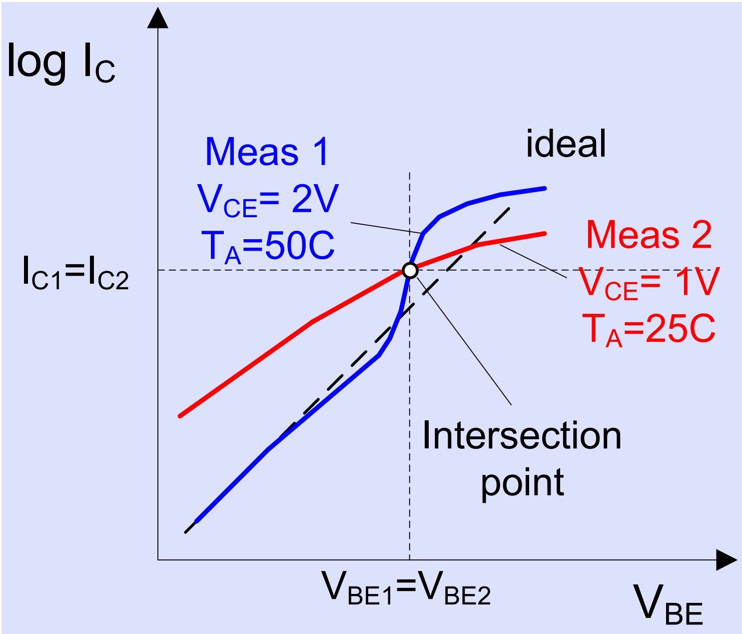
Rth extraction using the Intersection method
Rth equation

- 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



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

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

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

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

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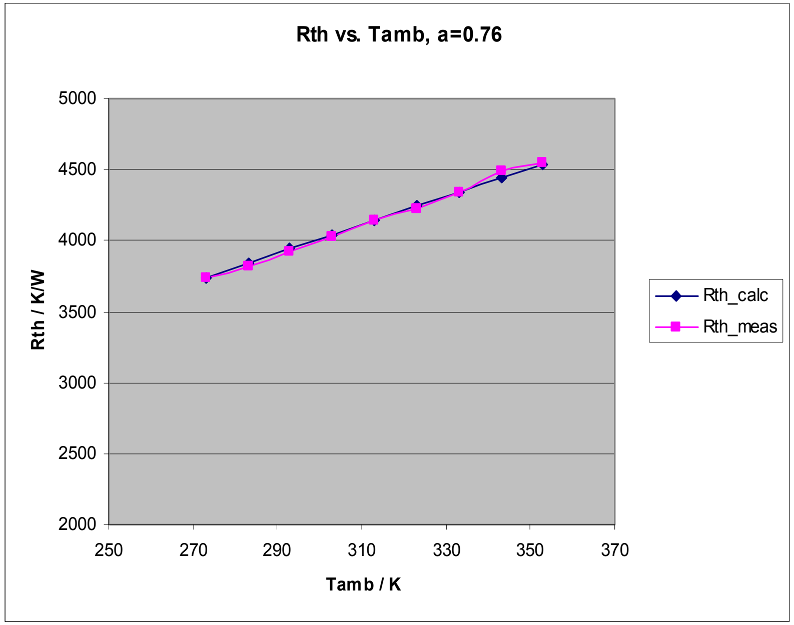
Rth extraction using the Intersection method
Measurement example (1)

- For a small device Rth = 3700 K/W is extracted at T_A = 273 K
- The Rth ambient temperature dependence was found by alpha = 0.76

