A SPECTRE Sub-Circuit Model for Resistors including Self-Heating

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Agenda

1 Introduction

2 The thermal resistance and capacitance

3 Basic resistor model resistor_sh with self-heating

4 resistor_sh with feedback of S-H to the electrical resistance

5 resistor_sh with feedback of S-H to the thermal resistance

6 The final model

7 Conclusions

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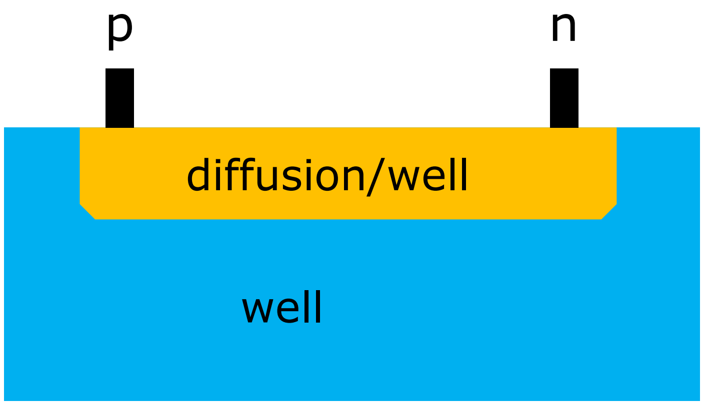
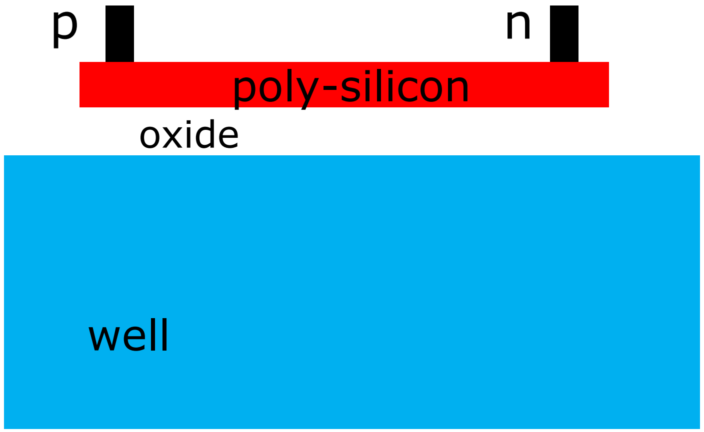
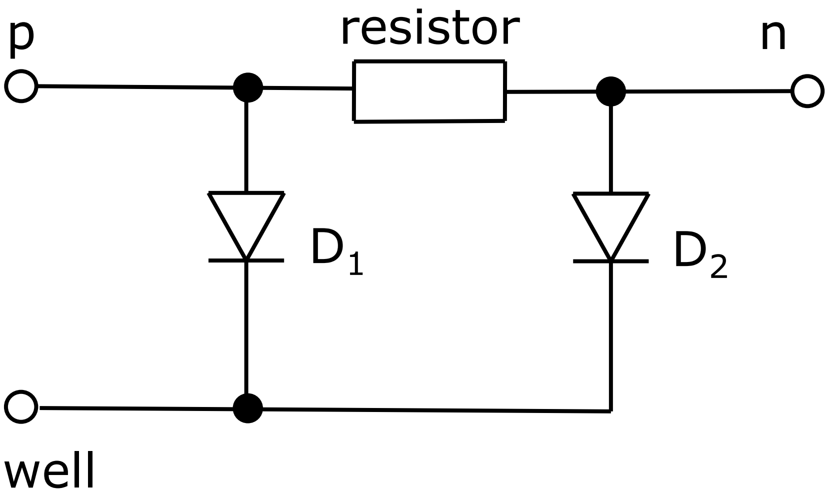
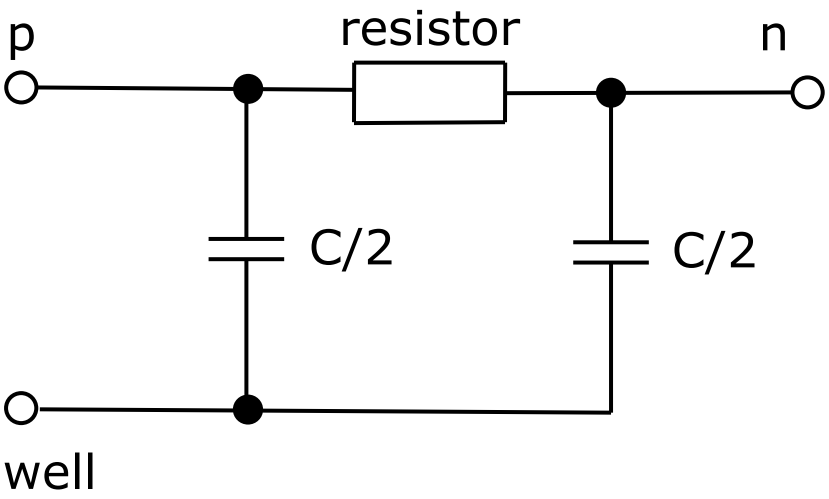
Resistors

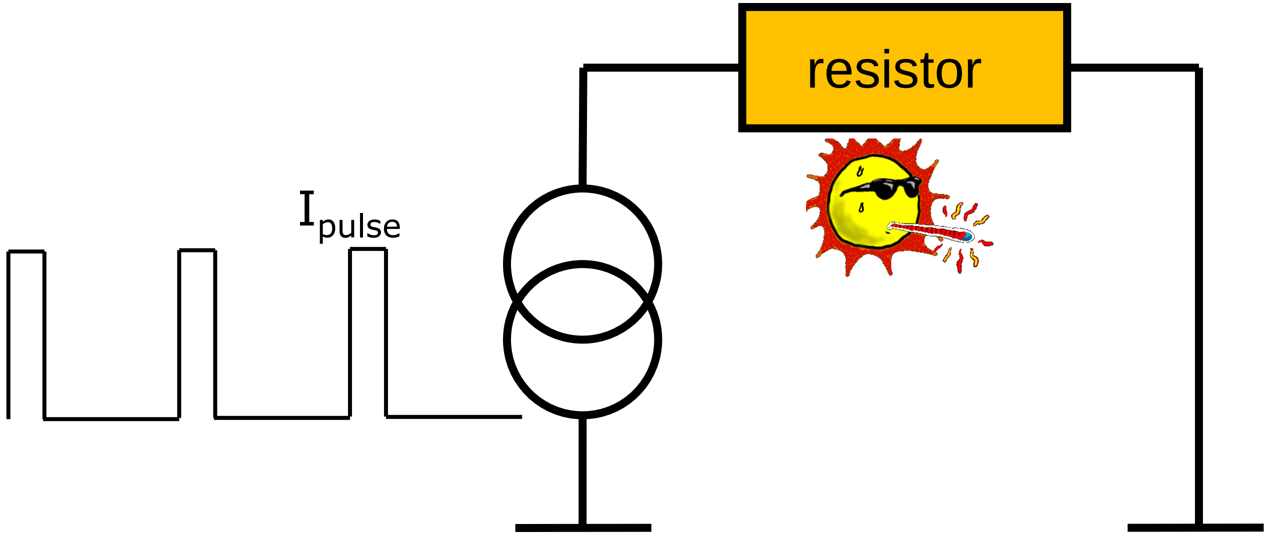

p
n
diffusion/well
well


p
n
poly-silicon
oxide
well


p
resistor
n
D1
D2
well


p
resistor
n
C/2
C/2
well

Resistors in operation become hot!



