

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



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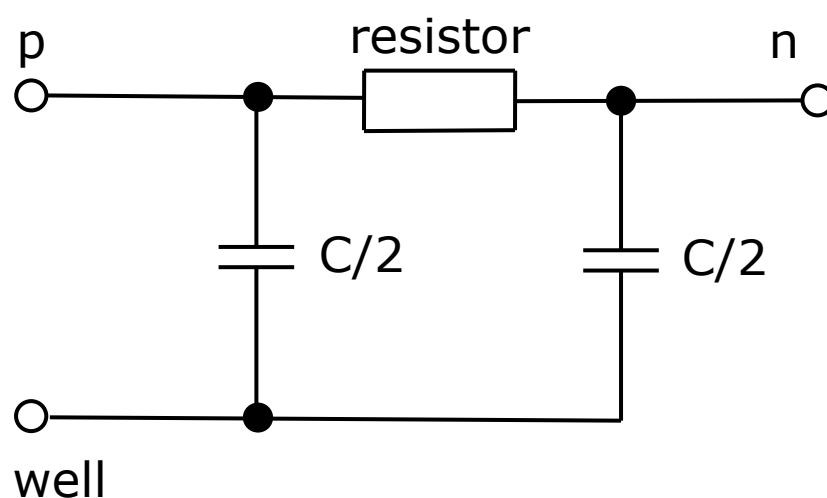
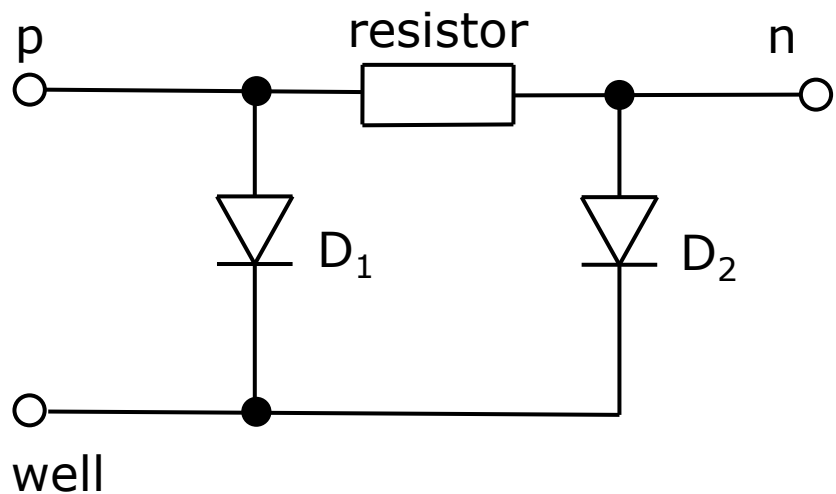
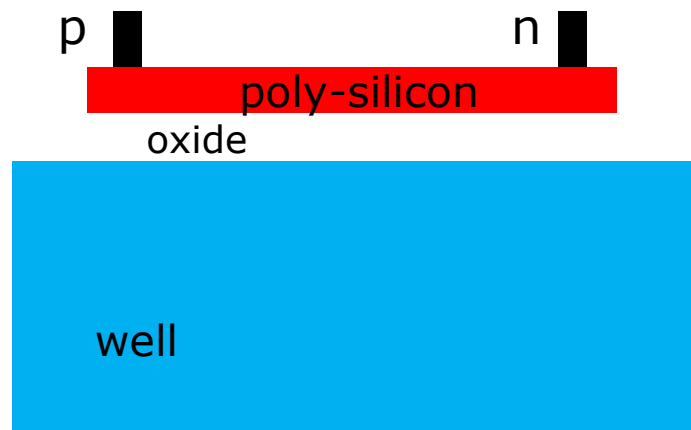
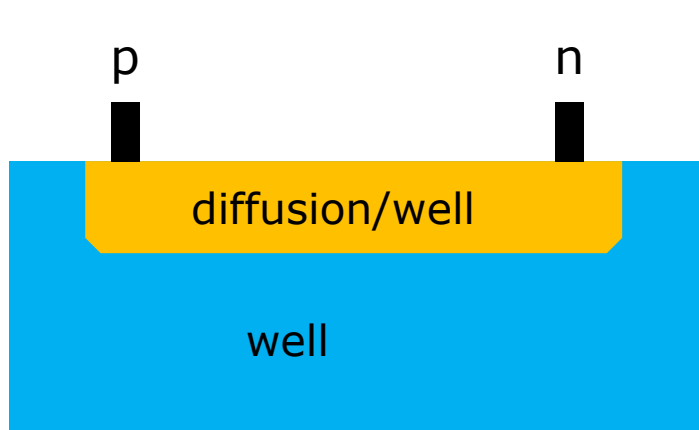
Agenda

- 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

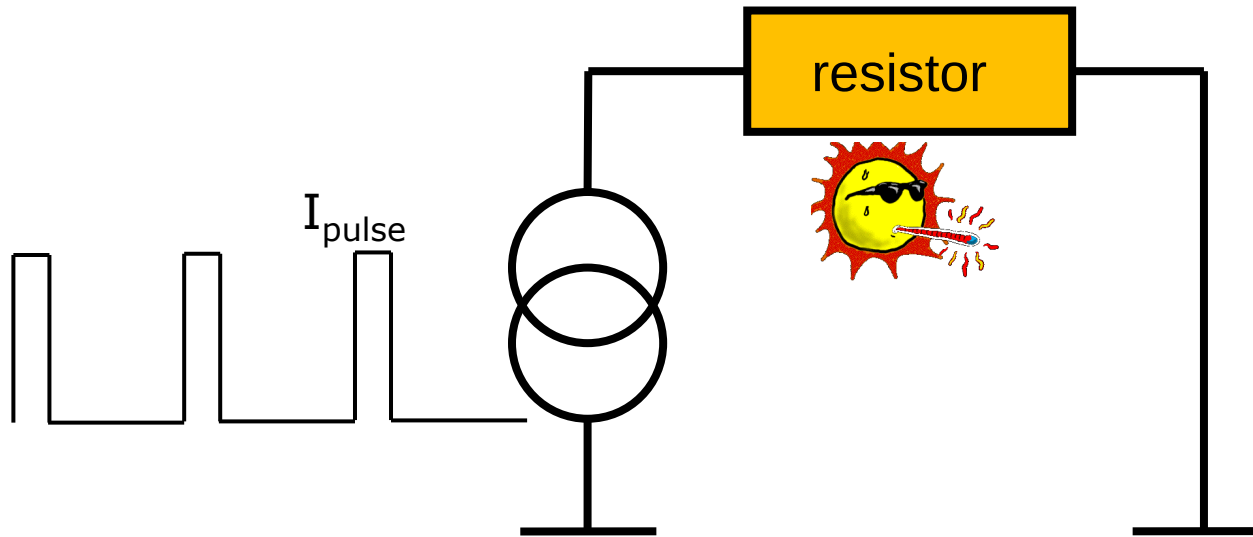
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Resistors



Resistors in operation become hot!



