Coupled extraction of RE and RTH based on DC output curves

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Outline

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- Method
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Introduction

- Several methods for R_E and R_{TH} extraction exist
  - Most for R_E based on S-parameters
- Also combined methods exist
- Here, a new method based on a simple self-heating model is presented
  - Only based on DC output curves
- Basic concept
  - Calculation of temperature increase from $I_B(V_{BE})$ values
  - Calculation of R_E from dissipated power and difference of V_{CEi} and V_{CE}

Method

Base current

- In forward active mode $I_B = \mathrm{f}(V_{BEi}, T, V_{BCi})$
- $V_{BEi} = V_{BE} - I_E * R_E - I_B * R_B$
- Known parameters: $I_{BEs}(T_0)$, m_{BE}, ζ_{BET}, V_{gB} -> $I_{BEs}(T)$
- Measured values: V_{BE}, I_B, $I_E(= I_C)$

Self-heating

- Simplified model: $\Delta T = I_C * V_{CEi} * R_{TH}$
- $V_{CEi} = V_{CE} - I_E * R_E - I_C * R_{Cx}$
- Measured values: V_{CE}, $I_E(= I_C)$

- Measurement at fixed I_C (using a control script adjusting V_{BE})
  - or forced I_B, if temperature dependence of beta is low
- Assuming I_B only consists of I_{BE}, ΔT can be calculated with known R_E from measured $I_B(V_{BE})$

$$I_B = I_{BEs}(T)\exp\left(\frac{V_{BE} - I_E R_E}{m_{BE} V_T}\right)$$ (solved for T with Newton-method)

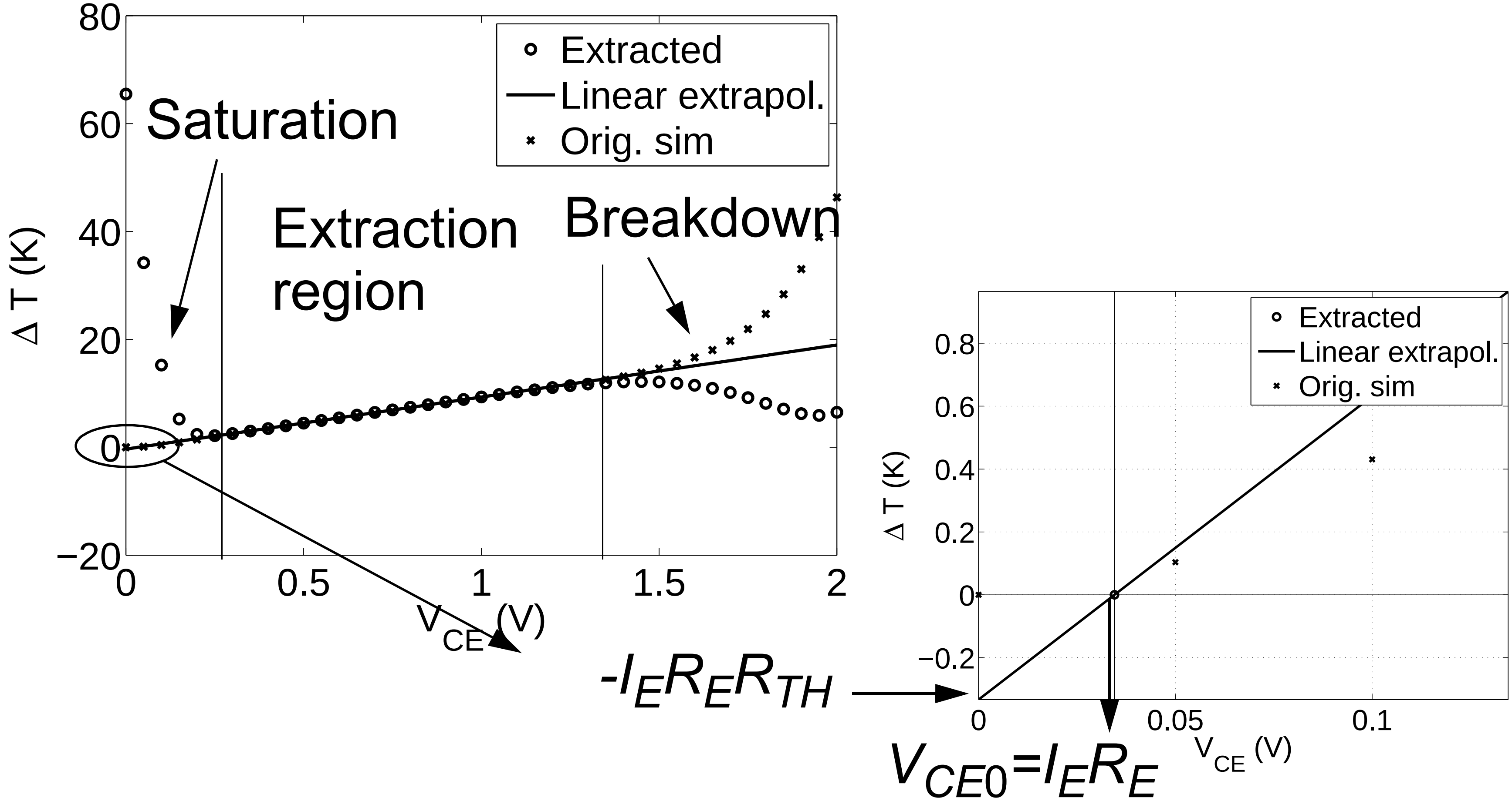
- Since fixed I_C (assuming $R_{TH}(T)$ = const and $R_E(T)$ = const)