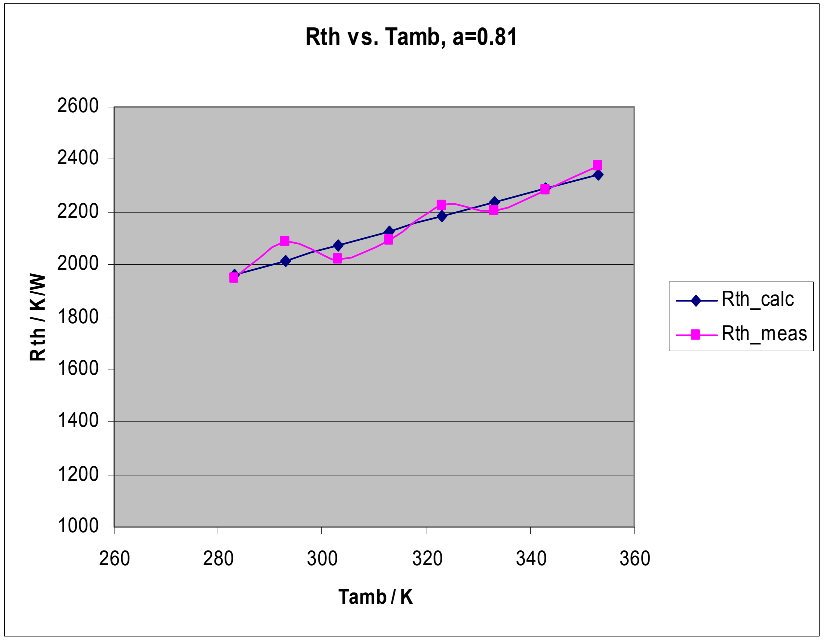


TA 1	Tref	alpha	Rth_calc	Rth_meas
273	273	0.76	3734	3734
283	273	0.76	3838	3819
293	273	0.76	3941	3922
303	273	0.76	4042	4028
313	273	0.76	4143	4139
323	273	0.76	4244	4226
333	273	0.76	4343	4344
343	273	0.76	4442	4491
353	273	0.76	4540	4549

- Device: npn, Ae = 1.35 µm²
- Temperature condition: T_{A1} = 10 to 80 C, T_{A2} = T_{A1} + 10K
- Measurement condition: V_{C1} = 3 V, V_{C2} = 1V

Rth extraction using the Intersection method Measurement example (2)

- For a medium device Rth =1950 K/W is extracted at T_A = 273 K
- The Rth ambient temperature dependence was found by alpha=0.81

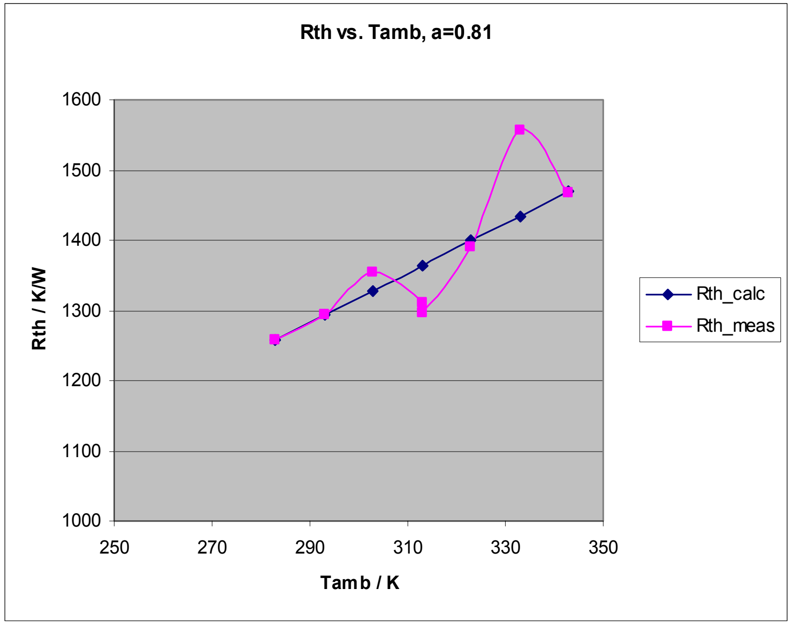


TA 1	Tref	alpha	Rth_calc	Rth_meas
283	283	0.81	1960	1950
293	283	0.81	2016	2086
303	283	0.81	2072	2020
313	283	0.81	2128	2093
323	283	0.81	2183	2227
333	283	0.81	2238	2206
343	283	0.81	2292	2286
353	283	0.81	2346	2374