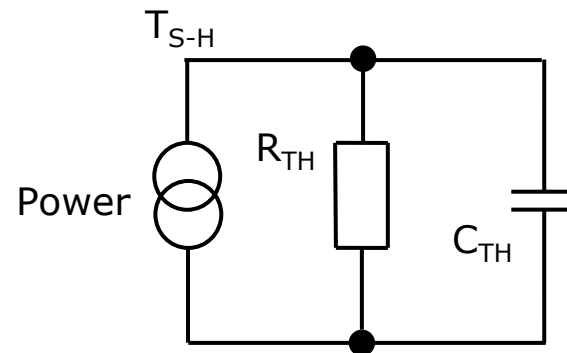
- › The conventional resistor model includes $R(T) = R_{nom} [1 + TC_1(T - T_{nom}) + TC_2(T - T_{nom})^2]$
- › The conventional resistor model includes
- › However self-heating is not included

thermal network



Example Resistor Model

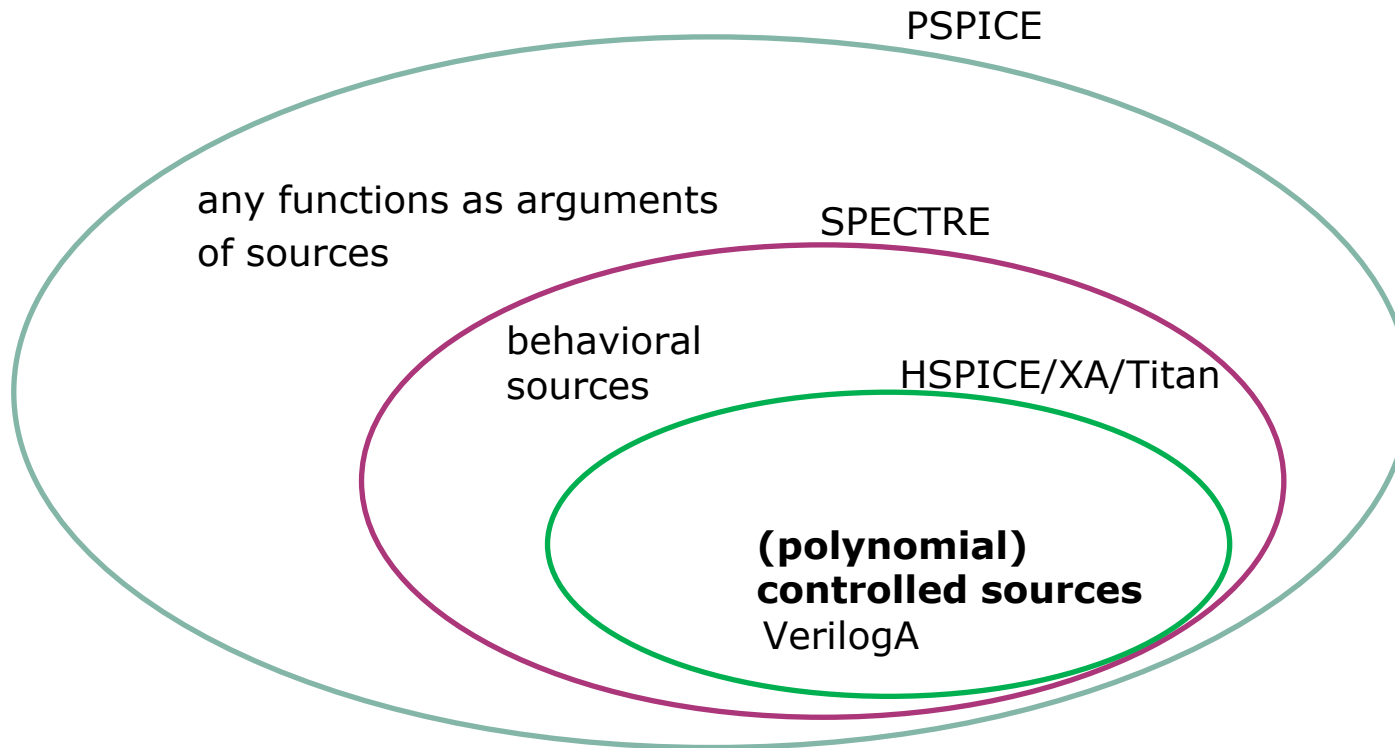
- › Conventional model
 $T = \text{Temp} + \text{TRISE}$
 T : parameter
- › Model with self-heating
 $T = \text{Temp} + \text{TRISE} + T_{S-H}$
 T : signal



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

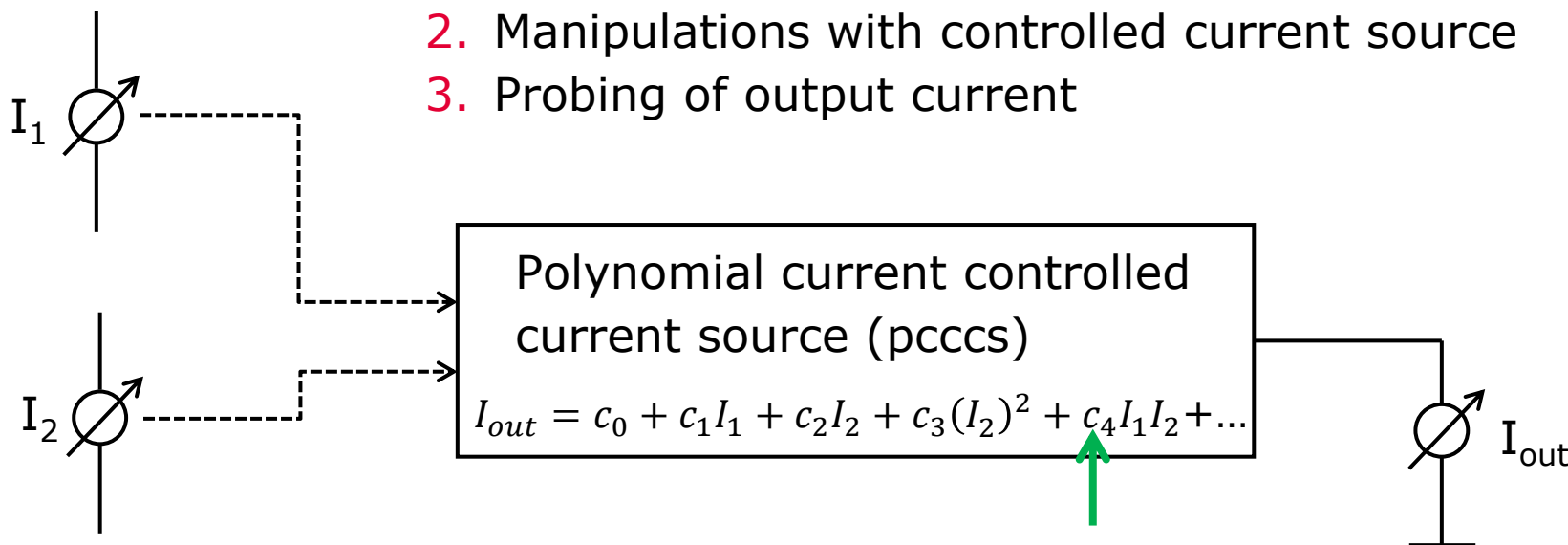
Introduction: How to write model equations?



