COMPACT MODELING OF NONLINEAR SELF-HEATING IN SIGE HBTS

Marnix Willemsen

AKB-WORKSHOP

2023, 9-10 NOVEMBER

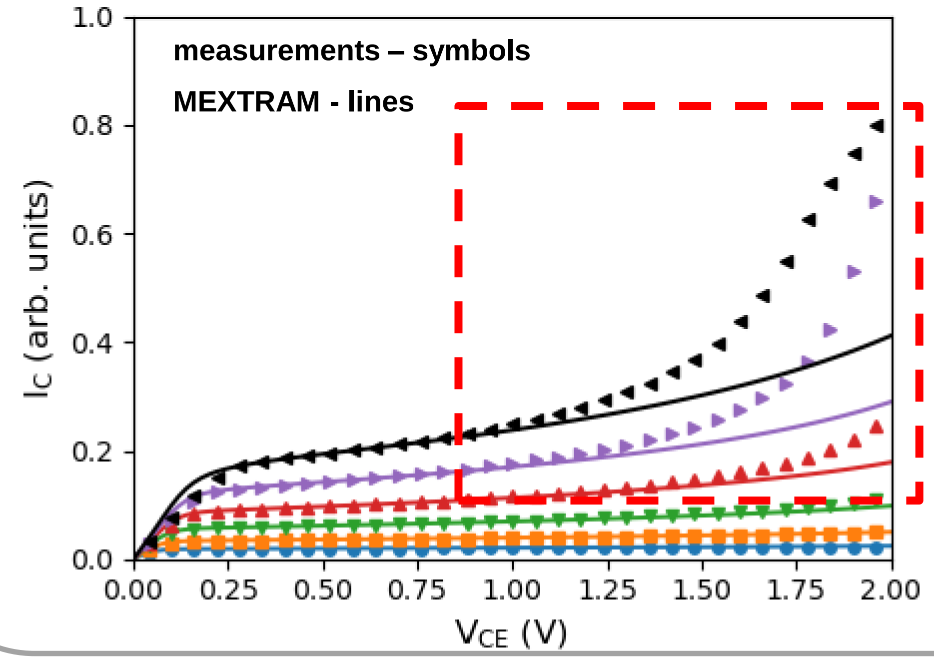
SECURE CONNECTIONS
FOR A SMARTER WORLD

PUBLIC

CONTENTS

INTRODUCTION

- SiGe HBTs are high current-density devices with strong self-heating.
- Compact modeling with Mextram model under conditions of strong self-heating is challenging.



Regime of strong self-heating (high V_{CE} & high V_{BE}) addressed in this presention.

CONTENTS

- Introduction.
- Background nonlinear self-heating.
- Results.
- Conclusions.

NONLINEAR SELF-HEATING

- What is nonlinear self-heating?
  - Nonlinear self-heating refers to a nonlinear relationship between the temperature increase ΔT and dissipated power P_{diss}, instead of a linear equation, *i.e.*, $\Delta T = R_{TH} \cdot P_{diss}$.

- Nonlinear self-heating has been investigated for transistors, for example GaAs HBTs.[1]

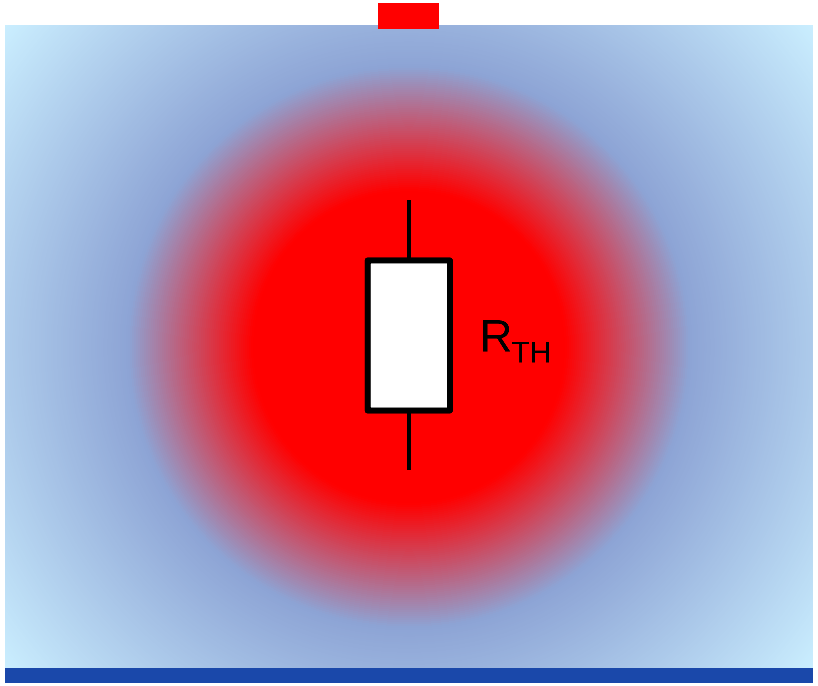
- *This presentation*:
  - Review of nonlinear self-heating in SiGe HBTs.

1. “Dependence of thermal resistance on ambient and actual temperature”, J.C.J. Paasschens et al., IEEE BCTM 2004

SELF-HEATING AND THERMAL RESISTANCE

Device (heat source)

at temperature T_{DEV}



Ambient (heat sink)

at temperature T_{AMB}

Semiconductor material:

- Thermal conductivity depends on temperature*:

$$\kappa(T) = \kappa_{ref}\left(\frac{T}{T_{ref}}\right)^{-\alpha}$$

- Thermal resistance*:

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

* α thermal coefficient of the thermal resistance. Typical Si-value: 1.3 (ATH-model parameter in Mextram)

SELF-HEATING AND THERMAL RESISTANCE

Semiconductor material:

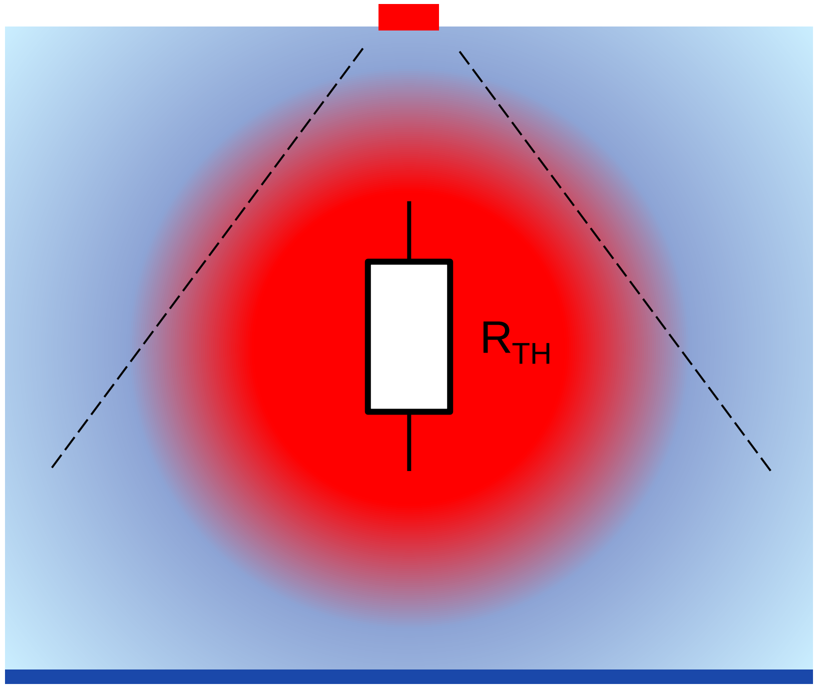
- Thermal conductivity depends on temperature*:

$$\kappa(T) = \kappa_{ref}\left(\frac{T}{T_{ref}}\right)^{-\alpha}$$

- Thermal resistance*:

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

Device (heat source)
at temperature T_{DEV}



Ambient (heat sink)
at temperature T_{AMB}

<u>Which temperature to use in the thermal resistance?</u>

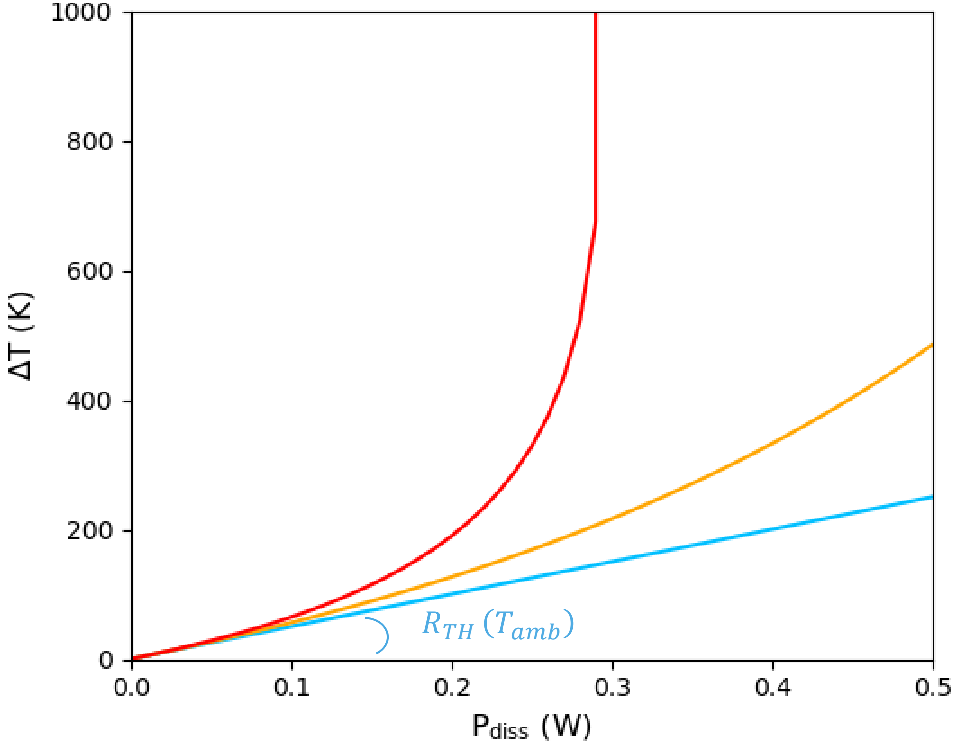
1. Thermal resistance dependent on ambient temperature.
   - Good first order approximation.
     (“most of the thermal resistance is close to the ambient temperature”)
   - Implemented in Mextram.

2. Thermal resistance dependent on device temperature.
   - Less realistic.
   - It results in huge amounts of self-heating.
   - See benchmark on the next slide.

3. Nonlinear self-heating.
   - The temperature gradient between the device and the heat sink is included, leading to a <u>nonlinear</u> relationship between the temperature increase and dissipated power.

* α thermal coefficient of the thermal resistance. Typical Si-value: 1.3 (ATH-model parameter in Mextram)

COMPARISON OF SELF-HEATING MODELS



Thermal resistance dependent on ambient temperature

$$\Delta T = R_{TH}\,(T_{amb}) \cdot P_{diss}$$

Nonlinear self-heating model (temperature gradient included)

$$\Delta T = T_{amb} \cdot \left[\left(1 + \frac{(1-\alpha)\cdot R_{TH\,amb} \cdot P_{diss}}{T_{amb}}\right)^{\frac{1}{1-\alpha}} - 1\right]$$