- Device: npn, Ae = 3.0 μm^2
- Temperature condition: T_{A1} = 10 to 80 C, T_{A2} = T_{A1} + 10K
- Measurement condition: V_{C1} = 3 V, V_{C2} = 1V

Rth extraction using the Intersection method
Measurement example (3)

- For a long device Rth =1250 K/W is extracted at T_A = 273 K
- The Rth 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, Ae = 5.2 μm^2
- Temperature condition: T_{A1} = 10 to 70 C, T_{A2} = T_{A1} + 10K
- Measurement condition: V_{C1} = 3 V, V_{C2} = 1V

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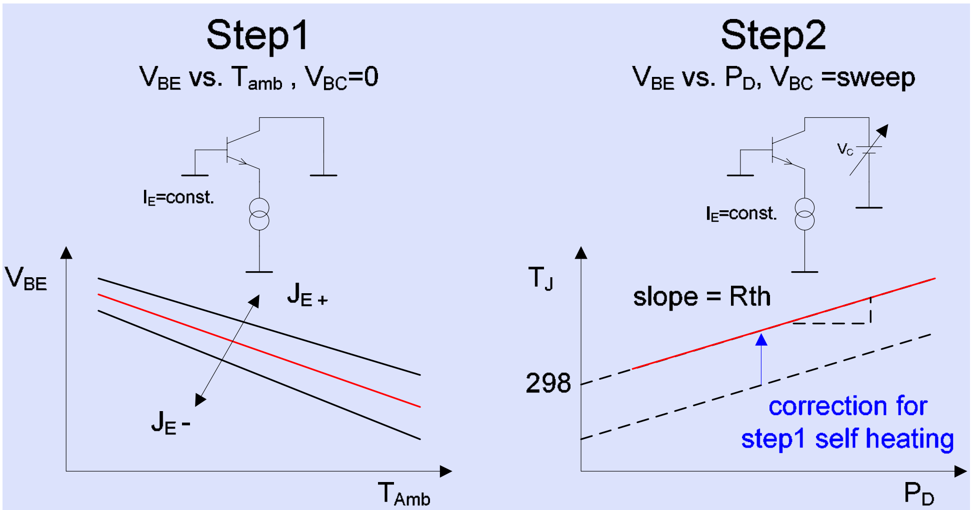
Rth extraction according to Rieh (2001) Principle: TSP = V_{BE}

- 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 =const. ,
  DT is calculated for each curve
- Step 2: Power dissipation measurement
  V_{BE} measured at T = 298 K and at the same IE = const., as in step 1.
  V_{BC} is swept from – 0.2 to 3V, in this way the dissipated power is varied
- Rth is calculated from the slope of the characteristic T_J vs. P_D



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

$$T_J(P_D) = \frac{V_{BEmeas} - V_{BE0}}{D_T}$$

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

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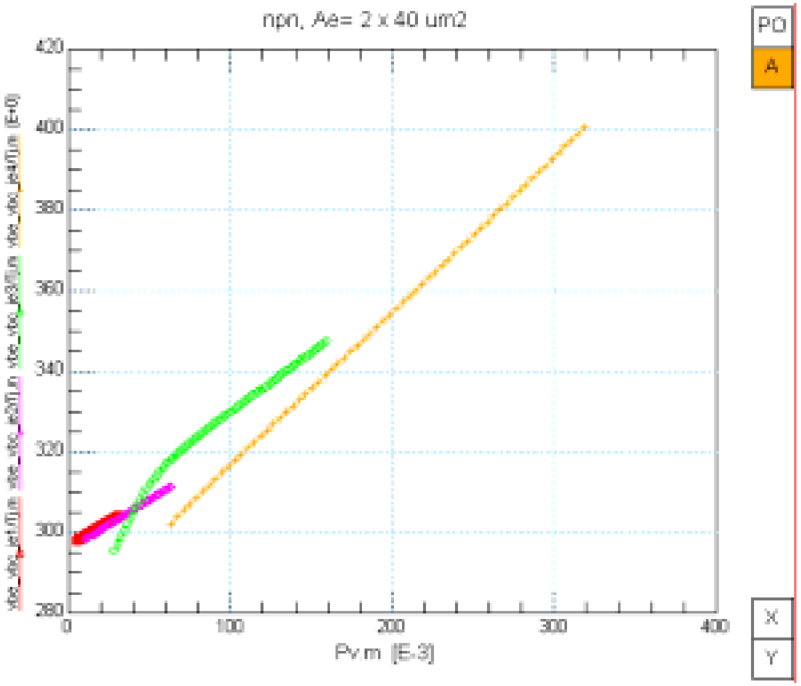
Rth extraction according to Rieh (2001)
Measurement example (1)