- › 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

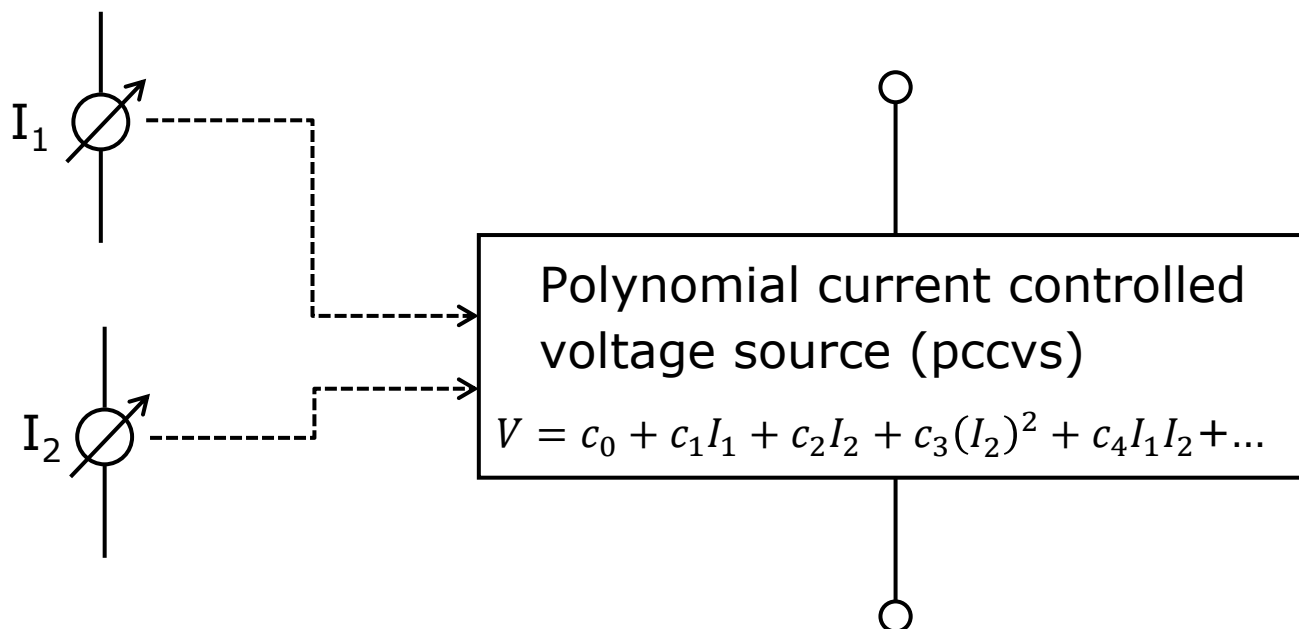
1. Signals have to be converted to current probes
2. Manipulations with controlled current source
3. Probing of output current



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



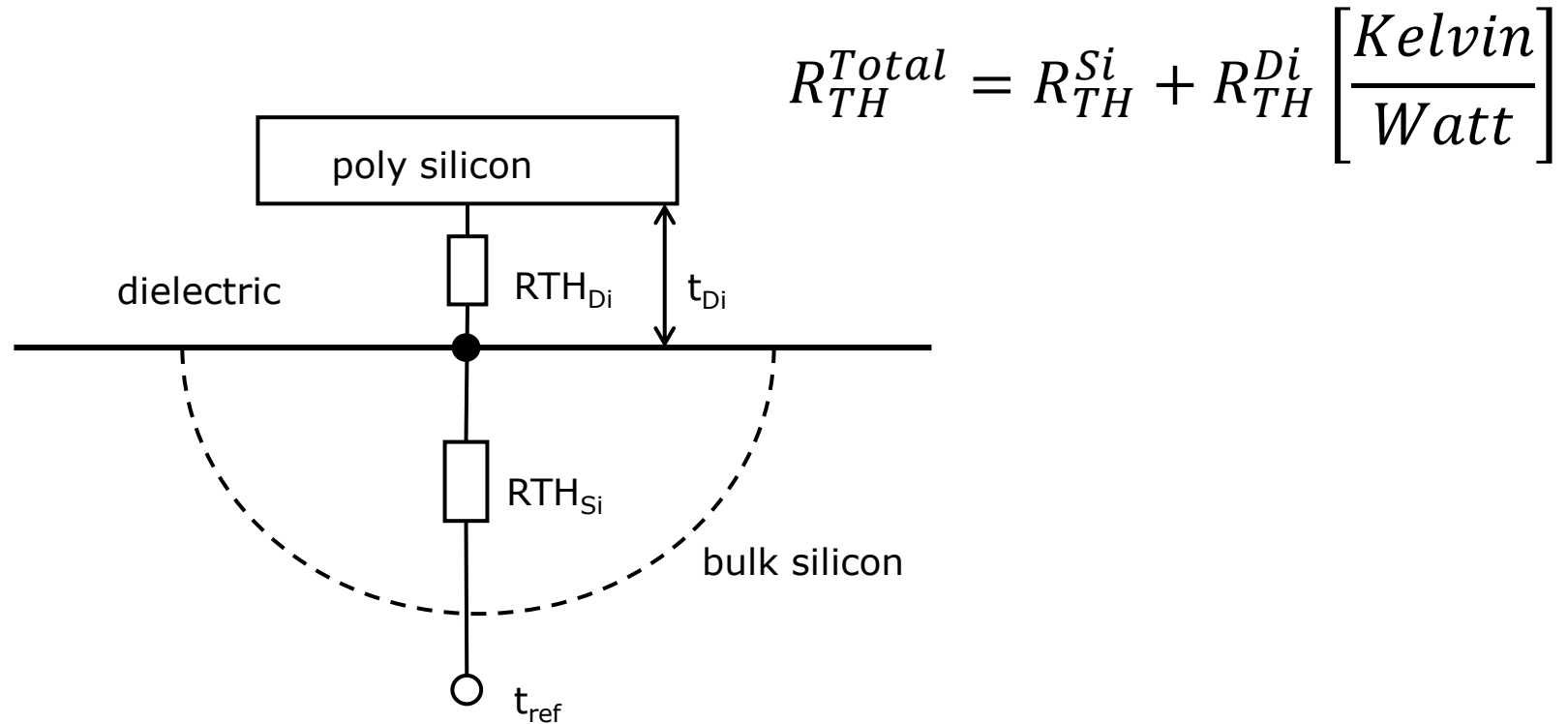
Example $V=R \cdot I$ (Ohm's law)

```
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



Diffusion resistor : R^{Si} only

Thermal resistance in silicon

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

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

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

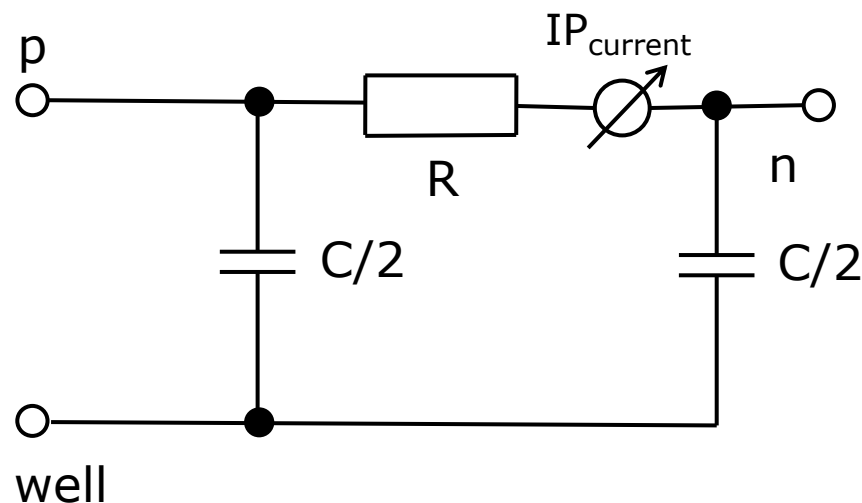
$$C_{TH} = \frac{\tau_{thermal}}{R_{TH}^{Total}(T - T_{nom})}$$

	Diffusion resistors	Poly resistors
Thermal time constant τ_{TH}	~100us	~200ns

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Calculation of Power

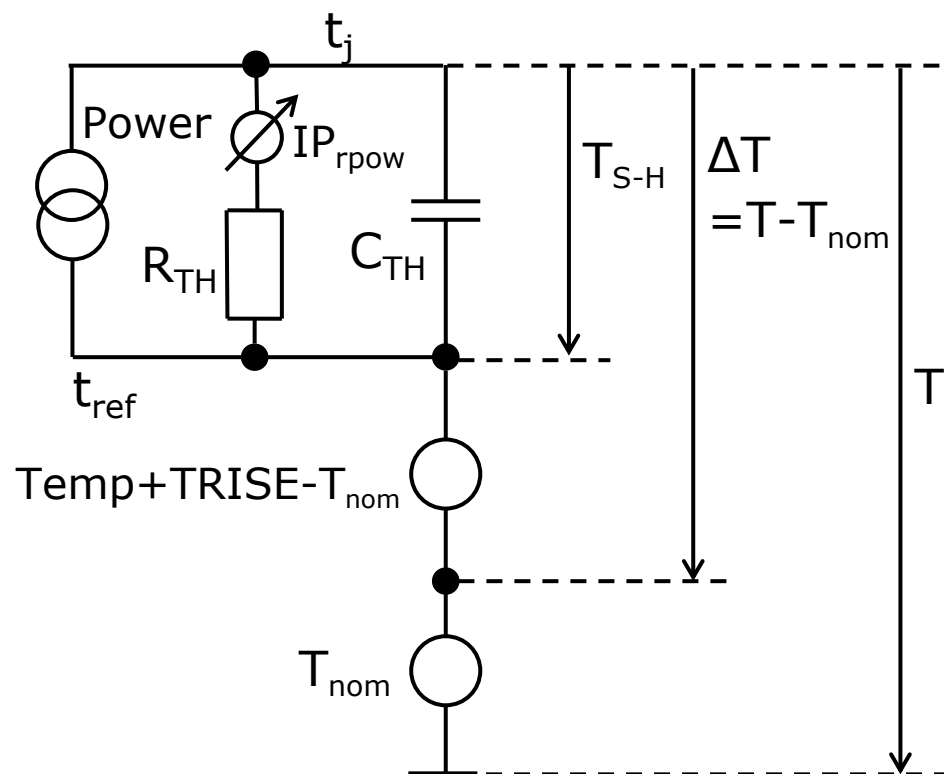


$$Power = (I_{Res})^2 R_{core}$$