Thermal resistance dependent on device temperature

$$\Delta T = R_{TH}\,(T_{device}) \cdot P_{diss}$$

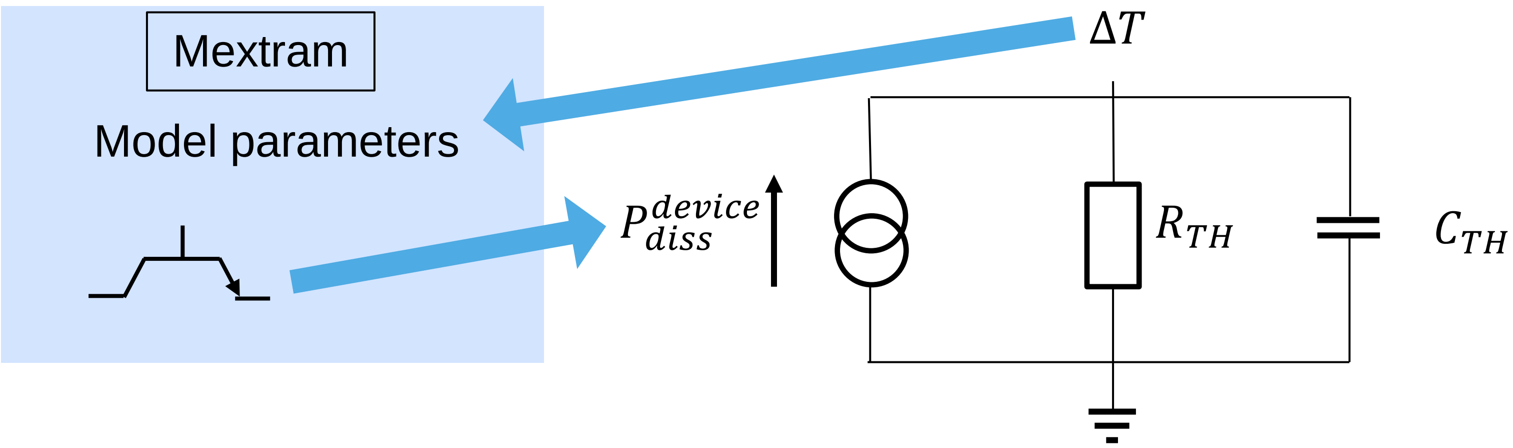
- Nonlinear self-heating model shows more self-heating in comparison to a thermal resistance dependent on the ambient temperature (linear self-heating $\Delta T = R_{TH}\,(T_{amb}) \cdot P_{diss}$)
- Thermal resistance dependent on the device temperature shows huge amounts of self-heating. Not addressed further.

BACKGROUND SELF-HEATING

- Self-heating:
  - Linear relationship between the temperature increase ΔT and dissipated power P_{diss} via the thermal resistance $R_{TH}\,(T_{amb})$.

$$\boxed{\Delta T = T_{dev} - T_{amb} = R_{TH}\,(T_{amb}) \cdot P_{diss} \quad \text{or} \quad P_{diss} = \frac{\Delta T}{R_{TH}\,(T_{amb})}}$$

  - Implementation as a linear network in Mextram.

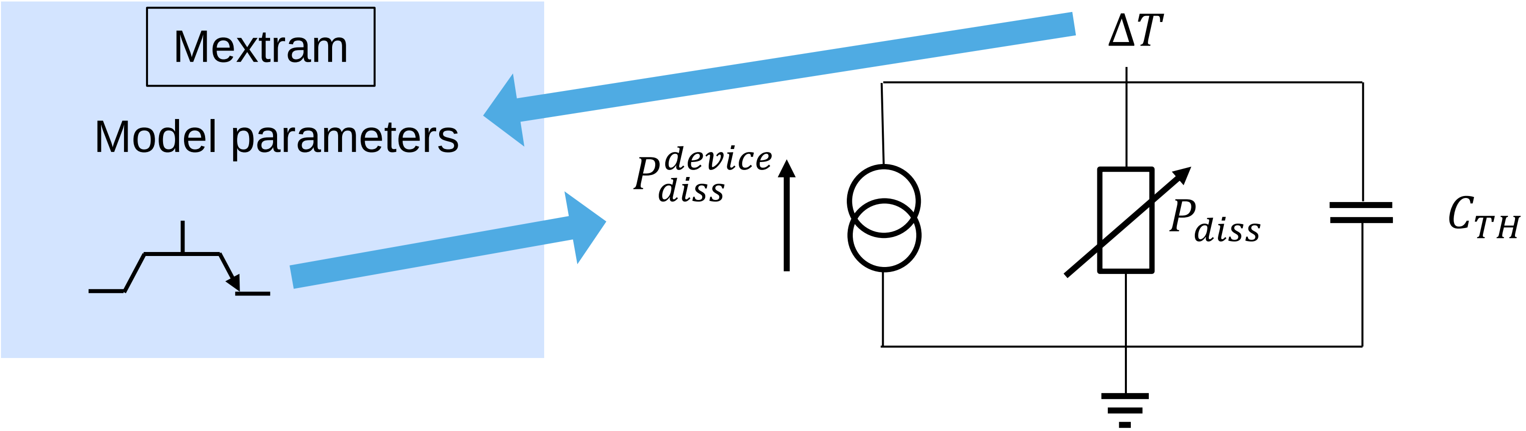


BACKGROUND NONLINEAR SELF-HEATING

- Nonlinear self-heating (as a result of including the temperature gradient between the device and heat-sink):
  - Nonlinear relationship between the temperature increase ΔT and dissipated power P_{diss}.

$$\boxed{\Delta T = T_{amb} \cdot \left[\left(1 + \frac{(1-\alpha) \cdot R_{TH}\,(T_{amb}) \cdot P_{diss}}{T_{amb}} \right)^{\frac{1}{1-\alpha}} - 1 \right] \quad \text{or} \quad P_{diss} = \frac{T_{amb}}{R_{TH}\,(T_{amb}) \cdot (1-\alpha)} \cdot \left[\left(1 + \frac{\Delta T}{T_{amb}} \right)^{1-\alpha} - 1 \right]}$$

  - Implementation



BACKGROUND NONLINEAR SELF-HEATING

- Nonlinear self-heating (as a result of including the temperature gradient between the device and heat-sink):
  - Nonlinear relationship between the temperature increase ΔT and dissipated power P_{diss}.

$$\boxed{\Delta T = T_{amb} \cdot \left[\left(1 + \frac{(1-\alpha) \cdot R_{TH}\,(T_{amb}) \cdot P_{diss}}{T_{amb}} \right)^{\frac{1}{1-\alpha}} - 1 \right] \quad \text{or} \quad P_{diss} = \frac{T_{amb}}{R_{TH}\,(T_{amb}) \cdot (1-\alpha)} \cdot \left[\left(1 + \frac{\Delta T}{T_{amb}} \right)^{1-\alpha} - 1 \right]}$$

- Few remarks on the equations:
  - The nonlinear equations reduce to linear self-heating in the limit of small amounts of dissipated powers or self-heating.

Taylor expansion: $\Delta T \approx T_{amb} \cdot \left[1 + \frac{R_{TH}\,(T_{amb}) \cdot P_{diss}}{T_{amb}} - 1 \right] = R_{TH}\,(T_{amb}) \cdot P_{diss}$

  - The nonlinear equations are <u>not</u> defined for a temperature scaling constant $\alpha = 1$.
    Equations for the temperature coefficient of the thermal resistance $\alpha = 1$ can be derived as well.

$$\boxed{\alpha = 1 \qquad \Delta T = T_{amb} \cdot \left[e^{R_{TH}(T_{amb}) \cdot P_{diss}/T_{amb}} - 1 \right] \quad \text{or} \quad P_{diss} = \frac{T_{amb}}{R_{TH}\,(T_{amb})} \cdot ln \left(1 + \frac{\Delta T}{T_{amb}} \right)}$$

BACKGROUND NONLINEAR SELF-HEATING

- Nonlinear self-heating (as a result of including the temperature gradient between the device and heat-sink):
  - Nonlinear relationship between the temperature increase ΔT and dissipated power P_{diss}.