- The conventional resistor model includes

$$R(T) = R_{nom}\,[1 + TC_1(T - T_{nom}) + TC_2(T - T_{nom})^2]$$

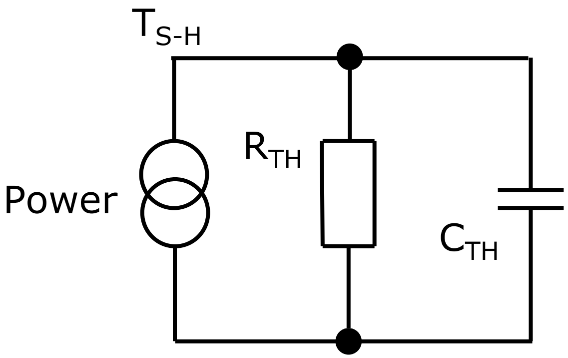
- The conventional resistor model includes
- However self-heating is not included

thermal network

Example Resistor Model

- Conventional model
  $T=Temp+TRISE$
  T: parameter

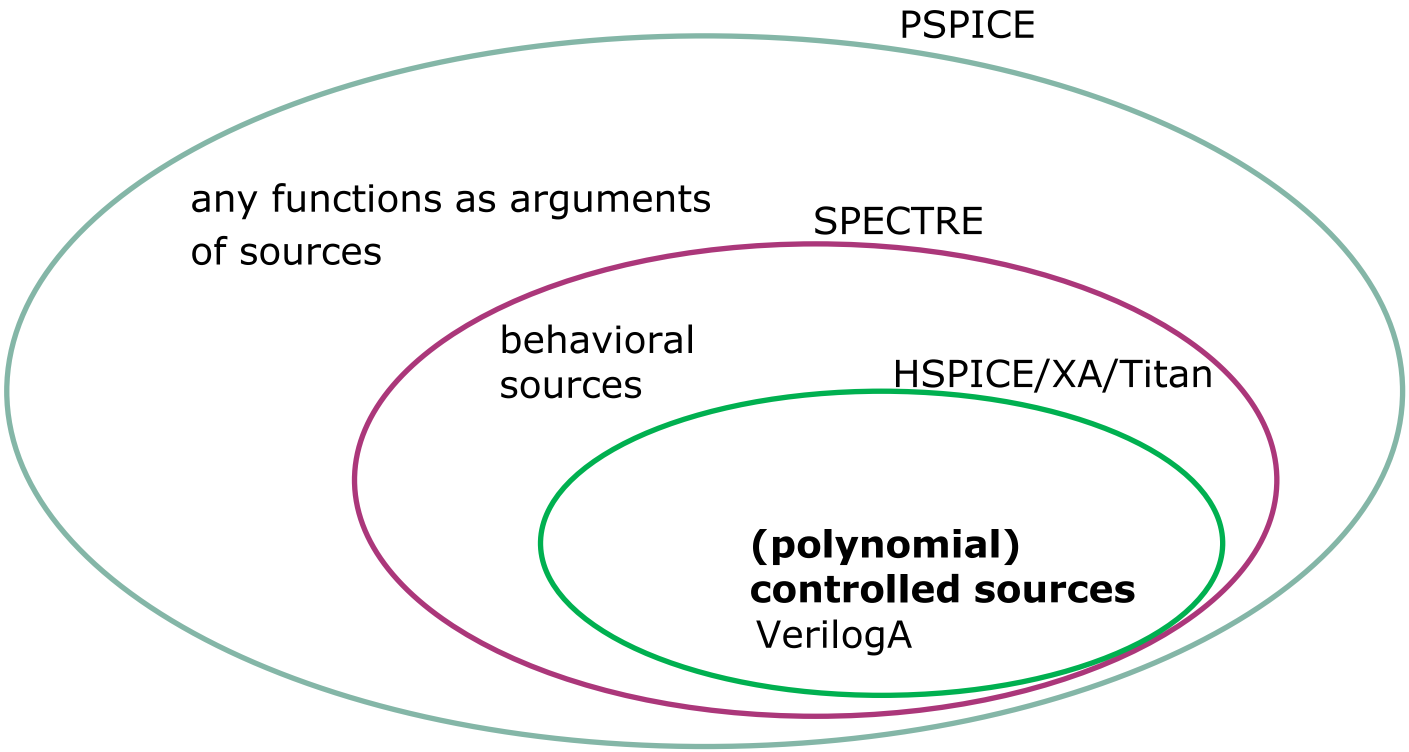
- Model with self-heating
  $T=Temp+TRISE+T_{S\text{-}H}$
  T: signal



Why is self-heating necessary in a resistor model?

- Safe operating area check gives warning if maximum allowed self-heating is exceeded
- Self-heating has an effect on the electrical resistance
- Self-heating has an effect on the thermal resistance

Introduction: How to write model equations?


PSPICE

any functions as arguments of sources

SPECTRE

behavioral sources

HSPICE/XA/Titan

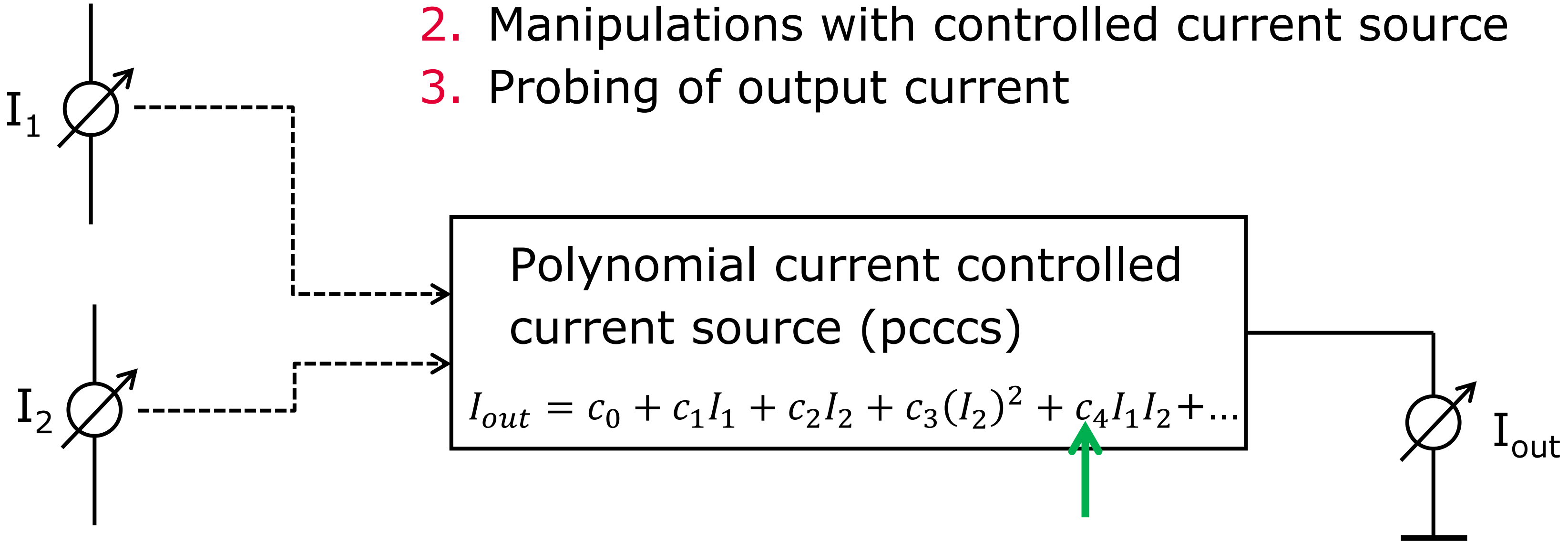
(polynomial) controlled sources

VerilogA

- Polynomial controlled sources are available in every simulator
- No compilation has to be done before simulation, like for verilogA/b-sources

Polynomial controlled sources example 1

1. Signals have to be converted to current probes
2. Manipulations with controlled current source
3. Probing of output current