```
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-H}
- › Node tj for absolute junction temperature of the device

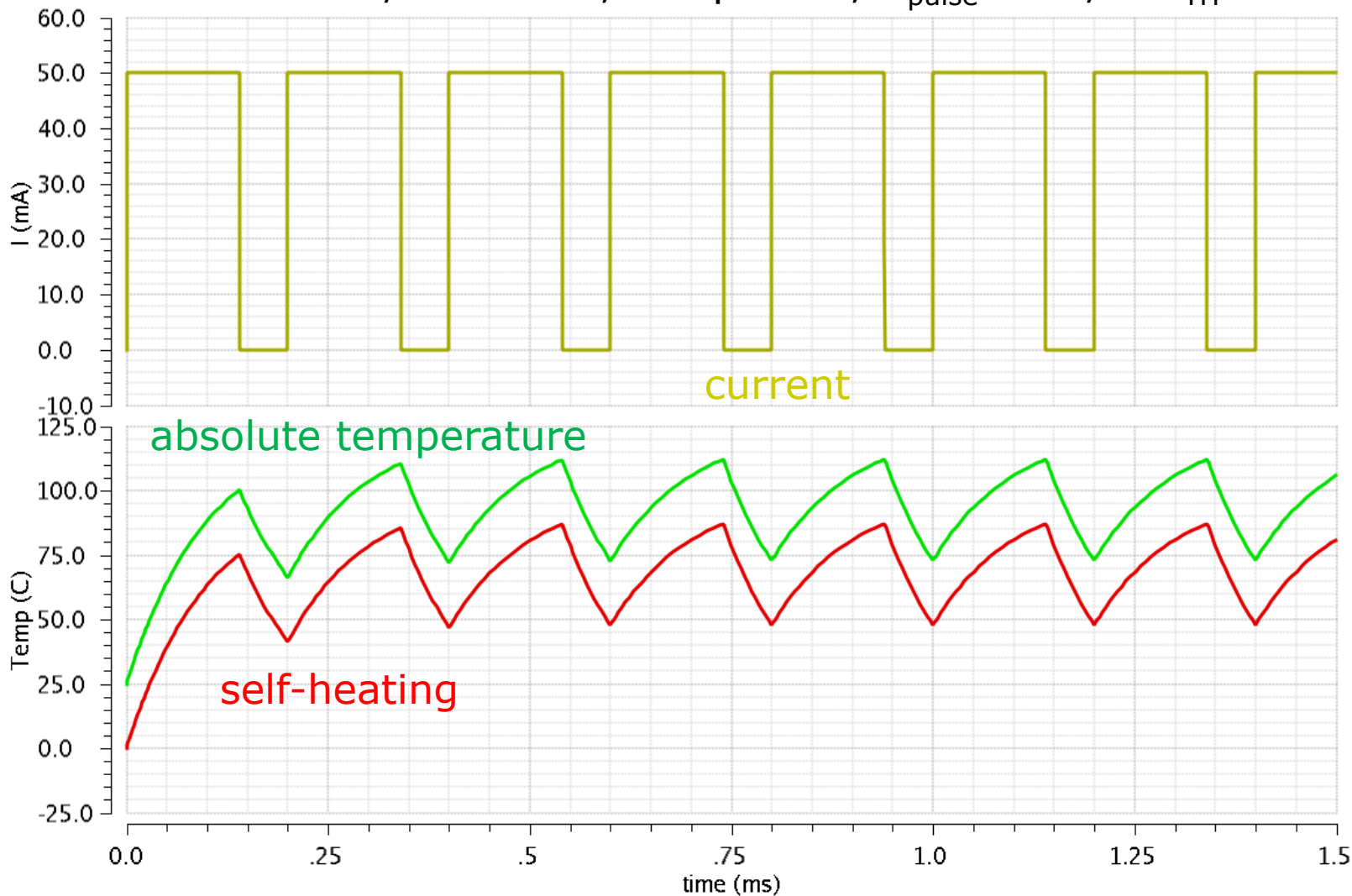
```
rndiff (p n dt)      resistor_sh
+ l                = rndiff_lress
+ w                = rndiff_wres
+ value            = rndiff_final_value
+ ...
```

```
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 $R=200\Omega$, $W=10\mu\text{m}$, $\text{Temp}=25\text{C}$, $V_{\text{pulse}}=10\text{V}$, $\text{Tau}_{\text{TH}}=100\mu\text{s}$