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



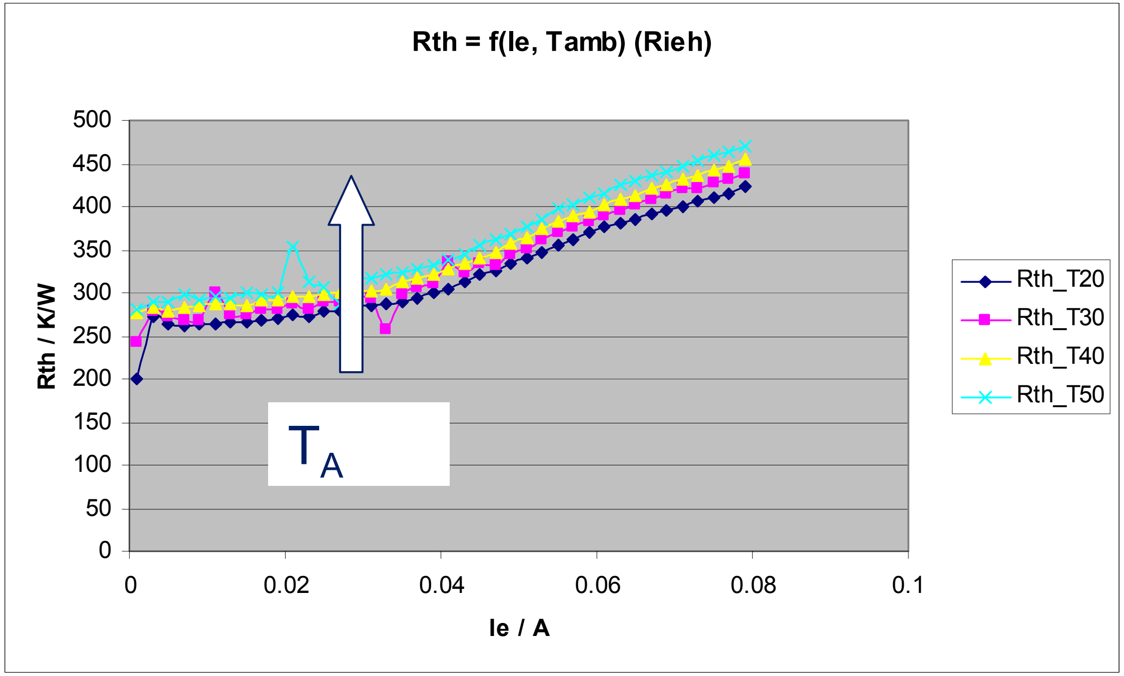
Je mA/µm2	Rth K/W
0.1	242
0.2	248
0.5	295
1	380

- Device: npn, Ae = 2 x 40 μm^2
- Measurement condition: V_C = - 0.2 … 3 V, Je = 0.1, 0.2, 0.5, 1 mA / µm2
- Temperature condition: T_A = 20 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, Ae = 2 x 40 µm²
- T_A = 20, 30, 40, 50 C