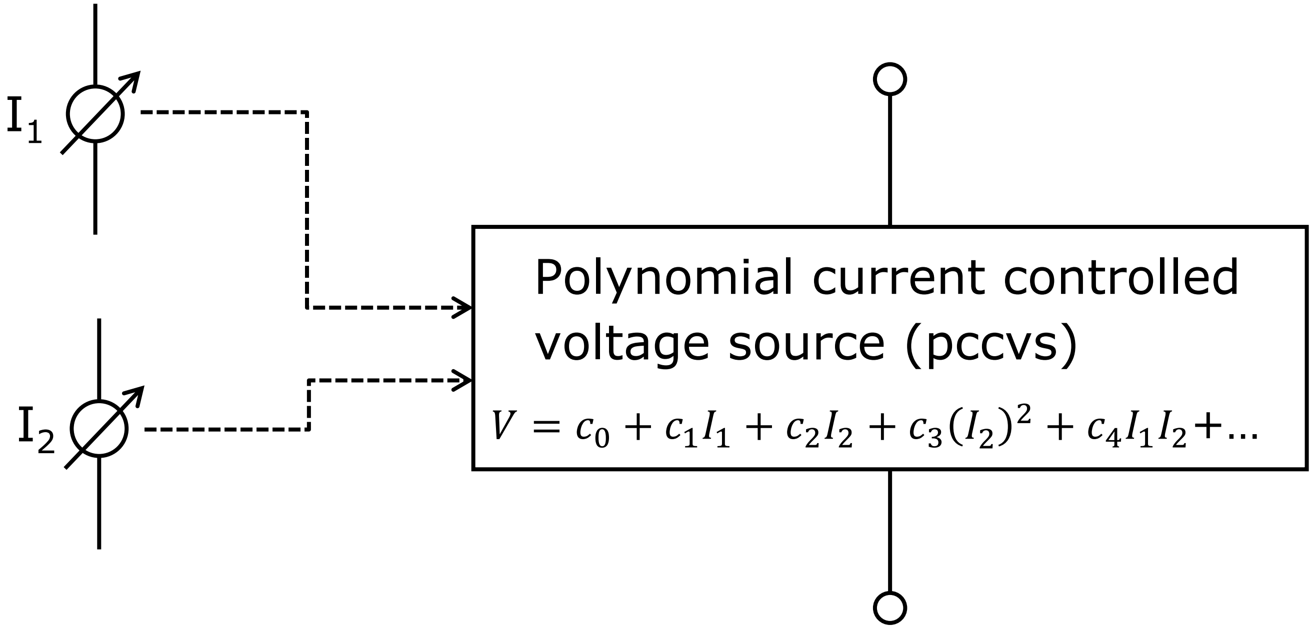
Polynomial current controlled current source (pcccs)

$$I_{out} = c_0 + c_1 I_1 + c_2 I_2 + c_3 (I_2)^2 + c_4 I_1 I_2 + \ldots$$

Example multiplication of two signals $I_{out}=I_1*I_2$

```
i1   (a b) iprobe
i2   (c d) iprobe
p1   (e 0) pcccs gain=1.0 probes=[i1 i2] coeffs=[0 0 0 0 1]
iout (e 0) iprobe
```

Polynomial controlled sources example 2



Polynomial current controlled voltage source (pccvs)

$$V = c_0 + c_1 I_1 + c_2 I_2 + c_3 (I_2)^2 + c_4 I_1 I_2 + \ldots$$

Example V=R*I (Ohm’s law)

```
r1    (a b) iprobe
i2    (c d) iprobe
p1    (e f) pccvs gain=1.0  probes=[r1 i1]  coeffs=[0 0 0 0 1]
```

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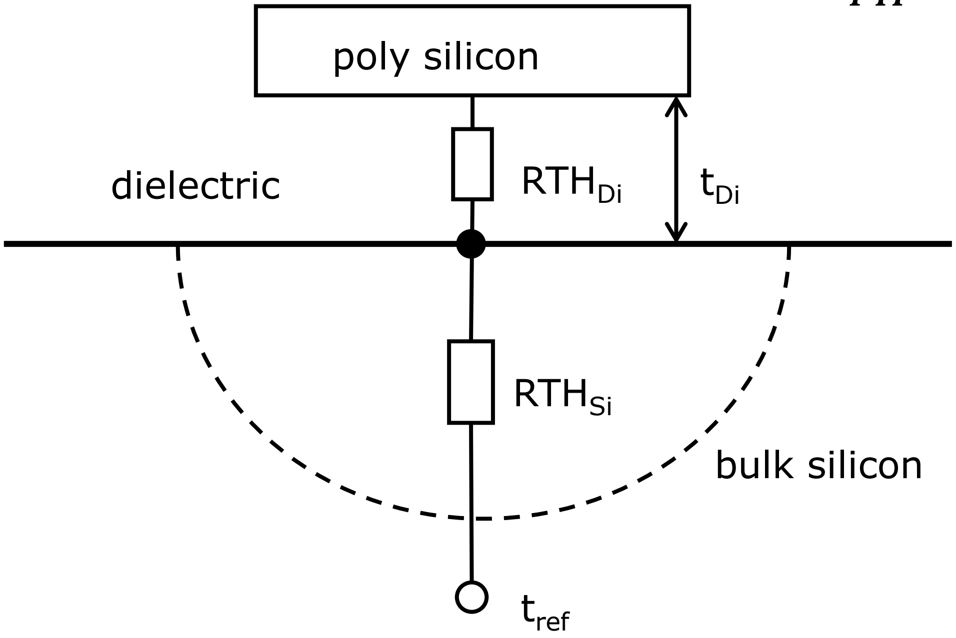
Poly resistor

$$R_{TH}^{Total} = R_{TH}^{Si} + R_{TH}^{Di} \left[\frac{Kelvin}{Watt}\right]$$



Diffusion resistor : R^{SI} only

Thermal resistance in silicon

$$R_{TH}^{Si} = \begin{cases} \dfrac{2.85 - 1.9\ln\left(\frac{w}{l}\right)}{2\pi K_{Si} l}\left[\dfrac{Kelvin}{Watt}\right], & \dfrac{w}{l} \leq 1 \\ \dfrac{2.85 - 1.9\ln\left(\frac{l}{w}\right)}{2\pi K_{Si} w}\left[\dfrac{Kelvin}{Watt}\right], & \dfrac{w}{l} > 1 \end{cases}$$

$$K_{Si} = \frac{148}{1 + 0.004\,(T - T_{nom}) + 2 \cdot 10^{-6}\,(T - T_{nom})^2}\left[\frac{Watt}{Kelvin\ m}\right]$$

See Gang Chen in “Nanoscale Heat Transfer and Nanostructured Thermoelectrics” in IEEE TRANSACTIONS ON COMPONENTS AND PACKAGING TECHNOLOGIES, VOL. 29, NO. 2. JUNE 2006 (Numerical fit of equation 3 and 4)

Thermal resistance in oxide

$$R_{TH}^{Di} = \frac{1}{K_{Di}\, l\, \frac{w}{t_{Di}} \left(1 + 0.88\, \frac{t_{Di}}{w}\right)} \left[\frac{Kelvin}{Watt}\right]$$

$$K_{Di} = \frac{K_{Di0}}{1 - 0.0007\,(T - T_{nom}) - 4 \cdot 10^{-8}\,(T - T_{nom})^2} \left[\frac{Watt}{Kelvin\, m}\right]$$

t_{Di}: oxide thickness

See Harry A. Schafft in “Thermal Analysis of Electromigration Test Structures” in
IEEE TRANSACTIONS ON ELECTRON DEVICES. VOL. ED-34. NO. 3, MARCH 1.987

Thermal capacitance and time constant Tau

$$C_{TH} = \frac{\tau_{thermal}}{R_{TH}^{Total}(T - T_{nom})}$$

	Diffusion resistors	**Poly resistors**
Thermal time constant Tau$_{TH}$	~100us	~200ns

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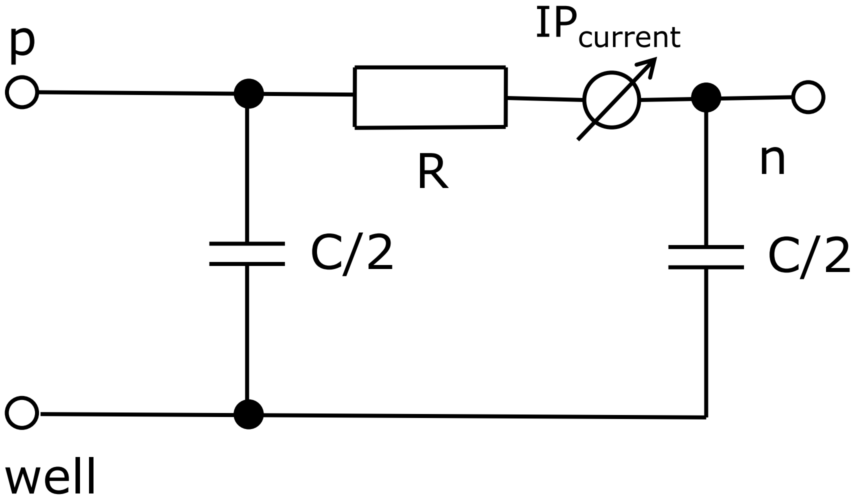
Calculation of Power