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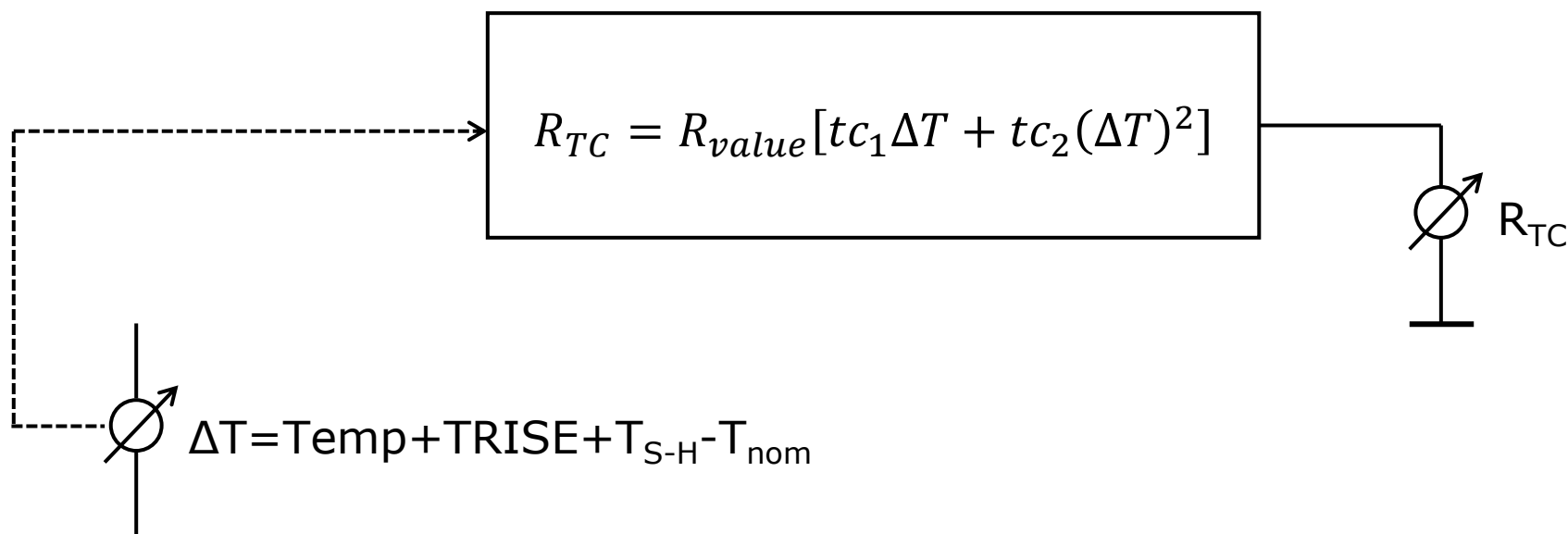
Feedback of self-heating to resistance

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

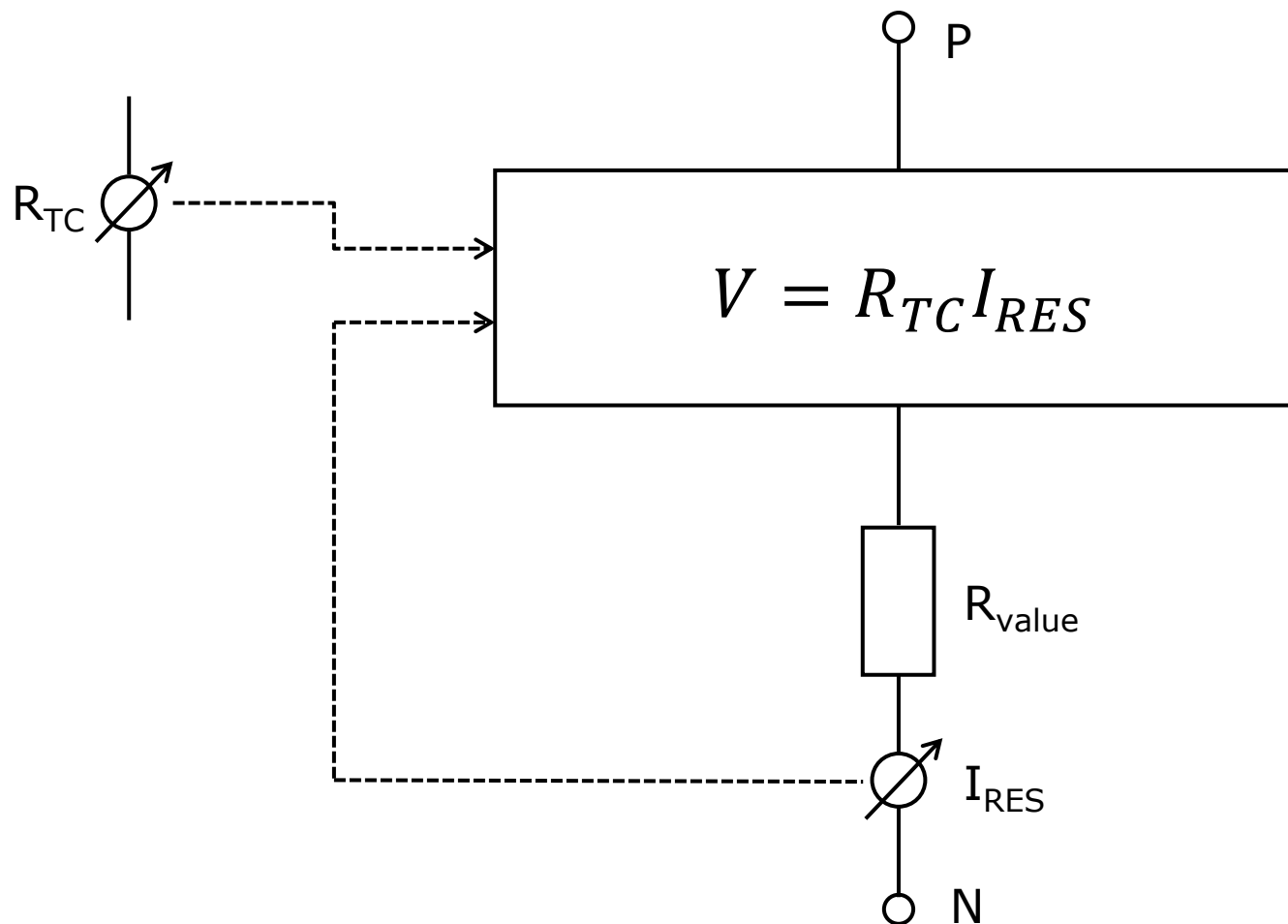
$$R(T) = \underbrace{R_{value}}_{parametric} + \underbrace{R_{value} [TC_1(T - T_{nom}) + TC_2(T - T_{nom})^2]}_{signal R_{TC}}$$

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

Create the signal part of the resistance

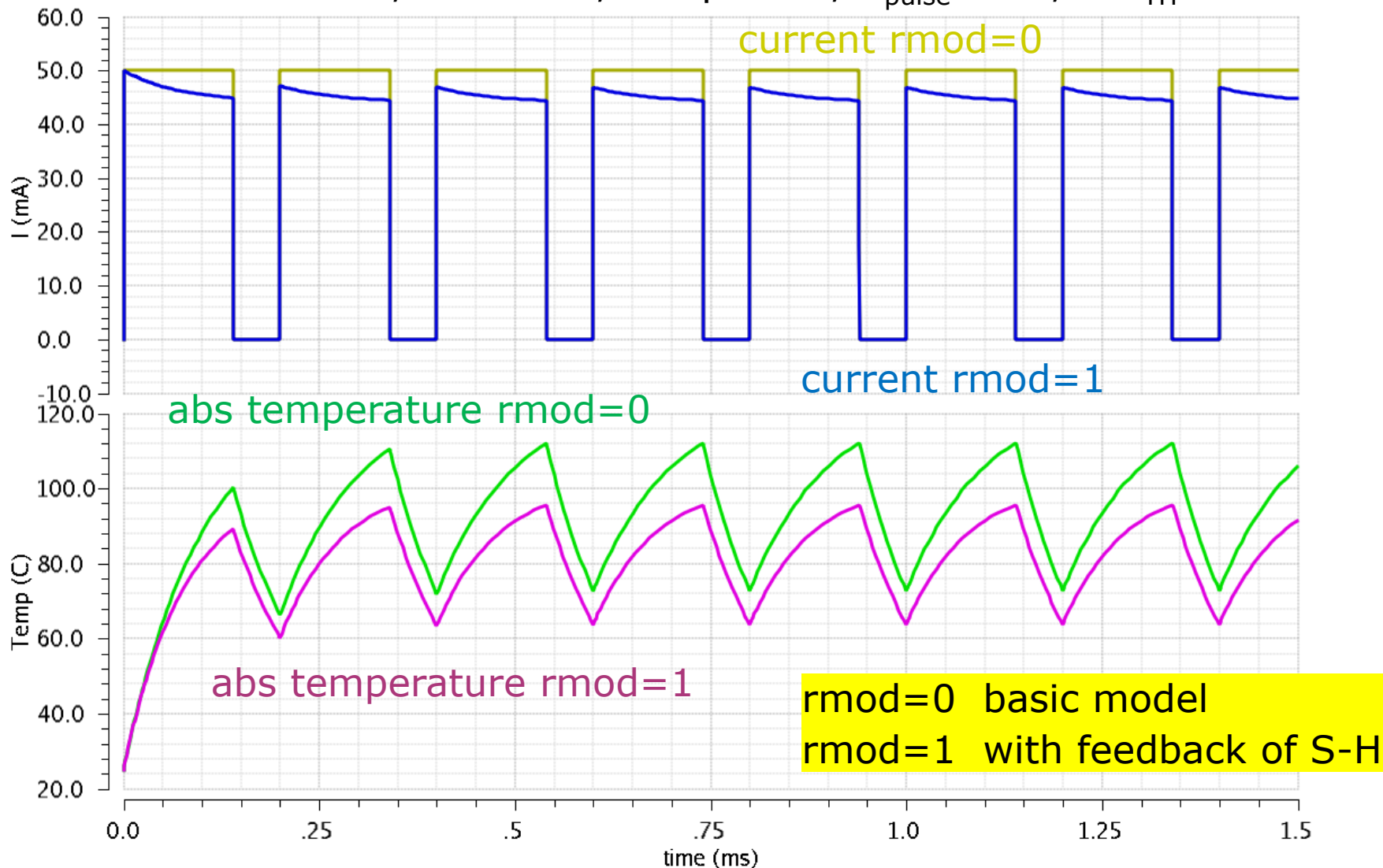


Create the total resistor



Simulation results

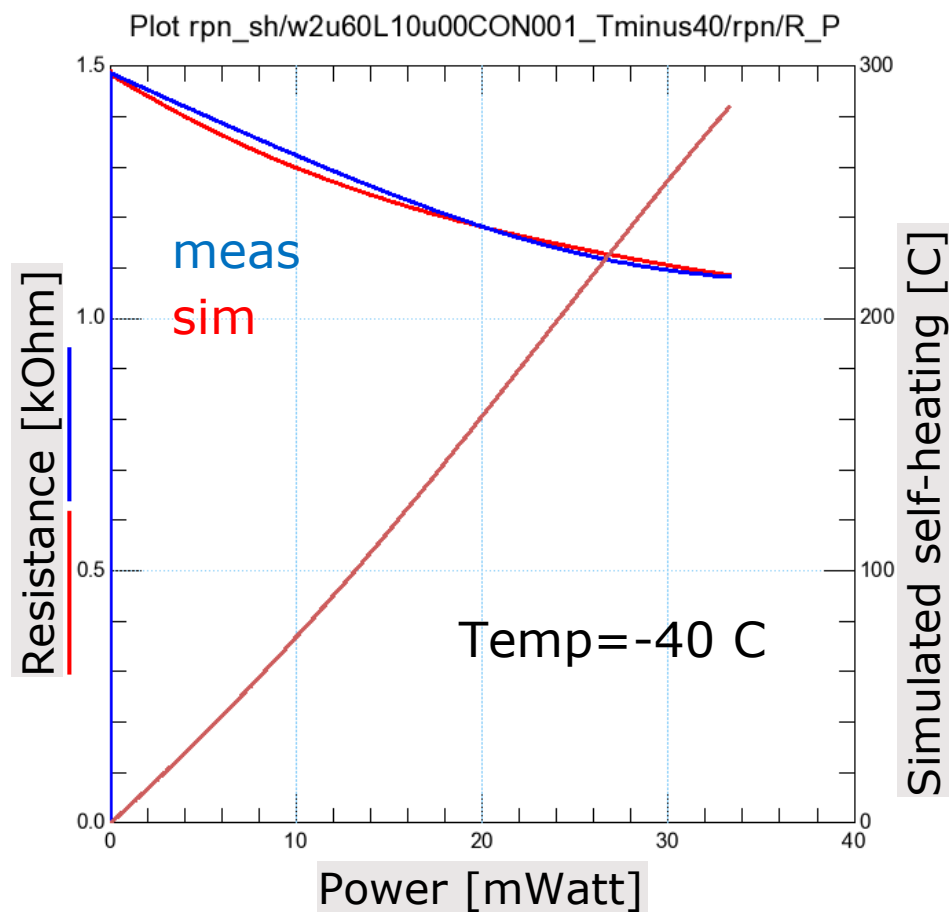