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

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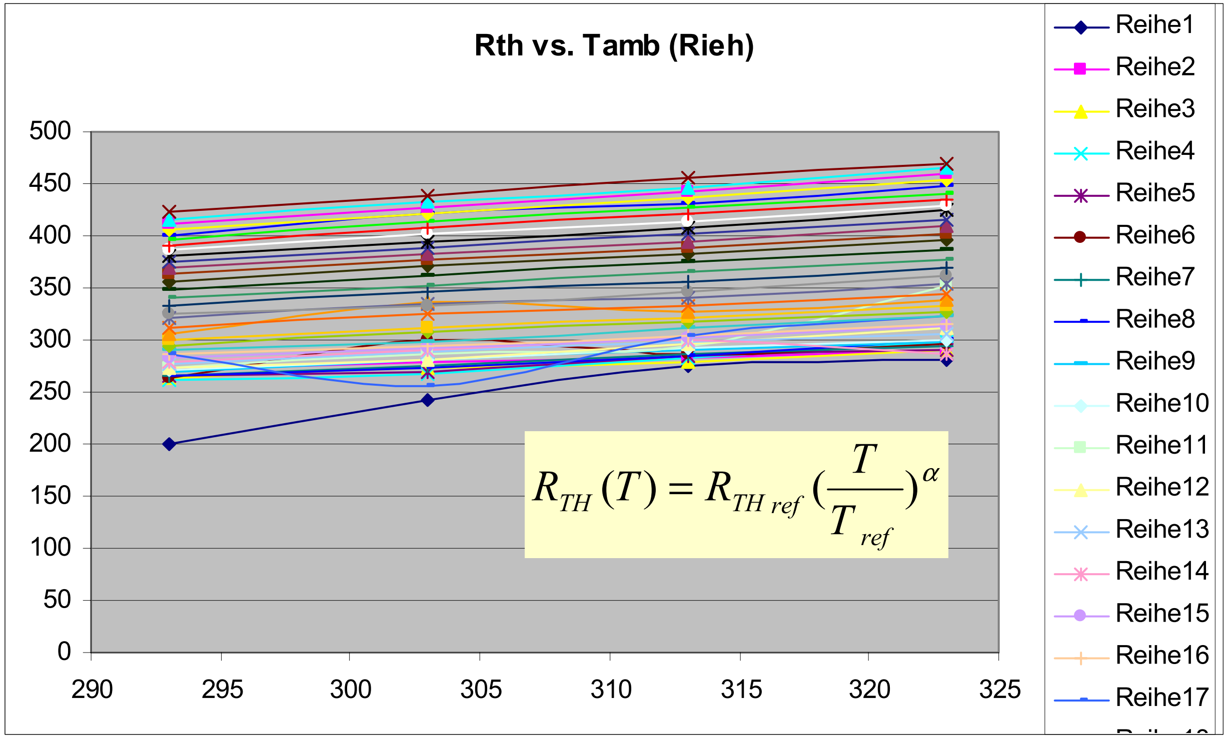
Rth extraction according to Rieh (2001)
Measurement example (3)