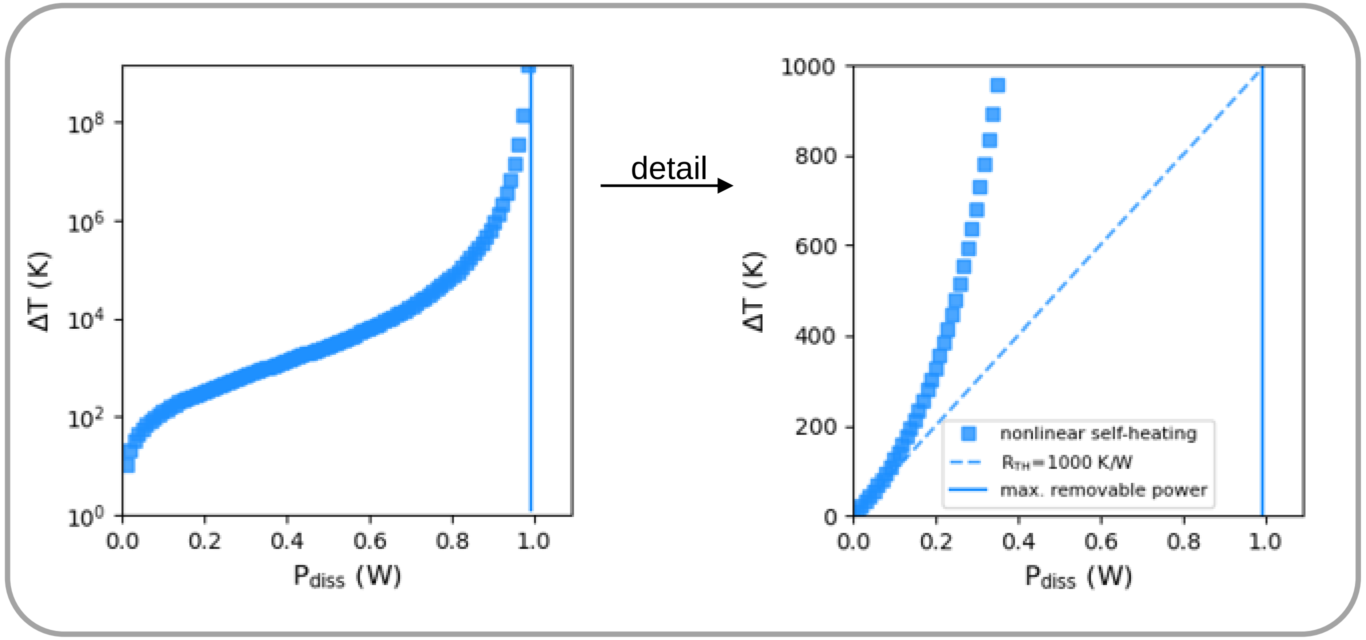
$$\boxed{\Delta T = T_{amb} \cdot \left[\left(1 + \frac{(1-\alpha) \cdot R_{TH}\,(T_{amb}) \cdot P_{diss}}{T_{amb}} \right)^{\frac{1}{1-\alpha}} - 1 \right] \quad \text{or} \quad P_{diss} = \frac{T_{amb}}{R_{TH}\,(T_{amb}) \cdot (1-\alpha)} \cdot \left[\left(1 + \frac{\Delta T}{T_{amb}} \right)^{1-\alpha} - 1 \right]}$$

  - Few remarks on the equations:
    - The nonlinear equations reduce to linear self-heating in the limit of small amounts of dissipated powers or self-heating.

Taylor expansion: $\Delta T \approx T_{amb} \cdot \left[1 + \frac{R_{TH}\,(T_{amb}) \cdot P_{diss}}{T_{amb}} - 1 \right] = R_{TH}\,(T_{amb}) \cdot P_{diss}$

    - There is a limit of high dissipation where ΔT cannot be calculated ($\alpha > 1$ and $P_{diss} > \frac{T_{amb}}{(\alpha-1) \cdot R_{TH}\,(T_{amb})}$), which is explained as thermal runaway, i.e., there is more power dissipated that can be removed leading to an infinite temperature increase. See next slide.

SELF-HEATING, NONLINEAR SELF-HEATING AND THERMAL RUNAWAY



$$\Delta T = T_{amb} \cdot \left[\left(1 + \frac{(1-\alpha) \cdot R_{TH}(T_{amb}) \cdot P_{diss}}{T_{amb}} \right)^{\frac{1}{1-\alpha}} - 1 \right]$$

Thermal runaway:

- $\alpha > 1$
- P_{diss} above maximum removable power:

$$\frac{T_{amb}}{(\alpha - 1) \cdot R_{TH}(T_{amb})}$$

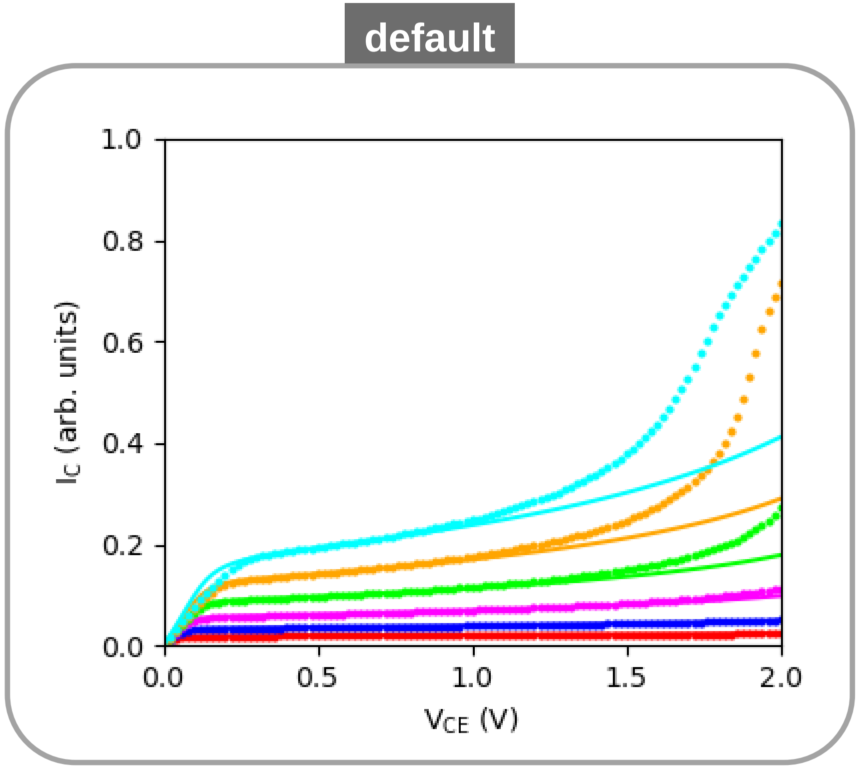
Thermal runaway effect in the equations occurs at very high device temperatures.