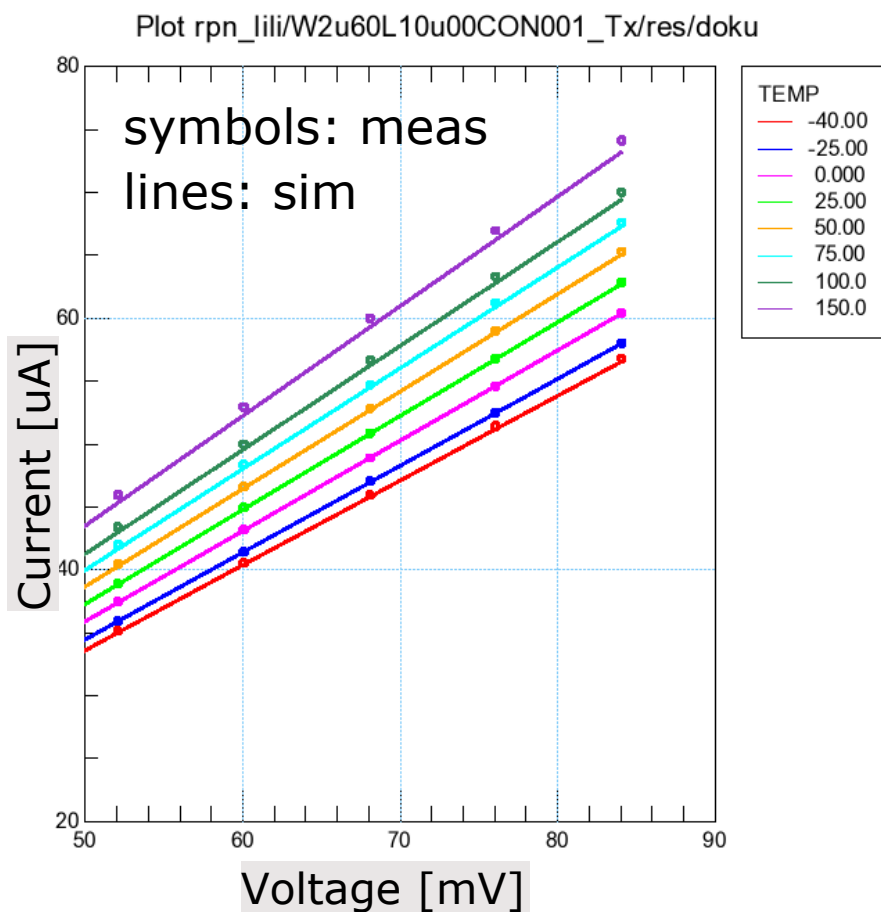
Ndiff resistor $R=200\Omega$, $W=10\mu\text{m}$, $\text{Temp}=25\text{C}$, $V_{\text{pulse}}=10\text{V}$, $\text{Tau}_{\text{TH}}=100\mu\text{s}$



Verification against measurement

Device: s7rpn, W=2.6 μ m, L=10 μ m

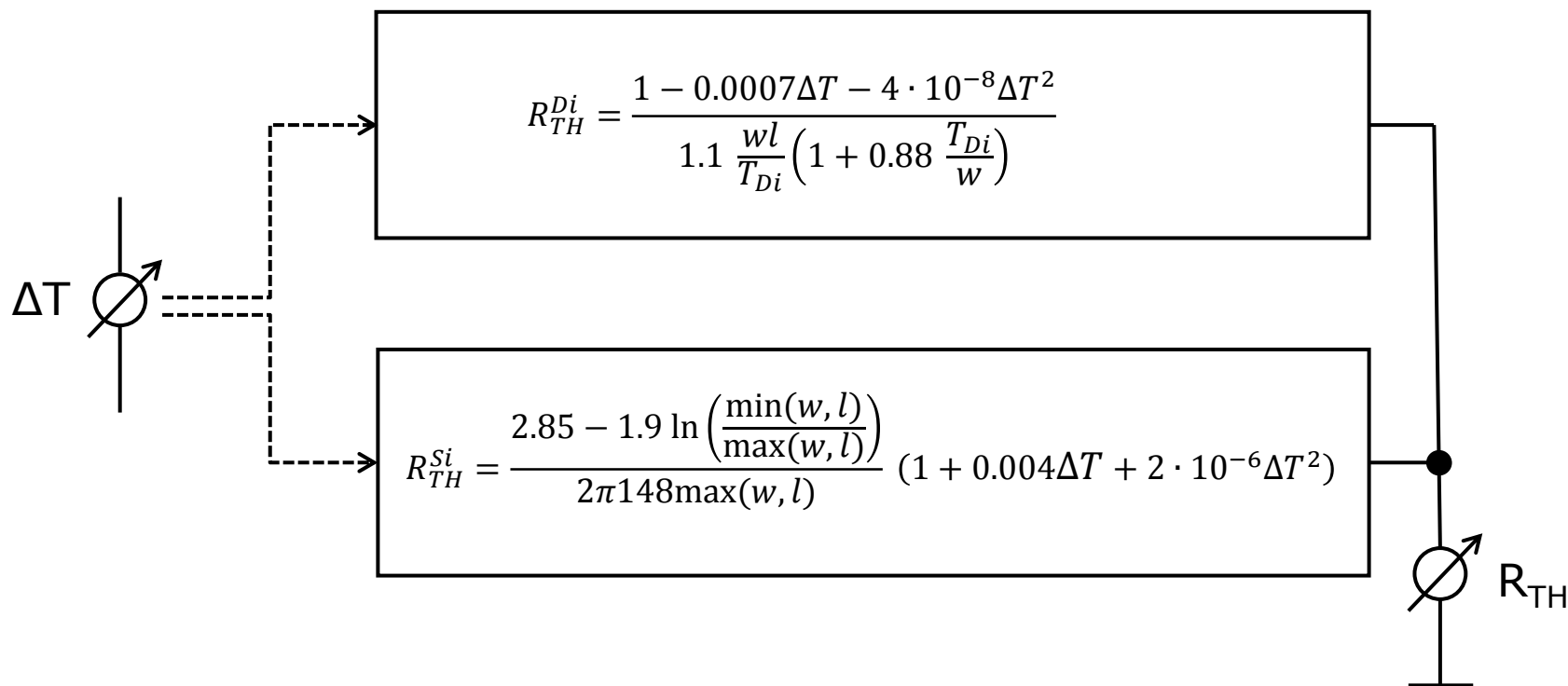
(KDI_0=2.2)



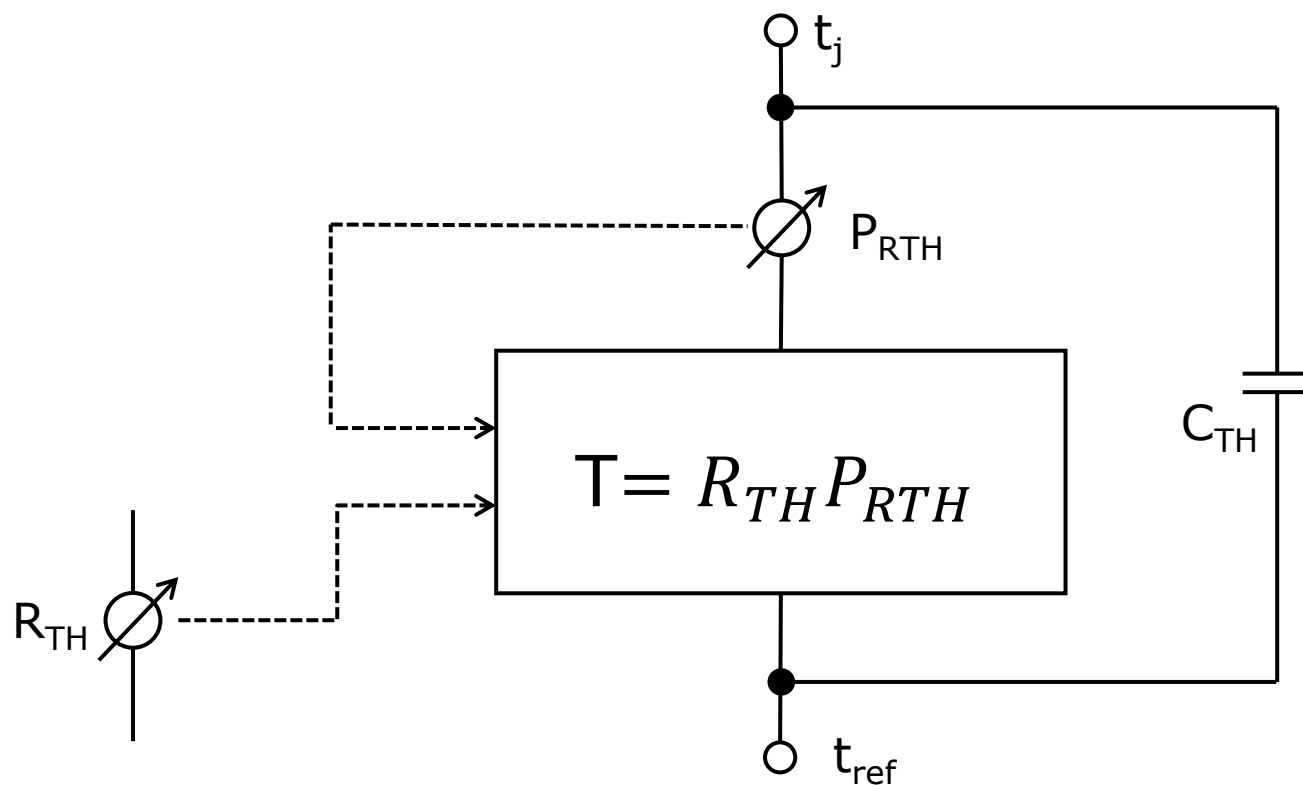
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Create the signal part of the thermal resistance

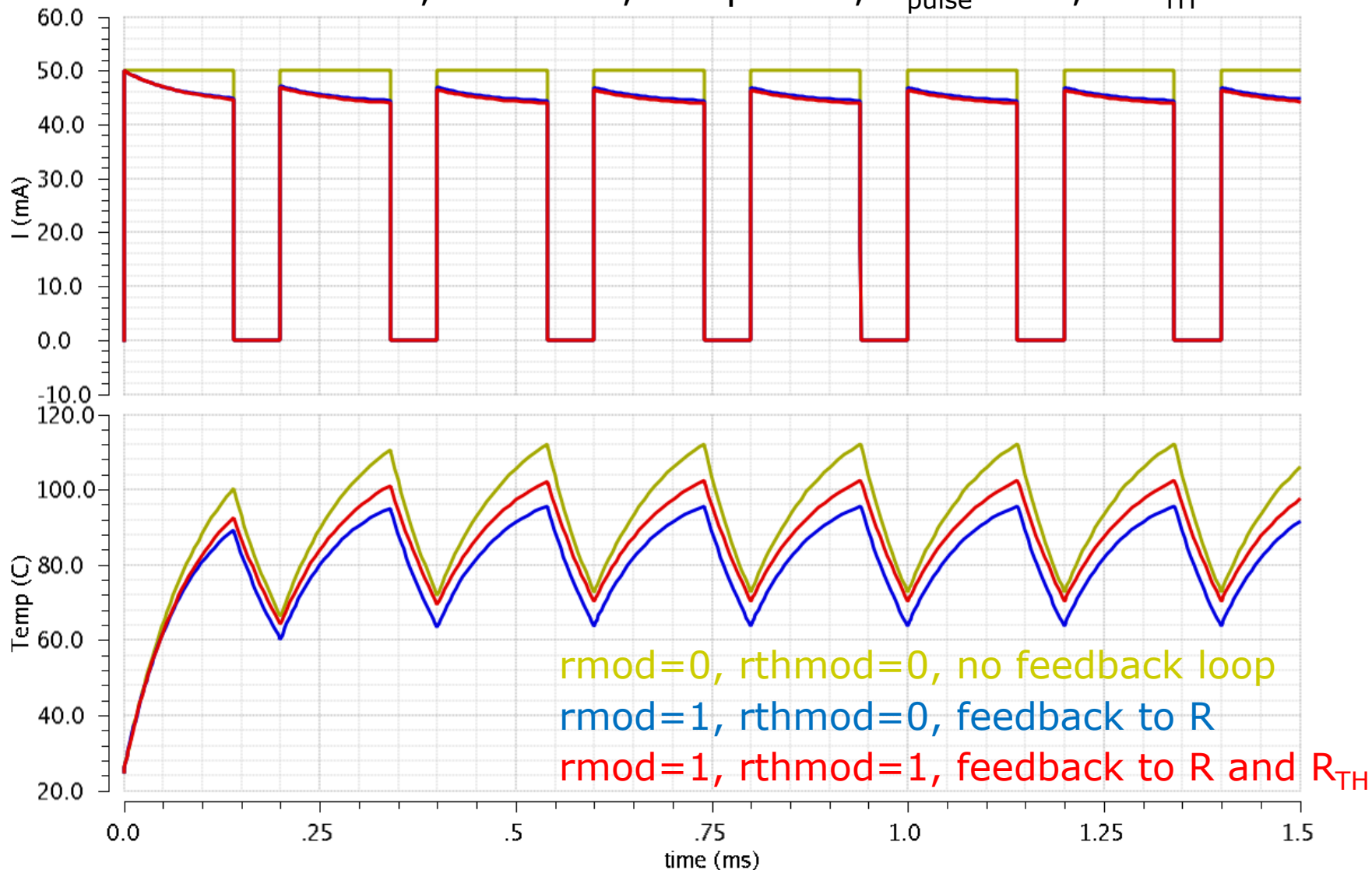


Create the thermal resistor