$$\frac{\Delta T}{I_C} = V_{CEi} R_{TH} = (V_{CE} - I_E R_E) R_{TH} = V_{CE} R_{TH} - I_E R_E R_{TH}$$

=> $\Delta T \sim V_{CEi}$ and $\Delta T = f_{lin}(V_{CE})$

  - Since generally $R_{TH}(T) \neq$ const and $R_E(T) \neq$ const => no ideally linear function => see results

- Linear extrapolation of ΔT to 0 => $\Delta T(V_{CE0}) = 0$



- In high current region, ΔT is wrong due to additional base current components

- BUT: R_E is not known
- R_E can be calculated from V_{CE0}

$$R_E = \frac{V_{CE0}}{I_E}$$

- ΔT and V_{CE0} are calculated by using an initial value of R_E
- Defining $R_{E,\text{temp}}$ for calculating ΔT and $R_{E,\text{extr}}$ from V_{CE0}

$$R_{E,\text{temp}} \Rightarrow \Delta T_{\text{extr}} \Rightarrow V_{CE0} \Rightarrow R_{E,\text{extr}}$$

$$I_B = I_{BEs}(T_{\text{extr}}) \exp\left(\frac{V_{BE} - I_E R_{E,\text{temp}}}{m_{BE} V_{T,\,\text{extr}}}\right), \quad R_{E,\,\text{extr}} = \frac{V_{CE0}}{I_E}$$

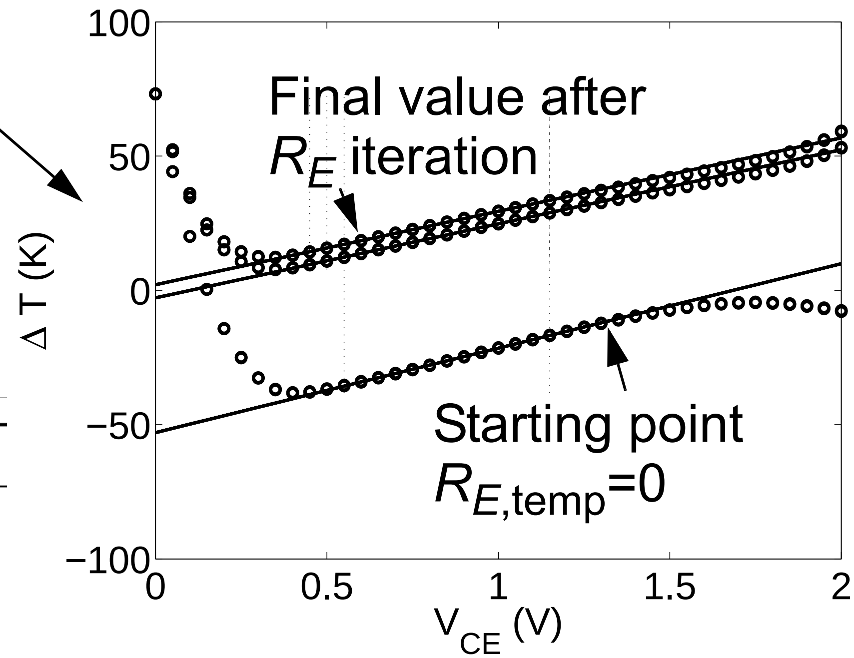
=> for one $R_{E,\text{temp}}$ => $R_{E,\text{temp}} = R_{E,\text{extr}} = R_E$