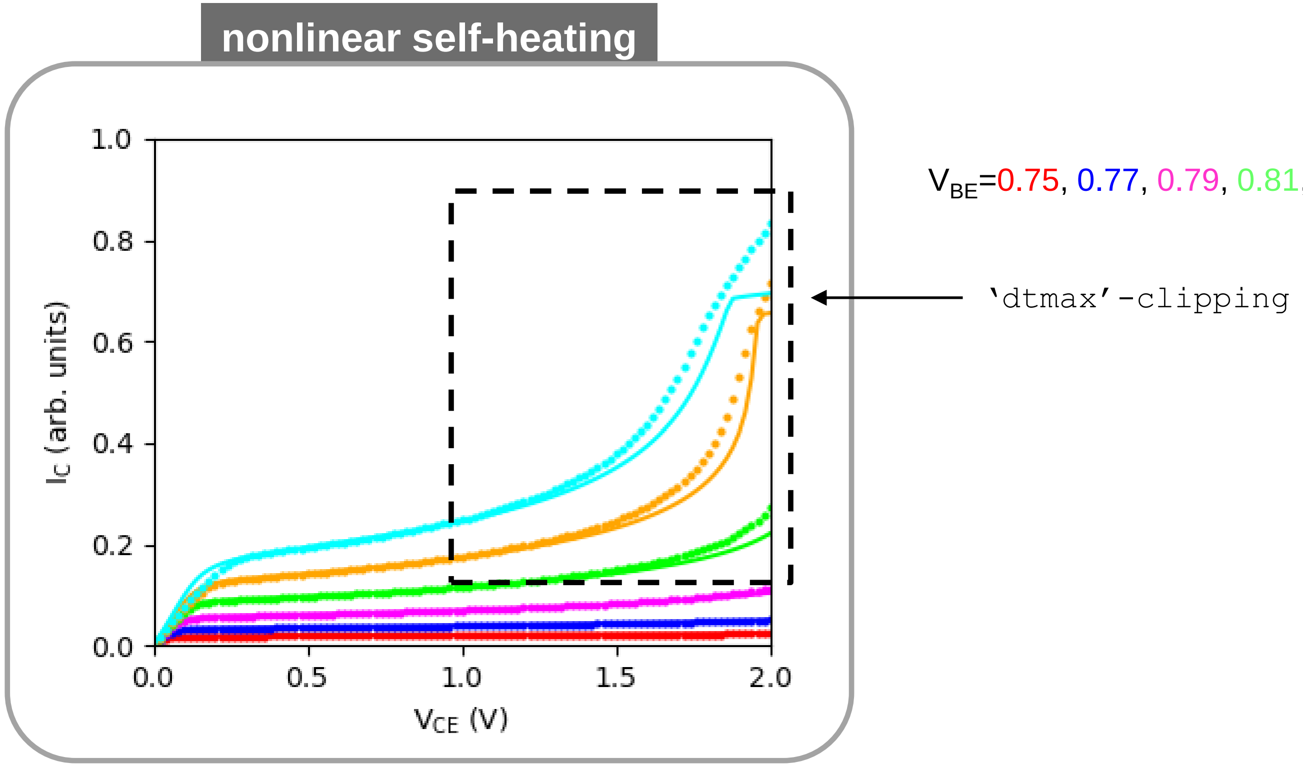
Note that the device temperature can be clipped in Mextram. (`'dtmax'` parameter)

Not of practical importance.