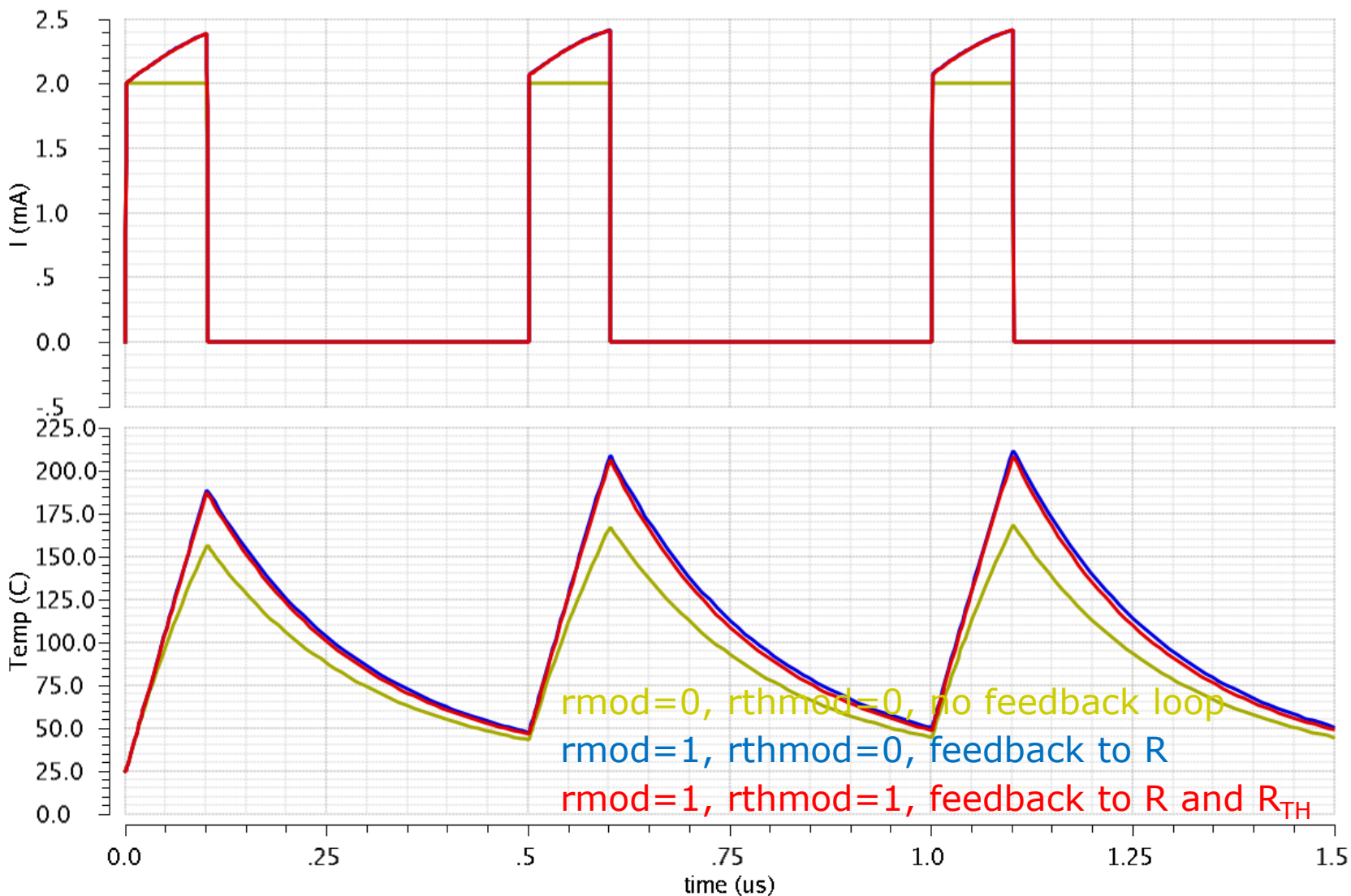
Simulation results

Ndiff resistor $R=200\Omega$, $W=10\mu\text{m}$, $\text{Temp}=25\text{C}$, $V_{\text{pulse}}=10\text{V}$, $\text{Tau}_{\text{TH}}=100\mu\text{s}$



Simulation results

Poly resistor $R=1k\Omega$, $W=1\mu m$, $Temp=25C$, $V_{pulse}=2V$, $\tau_{TH}=200ns$



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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}	$V, I, T=temp+T_{S-H}$	$RMOD=0, RTHMOD=0$
resistor_sh with S-H feedback to R	W, L, R_{TH}, C_{TH}	$V, I, R(T), T=temp+T_{S-H}$	$RMOD=1, RTHMOD=0$
resistor_sh with S-H feedback to R and R_{TH}	W, L, C_{TH}	$V, I, R(T), R_{TH}(T), T=temp+T_{S-H}$	$RMOD=1, RTHMOD=1$
resistor_sh with S-H feedback to R, R_{TH}, C_{TH}	W, L	$V, I, R(T), R_{TH}(T), C_{TH}(T), T=temp+T_{S-H}$	not yet implemented

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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
 - $R_{TH_{DI}}$ in oxide with just one model parameter TDI: thickness
 - $R_{TH_{SI}}$ 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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