• Automated optimization for R_E

- Using an iteration
- Convergence criteria change of R_E less than a specified value

- Using Newton-like iteration

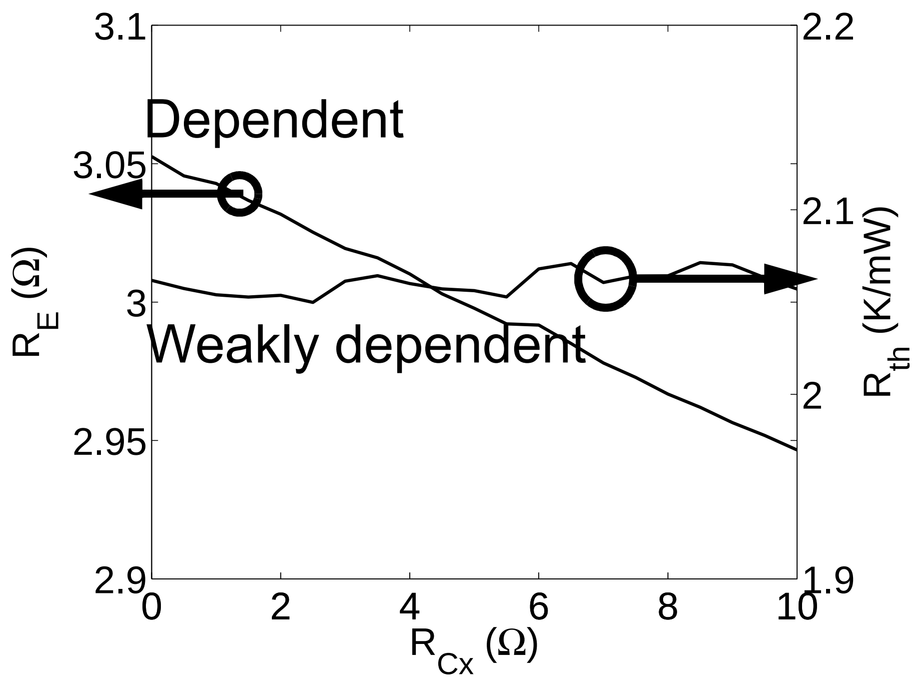
- Using some kind of bisection method



Iteration	Assumed R_E	Calculated R_E	Iteration		
01	0.000000	96.613437	34		
02	1.000000	46.972462	35		
03	2.000000	-5.898955	36		
04	1.000000	46.972462	37		
05	1.100000	41.785187	38	1.869820	1.870028
06	1.200000	36.569793	39	1.869810	1.869508
07	1.300000	31.326985	40	1.869811	1.870028
08	1.400000	26.066249	41	1.869812	1.869976
09	1.500000	20.779694	42	1.869813	1.869924
10	1.600000	15.474439	43	1.869814	1.869872