CONTENTS

EVALUATION NONLINEAR SELF-HEATING – LV

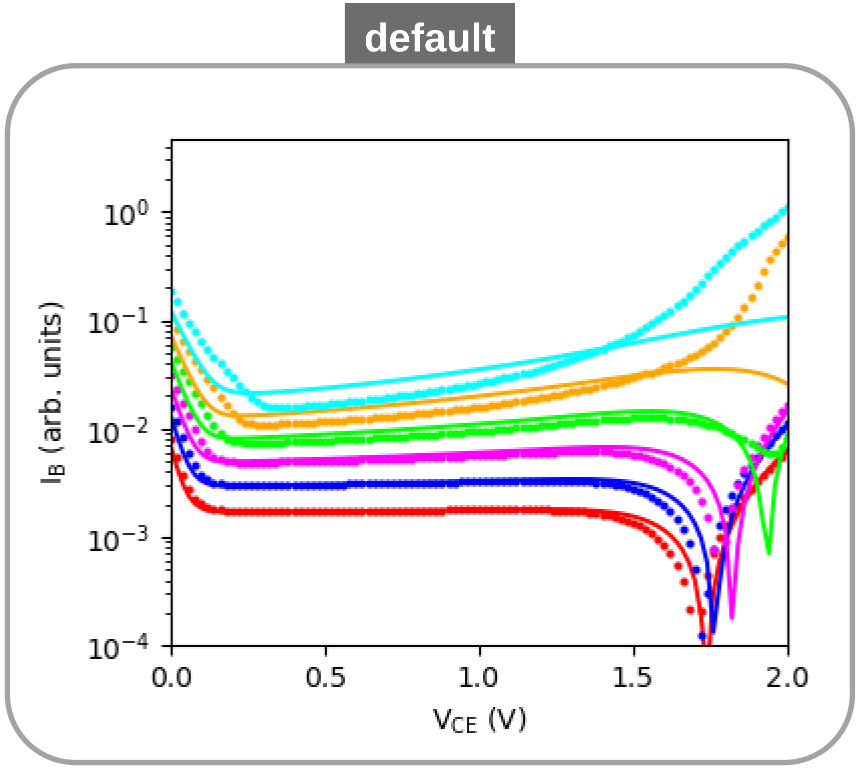


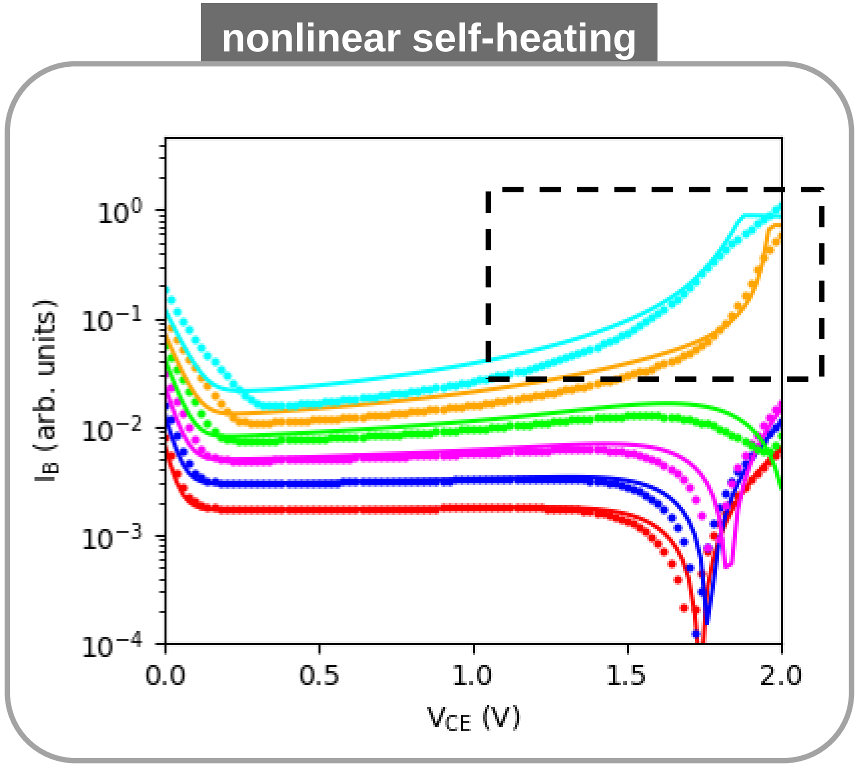


- Nonlinear self-heating turned on. No additional tuning of parameters.
- Collector current versus collector-emitter voltage.

EVALUATION NONLINEAR SELF-HEATING – LV

V_{BE}=0.75, 0.77, 0.79, 0.81, 0.83, 0.85 V



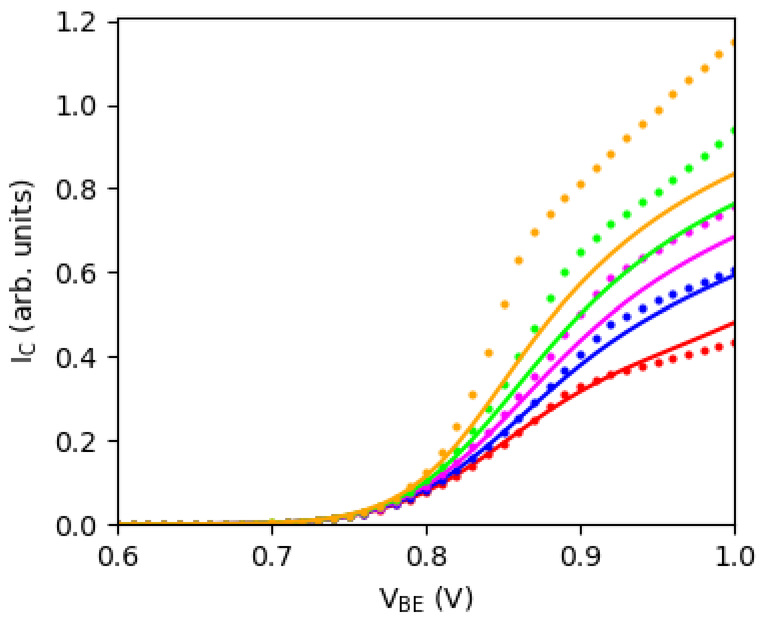


- Nonlinear self-heating turned on. No additional tuning of parameters.
- Base current versus collector-emitter voltage.