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



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

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

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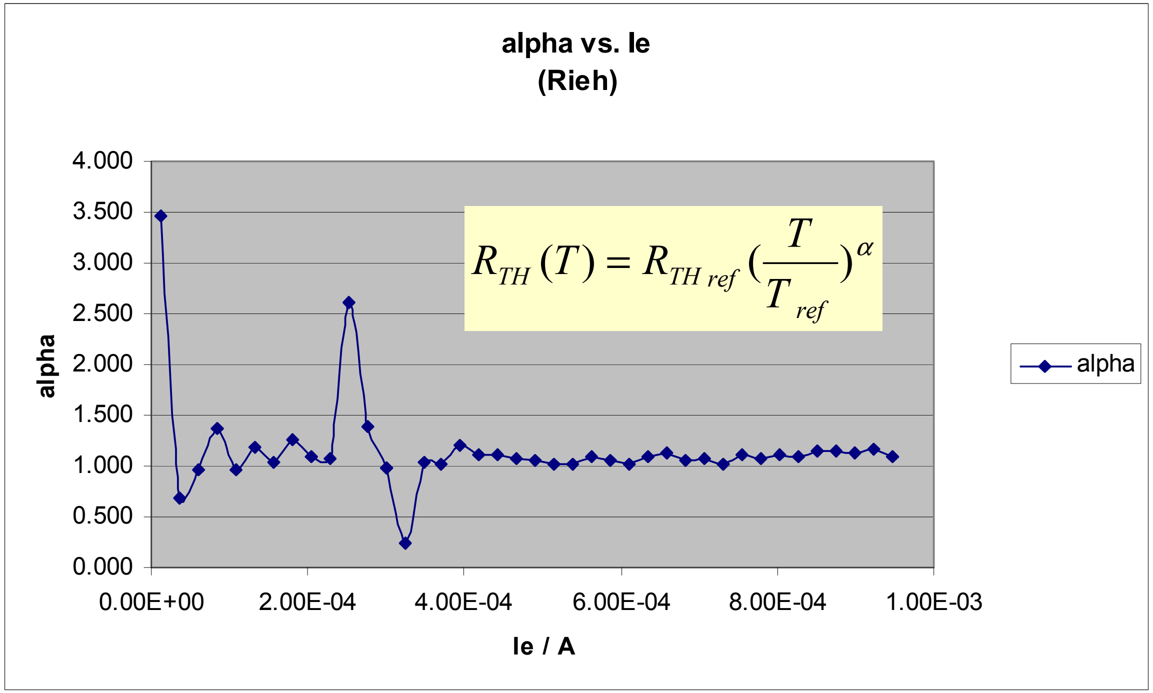
Rth extraction according to Rieh (2001) Measurement example (4)

- 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, Ae =2 x 40 µm²
- T_A = 20, 30 ,40, 50 C

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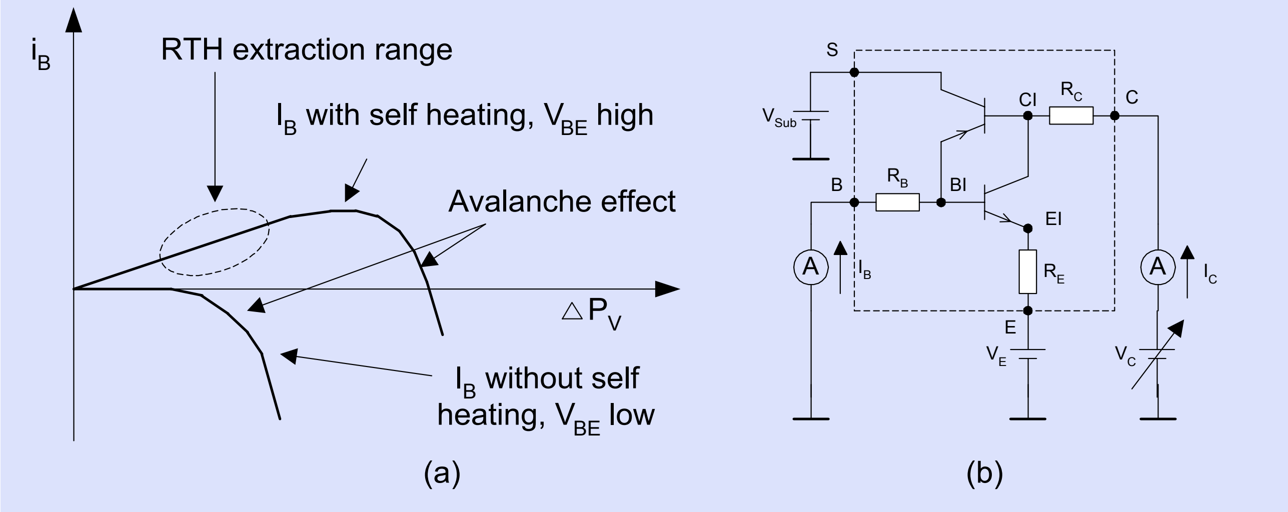
Rth extraction according Reisch (1992) Principle: TSP = IB