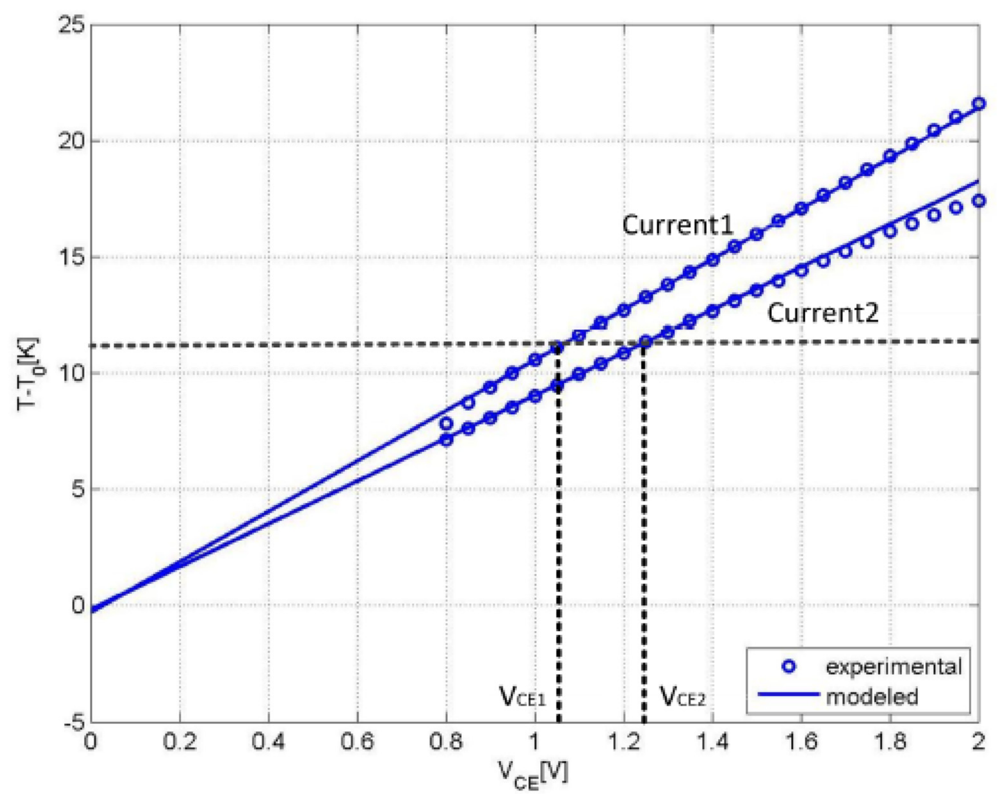
Influence of R_{Cx}

- $V_{CEi} = V_{CE} - I_E * R_E - I_C * R_{Cx}$
- Two methods:
  - Using known R_{Cx} from test structures



  - R_{Cx} including in extraction

- Using two different forced I_B or two constant I_C => I_{C1} and I_{C2}
- Same P_{diss} (=> same ΔT) for both
  - Choosing a fixed ΔT and $I_{C1} \neq I_{C2}$ => $V_{CE1} \neq V_{CE2}$
  - But same R_E, R_{Cx} and R_{TH} (as function of T)



- Calculation of R_{Cx} from temperature increases

$$P_{diss1} = P_{diss2}$$

$$\Downarrow$$

$$I_{C1}(V_{CE1} - R_E I_{E1} - R_{Cx} I_{C1}) R_{TH} = I_{C2}(V_{CE2} - R_E I_{E2} - R_{Cx} I_{C2}) R_{TH}$$

$$\Downarrow$$

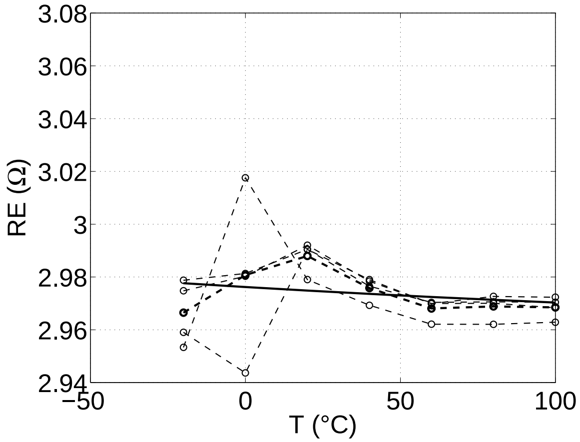
$$R_{Cx} = \frac{I_{C1} V_{CE1} - I_{C2} V_{CE2} - R_E (I_{C1} I_{E1} - I_{C2} I_{E2})}{I_{C1}^2 - I_{C2}^2}$$