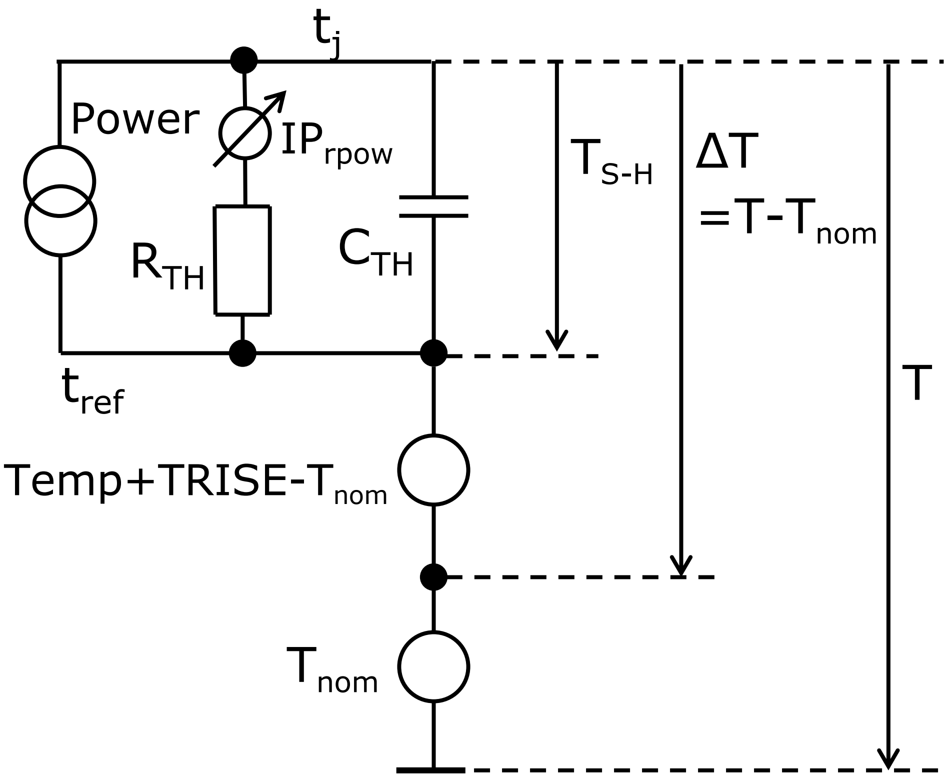


$$Power = (I_{Res})^2\ Rcore$$

```
ires         (n1  n) iprobe
resist       (p  n1) resmod  r=value
f01    (tj  tref) pcccs gain=-rcore probes=[ires] coeffs=[0 0 1]
```

- The flow through f01 is the power

Temperature network



Safe operating area check

The basic model provides

- Electrical resistance dependent on ambient temperature temp
- Thermal resistance dependent on ambient temperature temp
- Temperature offset resulting from self-heating $T_{S\text{-}H}$
- Node tj for absolute junction temperature of the device

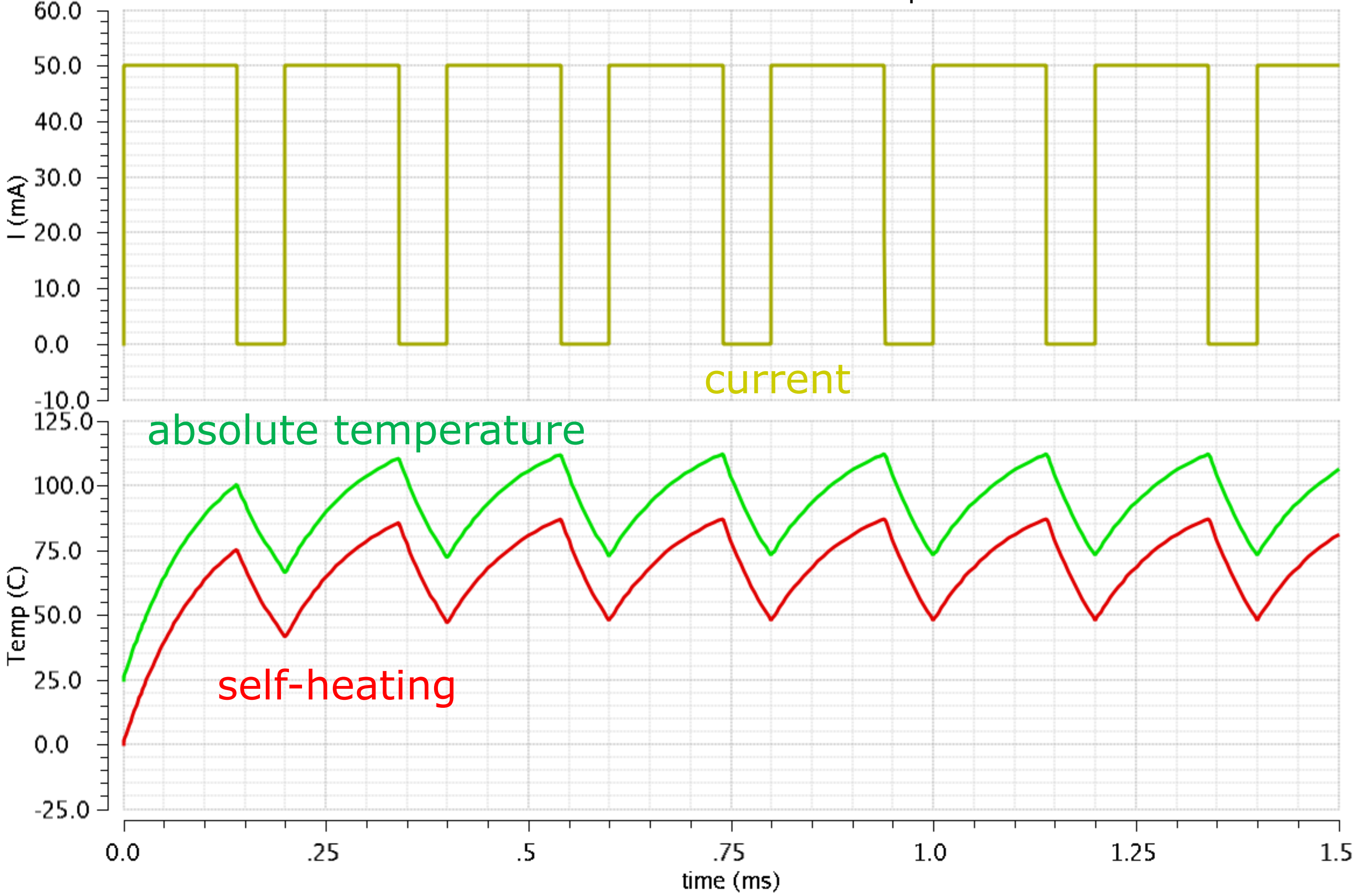
```
rndiff (p n dt)       resistor_sh
+   l           = rndiff_lress
+   w           = rndiff_wres
+   value       = rndiff_final_value
+   …

rellim  assert sub=rndiff expr="V(dt,0)"  max=5.0    duration=1n anal_types=[dc
tran] message="Resistor rndiff Self-Heating exceeds limit! (>5 Kelvin)“
level=warning

toohot  assert sub=rndiff expr="V(dt,0)"  max=500.0  duration=1n anal_types=[dc
tran] message="Resistor rndiff Self-Heating exceeds 500 Kelvin!"
level=error
```