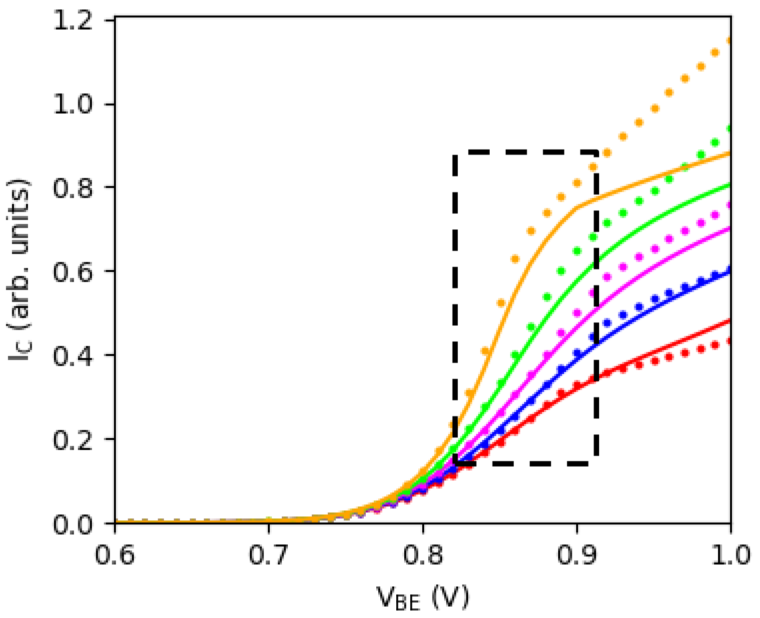
EVALUATION NONLINEAR SELF-HEATING – LV

V_{CE}=0.5, 0.8, 1.1, 1.4, 1.7 V

default



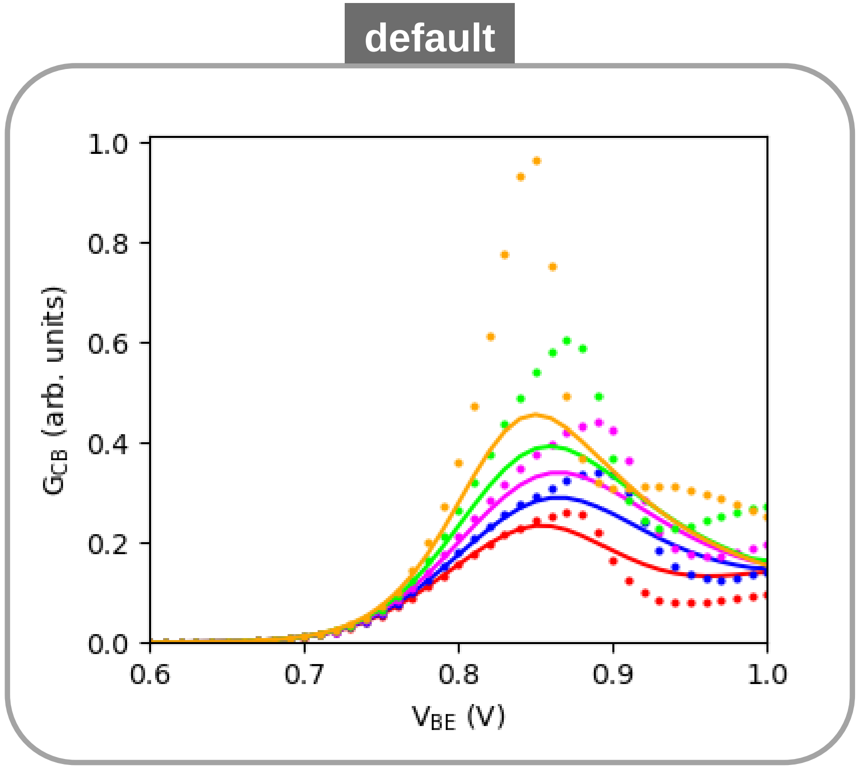
nonlinear self-heating

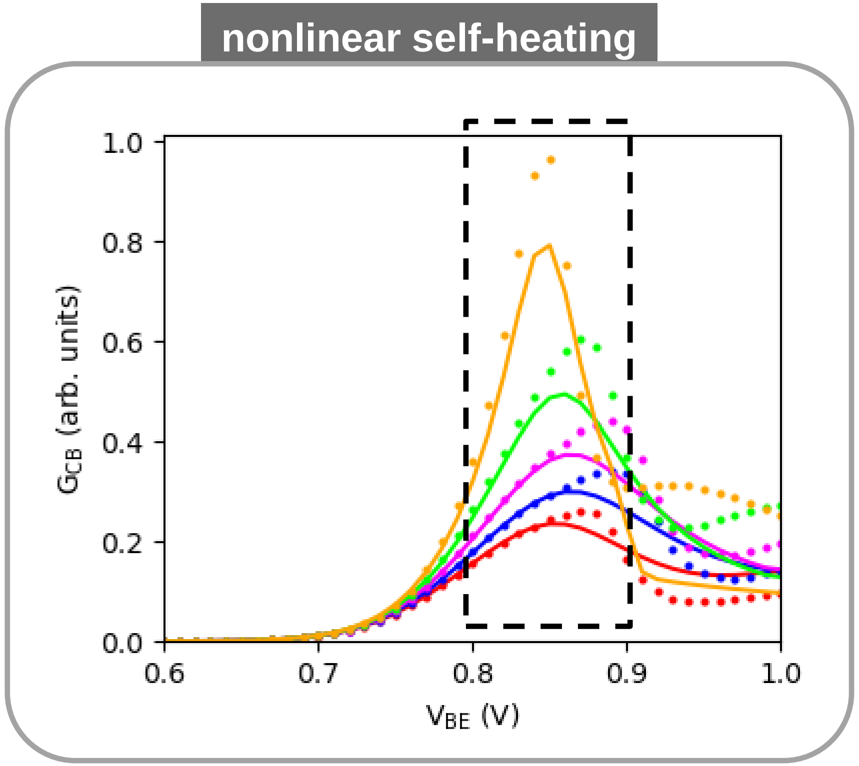


- Nonlinear self-heating turned on. No additional tuning of parameters.
- Collector current versus base-emitter voltage.
  - Note that peak f_T is at V_{BE}=0.85 V.