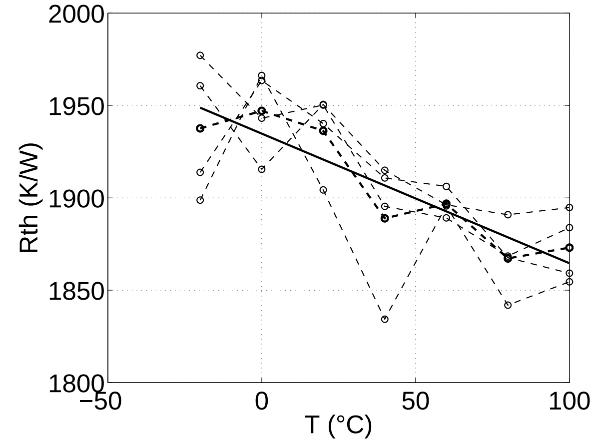
- Numerical optimization generally fails for experimental results
- Influence of R_{Ci}
  - Voltage drop for V_{BC} < punch-through
  - To be investigated

Results

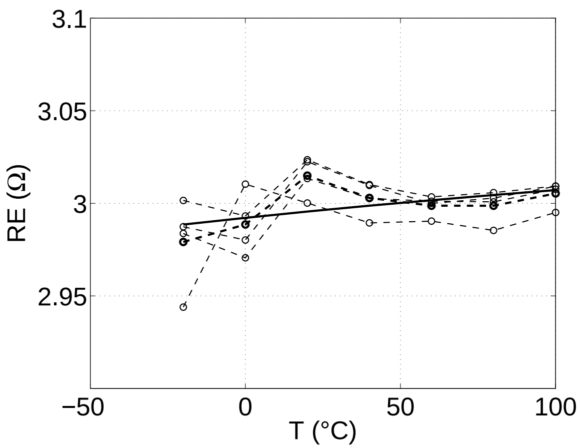
- Comparison versus model
- Test cases:
  - Ideal case: $R_E(T)$=const, $R_{TH}(T)$ = const, $R_C = R_B = 0$
  - External resistances: $R_E(T)$ = const, $R_{TH}(T)$ = const, $R_C \neq 0$, $R_B \neq 0$
  - T-dep RE: $R_E(T) \neq$ const, $R_{TH}(T)$ = const, $R_C \neq 0$, $R_B \neq 0$
  - Realistic case: $R_E(T) \neq$ const, $R_{TH}(T) \neq$ const, $R_C \neq 0$, $R_B \neq 0$
- R_C is assumed to be known in all cases
- Always four different values for I_B
  - Mean value of R_E and R_{TH} from each IB used