Simulation results

ndiff resistor R=200Ω, W=10um, Temp=25C, V_{pulse}=10V, Tau_{TH}=100us



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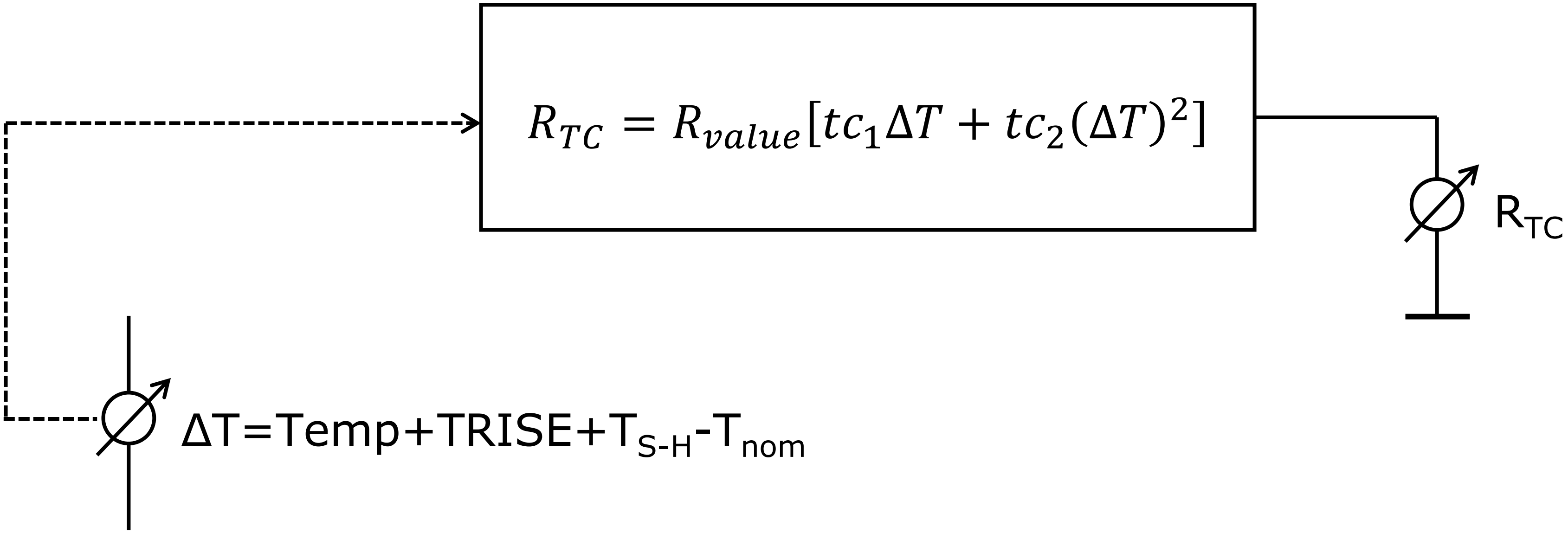
Feedback of self-heating to resistance

Temperature becomes a signal, if T=Temp+TRISE+$T_{S\text{-}H}$

$$R(T) = \underbrace{R_{value}}_{parametric} + \underbrace{R_{value}\left[TC_1(T - T_{nom}) + TC_2(T - T_{nom})^2\right]}_{signal\ R_{TC}}$$

R(T) is split into a conventional resistor and a resistance signal.