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



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

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

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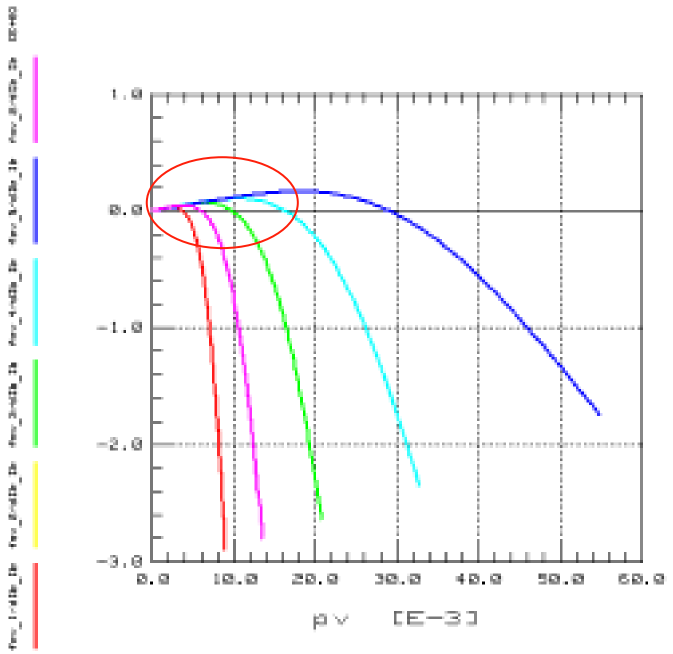
Rth extraction according Reisch (1992)
Measurement example (1)

- ΔI_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 x 40 µm²
- 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]

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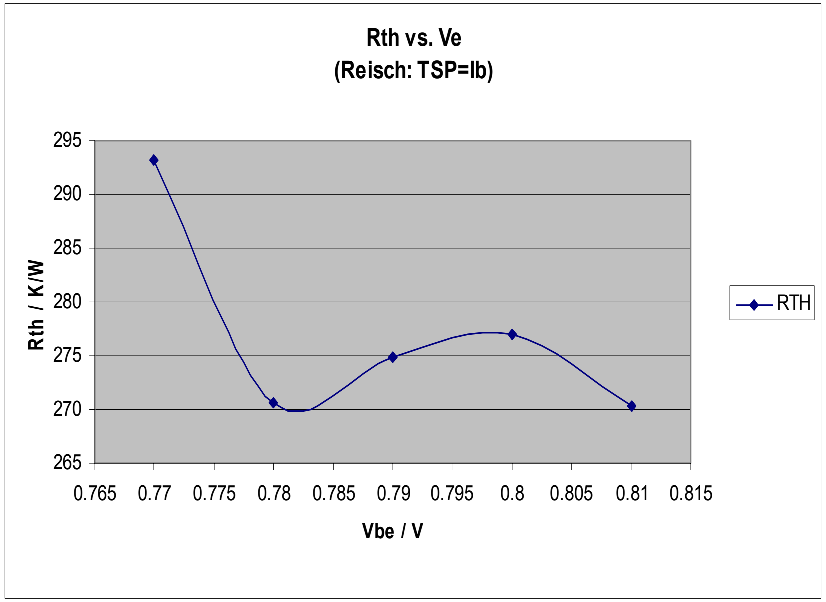
Rth extraction according Reisch (1992) Measurement example (2)

- 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	Ie(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, Ae = 2 x 40 µm^2
- Vc = sweep, start = 0, stop = 5 V
- Vbe = 0.77, 0.78, .79, 0.80, 0.81 V (Parameter)
- T_A = 25 C

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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=80mA; T_{A1}=25, T_{A2}=75	264 at I_E=5mA; T_A=20 C 290 I_E=5mA; T_A = 50 C	270 at I_E=6mA; T_A=25 C
Rth (T_A)	alpha = 0.8	alpha = 1.1	n.a.

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Rth extraction using DC measurements Literature

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