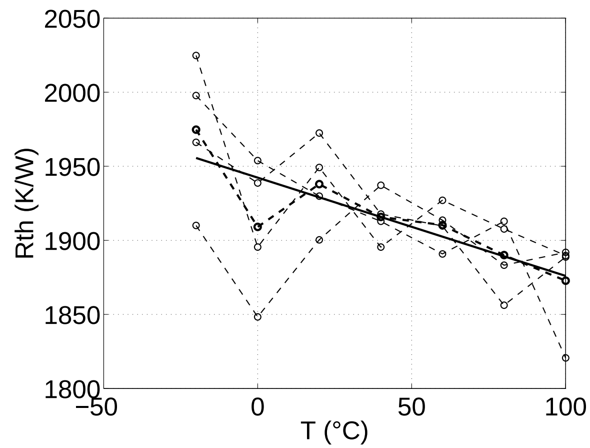
Ideal case



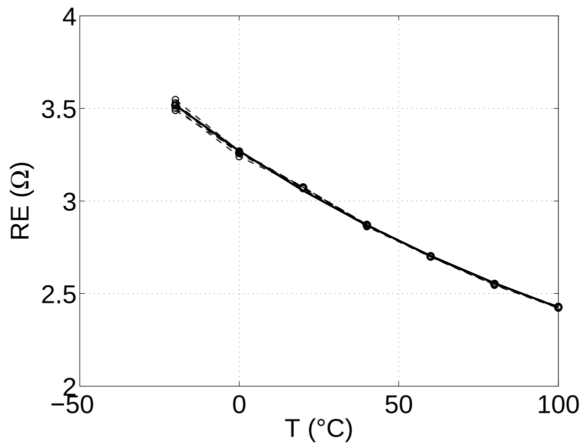


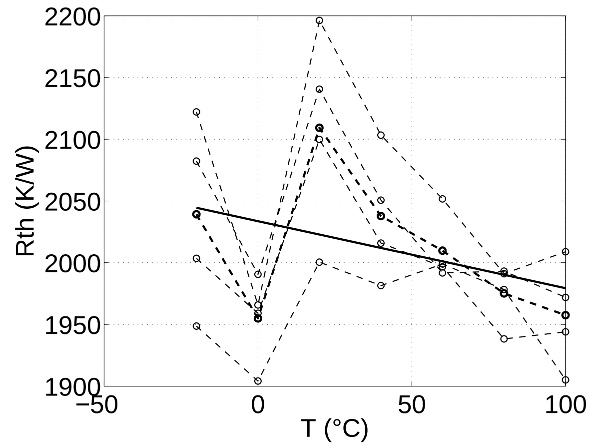
External resistances



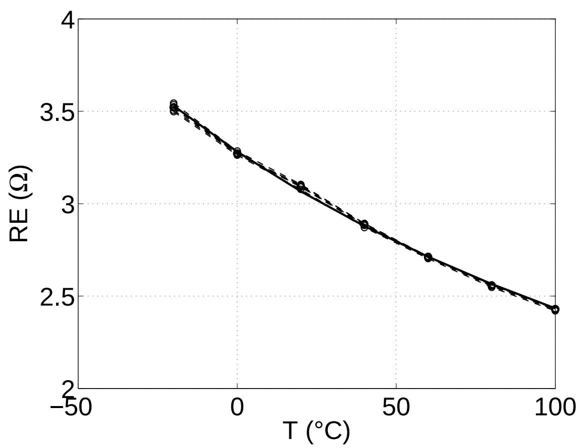


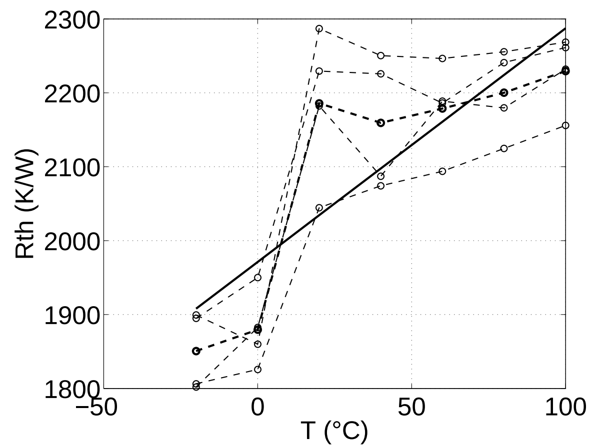
Temperature dependent R_E





Realistic case



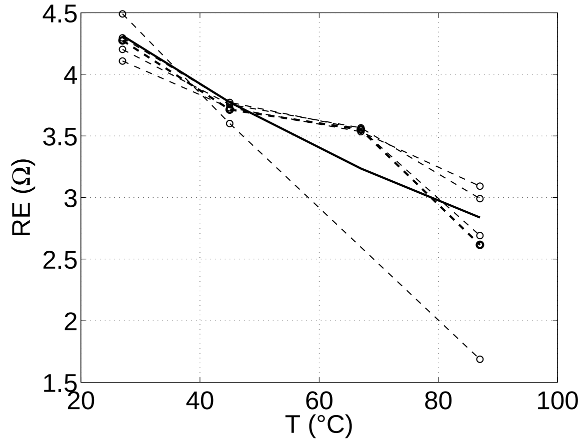


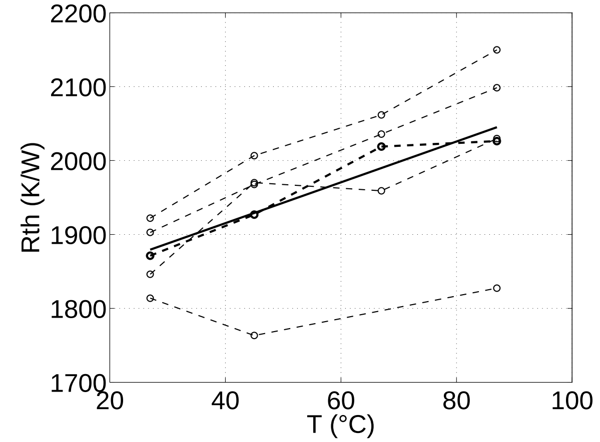
Comparison of results

Test case	R_E (model)	R_E (extract)	ζ_{RE} (model)	ζ_{RE} (extract)
Ideal	3.023 Ω	2.97 Ω	0	-0.006
Ext. res	3.023 Ω	3.0 Ω	0	0.016
T-dep. R_E	3.023 Ω	2.99 Ω	-0.96	-0.96
Realistic	3.023 Ω	3.0 Ω	-0.96	-0.96

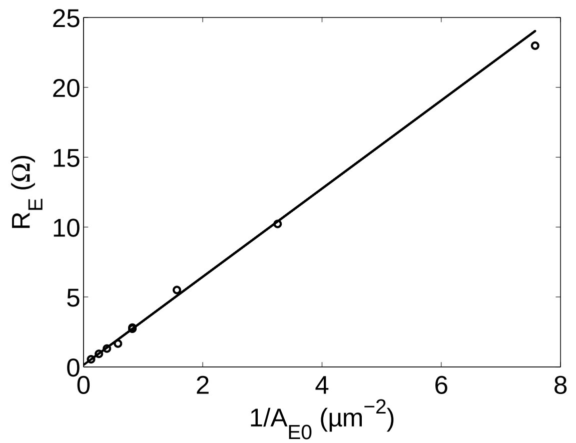
Test case	R_{TH} (model)	R_{TH} (extract)	ζ_{RTH} (model)	ζ_{RTH} (extract)
Ideal	1.98 K/mW	1.92 K/mW	0	-0.107
Ext. res	1.98 K/mW	1.92 K/mW	0	-0.11
T-dep. R_E	1.98 K/mW	2.02 K/mW	0	-0.078