Create the signal part of the resistance

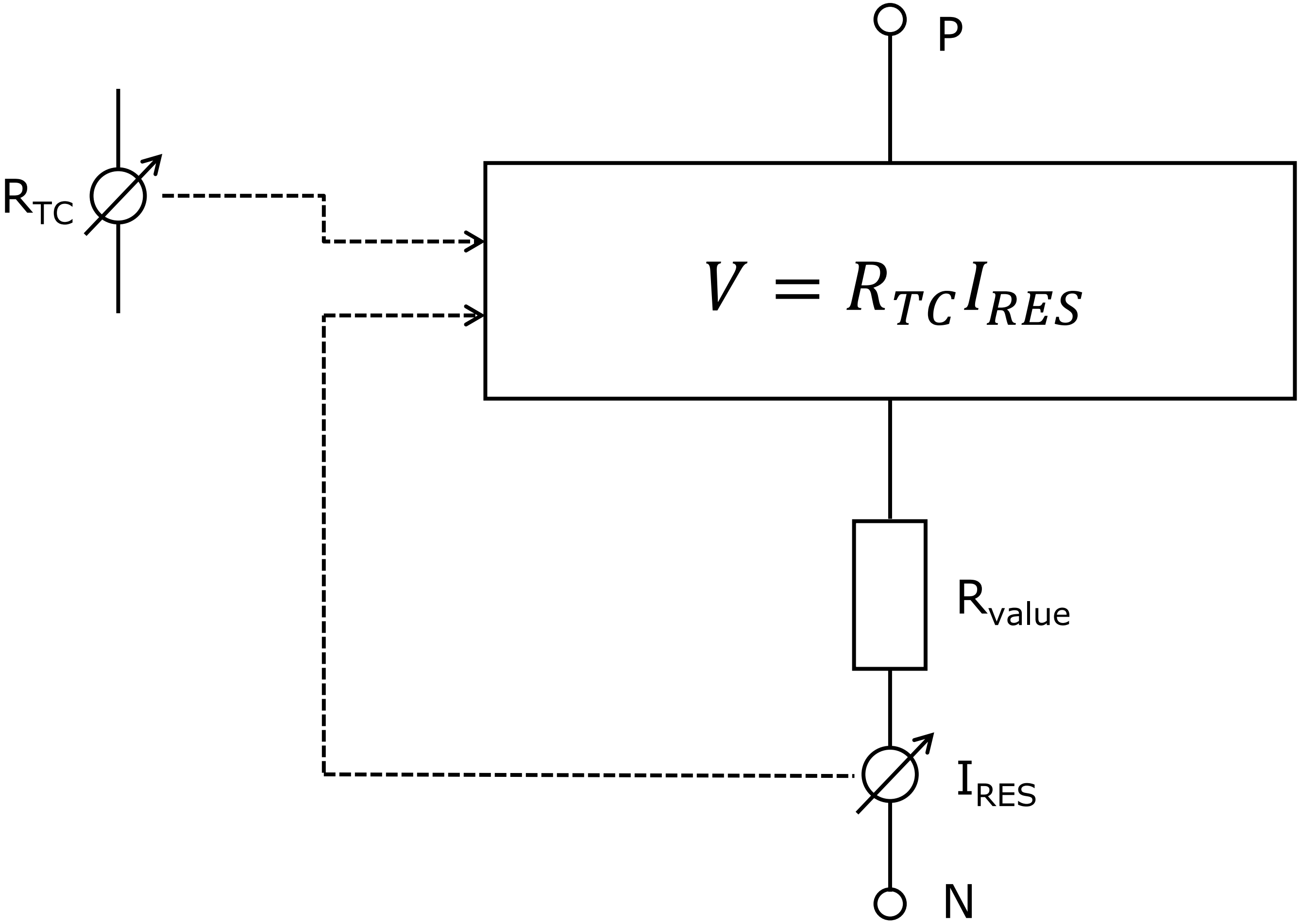


$$R_{TC} = R_{value}[tc_1 \Delta T + tc_2 (\Delta T)^2]$$

R_{TC}

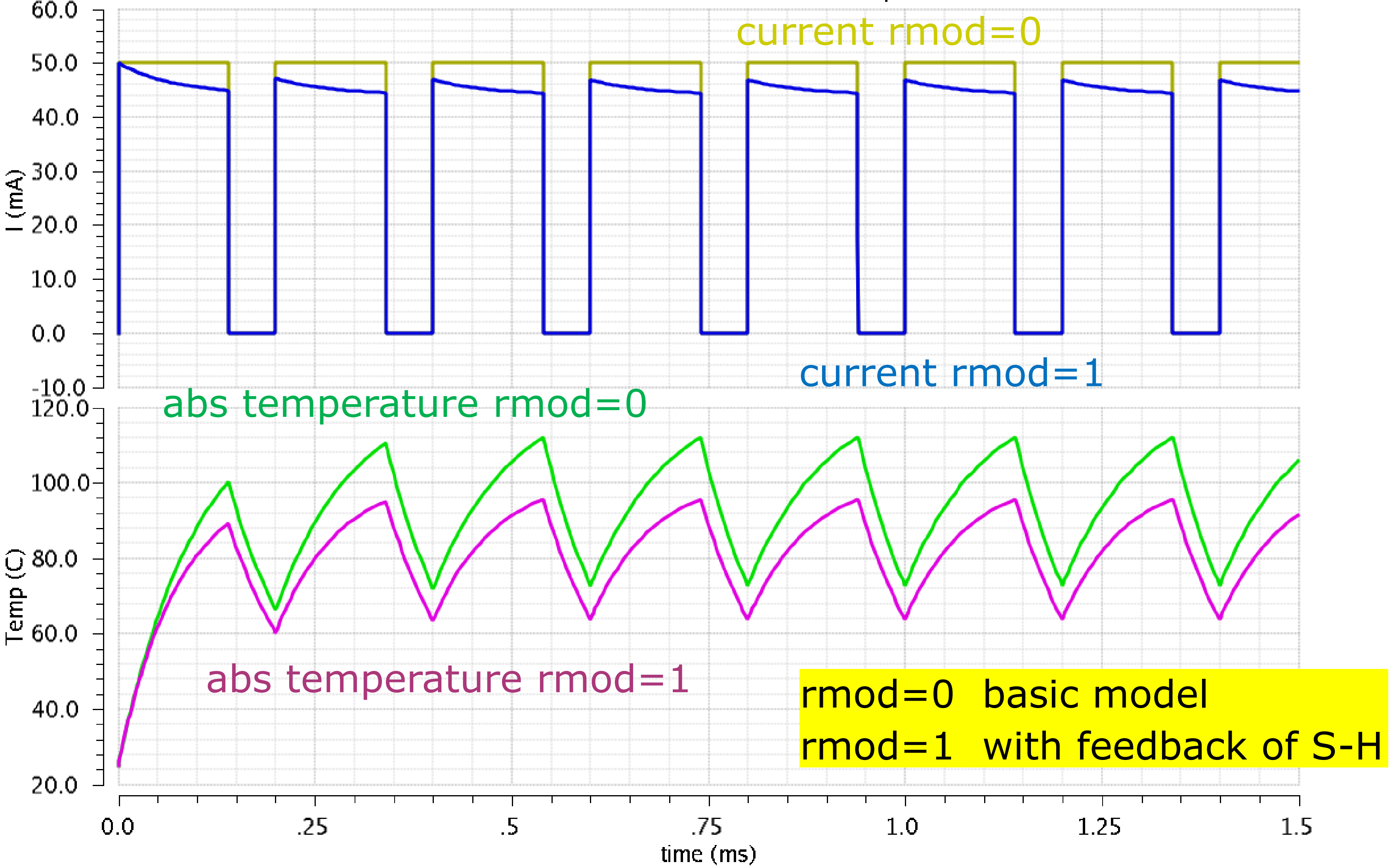
$\Delta T = Temp + TRISE + T_{S\text{-}H} - T_{nom}$

Create the total resistor



Simulation results

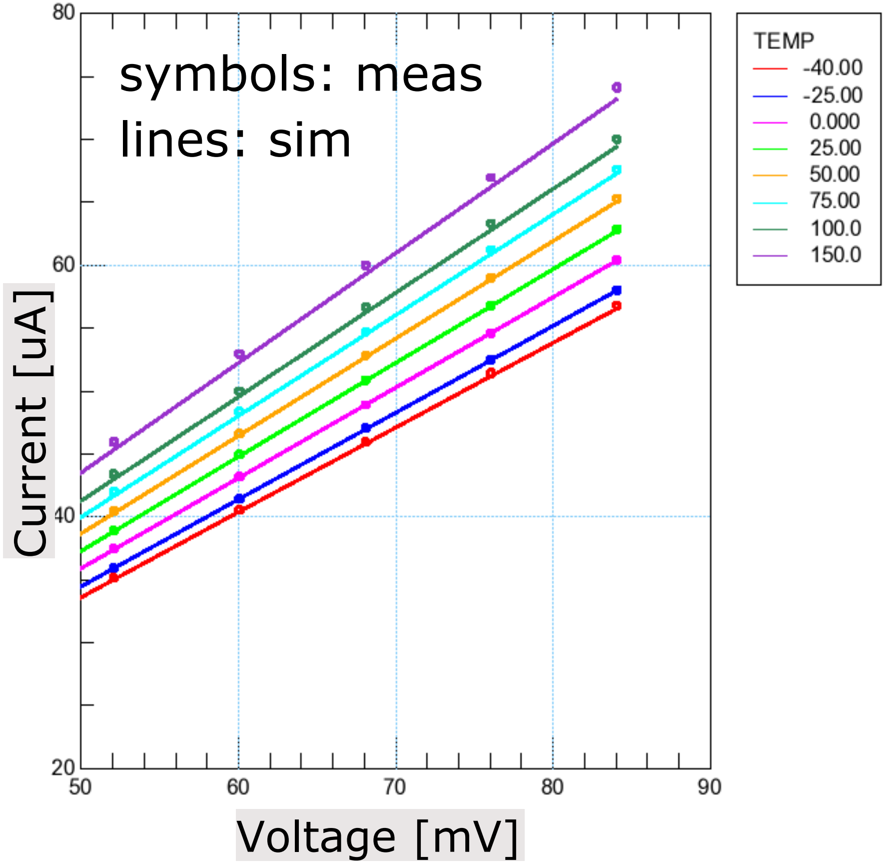
Ndiff resistor R=200Ω, W=10um, Temp=25C, V_{pulse}=10V, Tau_{TH}=100us



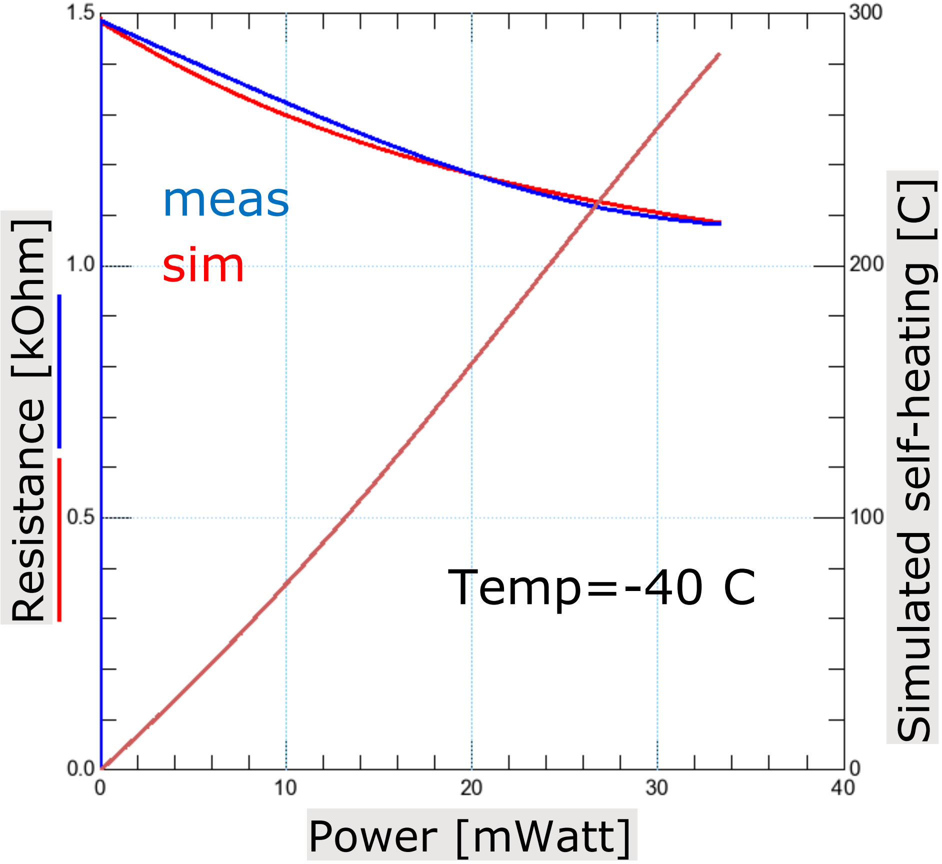
rmod=0 basic model
rmod=1 with feedback of S-H

Verification against measurement

Device: s7rpn, W=2.6um, L=10um (KDI_0=2.2)