EVALUATION NONLINEAR SELF-HEATING – LV

V_{CE}=0.5, 0.8, 1.1, 1.4, 1.7 V

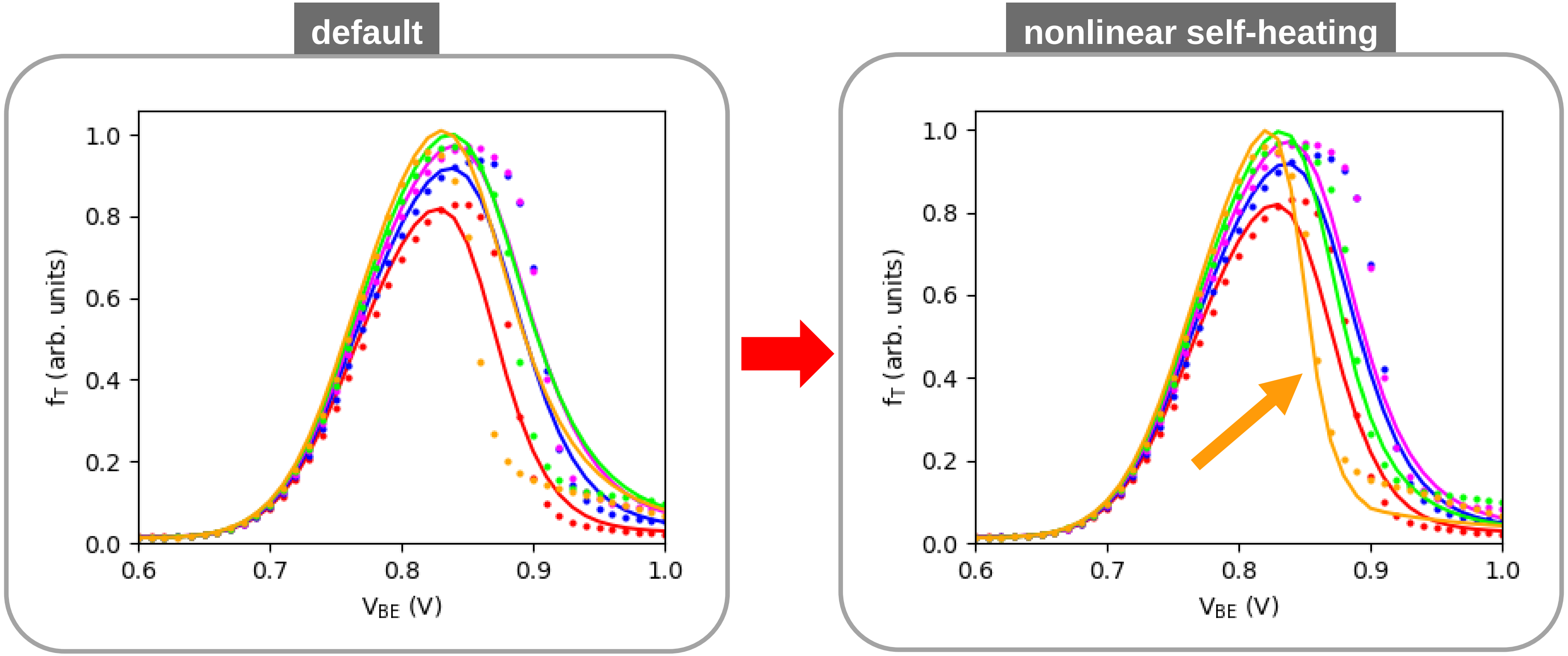




- Nonlinear self-heating turned on. No additional tuning of parameters.
- Trans-conductance versus base-emitter voltage.

EVALUATION NONLINEAR SELF-HEATING – LV

V_{CE}=0.5, 0.8, 1.1, 1.4, 1.7 V

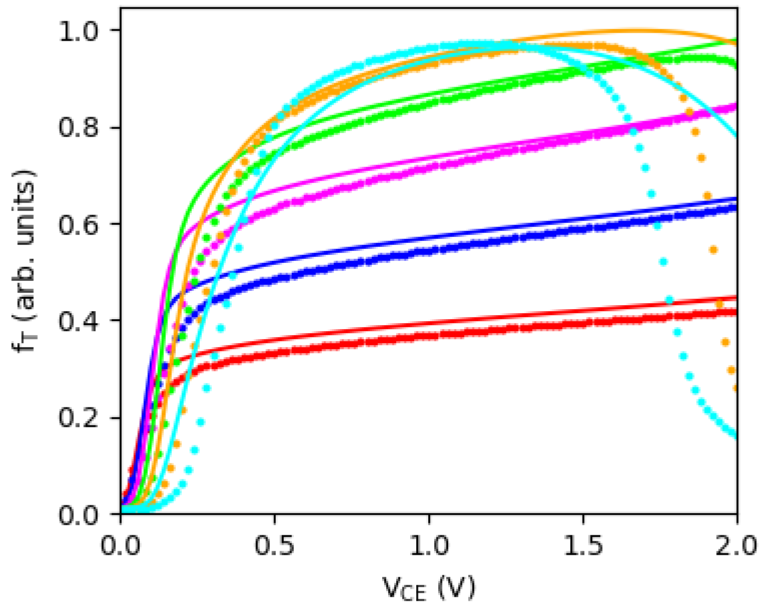


- Nonlinear self-heating turned on. No additional tuning of parameters.

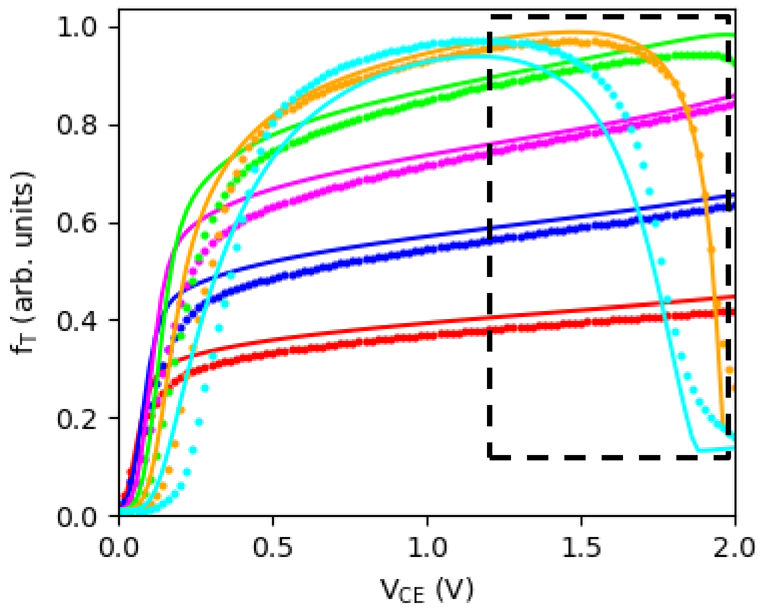
EVALUATION NONLINEAR SELF-HEATING – LV

V_{BE}=0.75, 0.77, 0.79, 0.81, 0.83, 0.85 V

default



nonlinear self-heating



- Nonlinear self-heating turned on. No additional tuning of parameters.

CONTENTS

STATUS MEXTRAM IMPLEMENTATION

- Nonlinear self-heating has been added to MEXTRAM by Auburn University. (NXP request)
  - Available starting in release 505.4
  - Parameter / switch `'swnlsh'` introduced for backward compatibility.
    - `swnlsh=0 (default)` : 'normal' self-heating.
    - `swnlsh=1` : nonlinear self-heating.
  - Furthermore, no additional parameters. The same self-heating model parameters are used in nonlinear self-heating.

CONCLUSIONS

- Nonlinear self-heating effect investigated for SiGe HBTs.
  - <u>Nonlinear self-heating</u>: The temperature gradient between the device and the heat sink is included, leading to a <u>nonlinear relationship between the temperature increase and dissipated power</u>.
- Nonlinear self-heating results in a more accurate description (wider range of bias conditions) of IV-data and f_T-data.
- Nonlinear self-heating added in Mextram.
  - Available starting from release 505.4

ACKNOWLEDGEMENTS

- Prof. Guofu Niu and co-workers from Auburn University.

SECURE CONNECTIONS
FOR A SMARTER WORLD

SHOWROOM.NXP.COM