Realistic	1.98 K/mW	2.06 K/mW	0.5	0.47

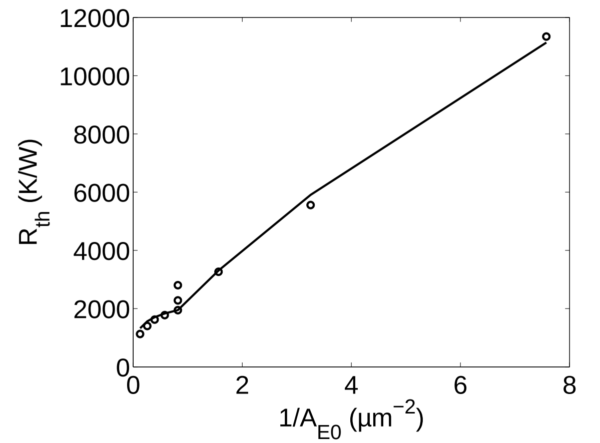
Measurements





- Meaningful scaling results





Summary

- Pros
  - Simple measurements, DC forced I_B
  - Robust => without R_C in the iteration always converges
  - Based on model equations => final model will agree well
- Cons
  - Temperature dependence of R_E and R_{TH} affects linear fit of $\Delta T(V_{CE})$
  - R_{Cx} should be known in advance
  - Based on model equations => physical value of extracted parameters dependent on model equations for self-heating
  - Limited range during extraction
    - V_{BE} large enough for self-heating but below high-current effects
    - V_{CE} between saturation and breakdown -> linear fit
- To do: evaluation for large geometry and technology range

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