Plot rpn_lili/W2u60L10u00CON001_Tx/res/doku

symbols: meas
lines: sim


Plot rpn_sh/w2u60L10u00CON001_Tminus40/rpn/R_P

meas
sim

Temp=-40 C

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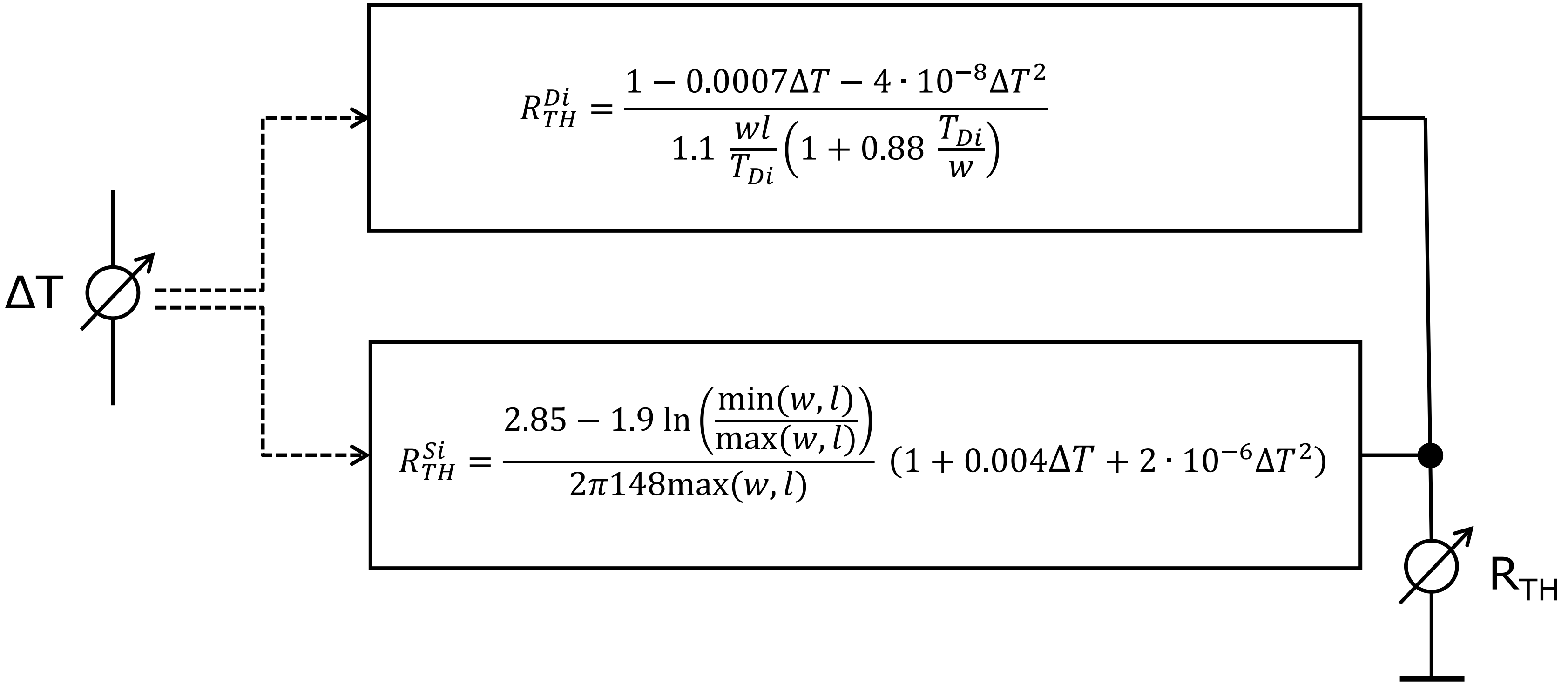
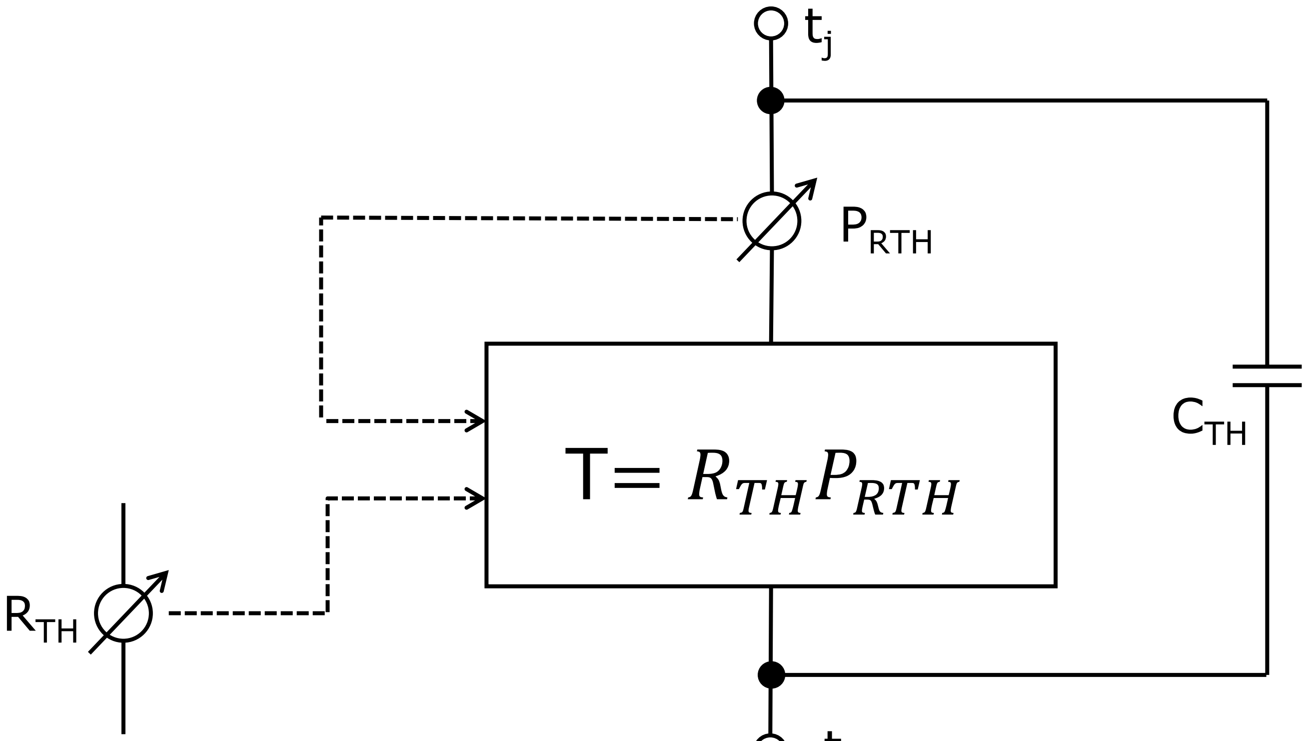
Create the signal part of the thermal resistance



$$R_{TH}^{Di} = \frac{1 - 0.0007\Delta T - 4 \cdot 10^{-8}\Delta T^2}{1.1\,\frac{wl}{T_{Di}}\left(1 + 0.88\,\frac{T_{Di}}{w}\right)}$$

$$R_{TH}^{Si} = \frac{2.85 - 1.9\ln\left(\frac{\min(w,l)}{\max(w,l)}\right)}{2\pi 148 \max(w,l)}\left(1 + 0.004\Delta T + 2 \cdot 10^{-6}\Delta T^2\right)$$

Create the thermal resistor



Simulation results

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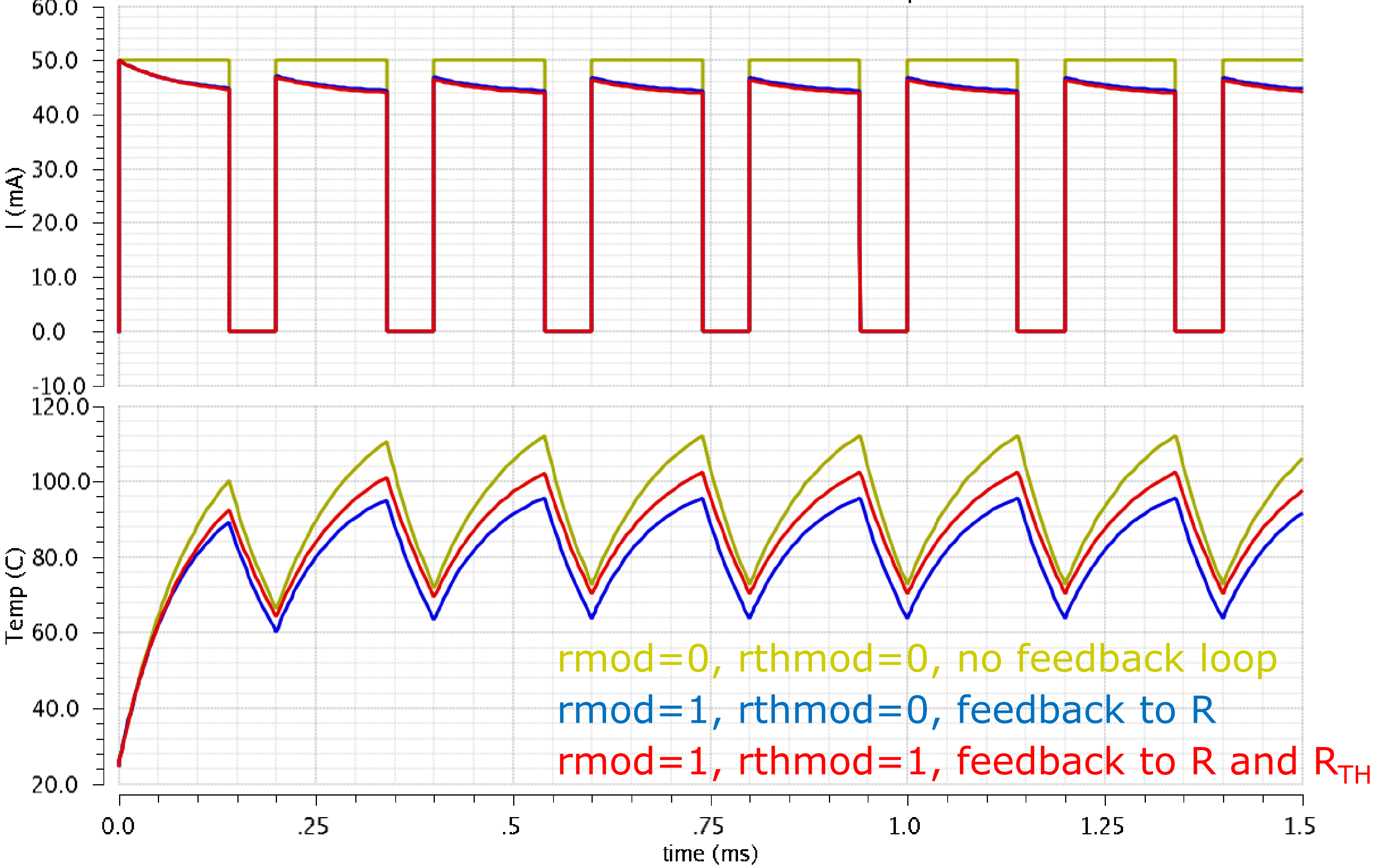
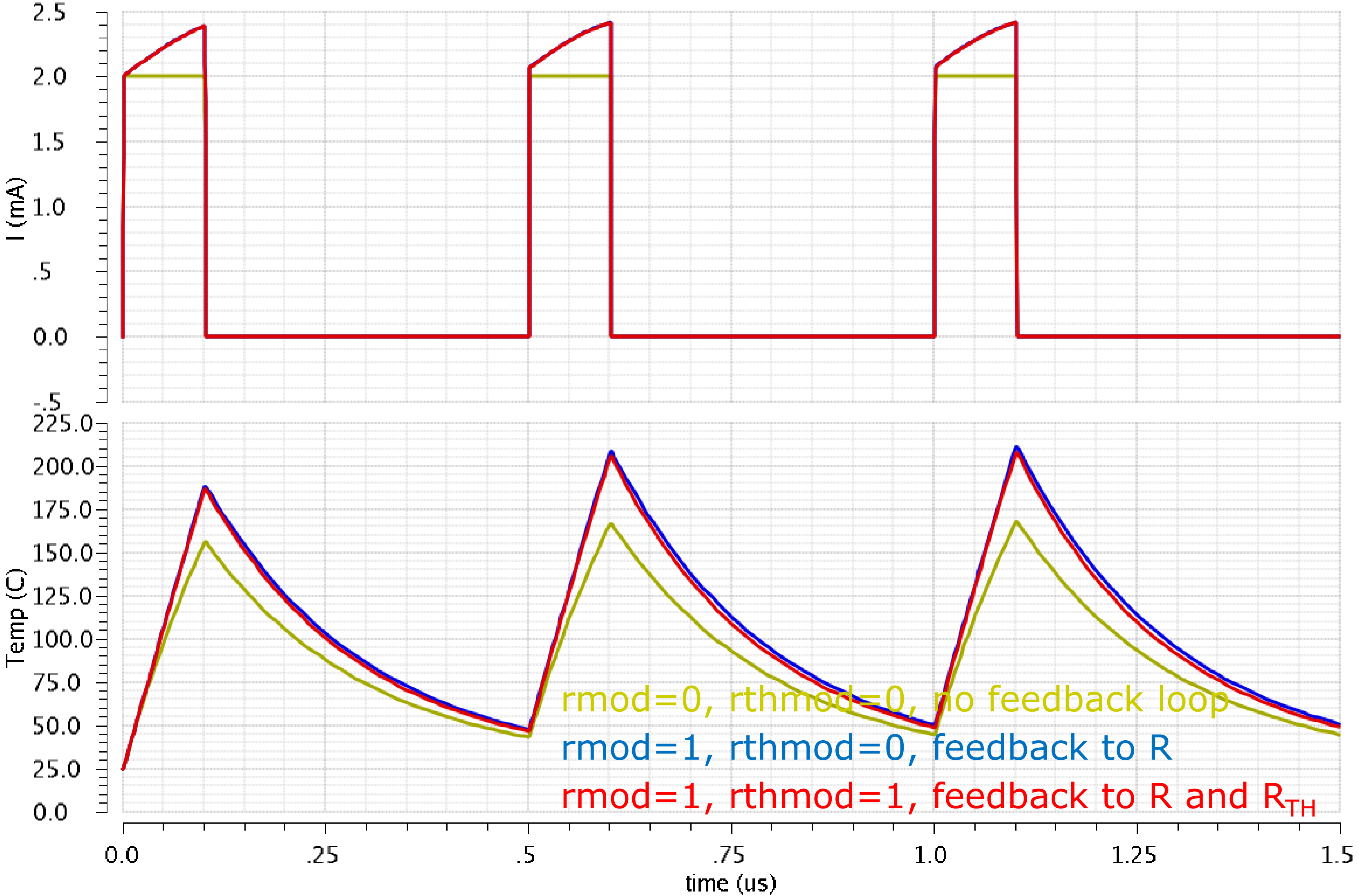


Simulation results

Poly resistor R=1kΩ, W=1um, Temp=25C, V_{pulse}=2V, Tau_{TH}=200ns



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Parameters and signals, model switches

	parameters	**signals**	**model switches**
Conventional resistor model	W, L, R, T=temp	V, I	
resistor_sh with S-H	W, L, R, R_{TH}, C_{TH}	V, I, T=temp+$T_{S\text{-}H}$	RMOD=0, RTHMOD=0
resistor_sh with S-H feedback to R	W, L, R_{TH}, C_{TH}	V, I, R(T), T=temp+$T_{S\text{-}H}$	RMOD=1, RTHMOD=0
resistor_sh with S-H feedback to R and R_{TH}	W, L, C_{TH}	V, I, R(T), R_{TH}(T), T=temp+$T_{S\text{-}H}$	RMOD=1, RTHMOD=1
resistor_sh with S-H feedback to R, R_{TH}, C_{TH}	W, L	V, I, R(T), R_{TH}(T), C_{TH}(T), T=temp+$T_{S\text{-}H}$	not yet implemented

Agenda

Conclusions

SPECTRE sub-circuit for a resistor with self-heating (resistor_sh)

- Applicable for poly and diffusion resistors
- Allows monitoring of operating temperature (absolute and self-heating)
- Contains warnings for SOA-check of self-heating
- Includes universal equations for the thermal resistances
  - RTH_{DI} in oxide with just one model parameter TDI: thickness
  - RTH_{SI} in silicon with no additional model parameter
- Includes parametric switches
  - RMOD: for feedback of S-H to electrical resistance
  - RTHMOD: for feedback of S-H to thermal resistance

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