6 MOS Model, level 3100

6.1 Introduction

The Junction-Field-Effect Transistor (JFET) and the depletion mode Metal-Oxide Semi-(MOSFET) are semiconductor devices whose operation is achieved by depleting an already existing channel via a voltage controlled p-n junction (JFET) or a gate controlled surface depletion (MOSFET). These devices are often used as a load in high voltage MOS devices. This long channel JFET/MOSFET model is special developed to describe the drift region of LDMOS, EPMOS and VDMOS devices. When the n-channel MOS transistor equations are used for p-channel MOS transistors, the sign of the terminal potentials, terminal currents and terminal charges must be changed.

6.1.1 Survey of modelled effects

- Accumulation at the surface (MOSFET)
- Depletion from the surface
- Depletion from the bulk
- Pinch off mode
- Velocity saturation in the channel
- Gate charge model
- Substrate charge model
- Self-heating
- Different temperature scaling for *RON* and *VSAT*
- Include temperature scaling for *RSAT*

Not included in the model

- Short channel effects
- Subthreshold currents
- Inversion at the surface at high negative gate voltages.

- Noise model

6.2 Symbols, parameters and constants

6.2.1 Parameter list

The parameters are listed below .

No.	Parameter	Units	Description
1	*LEVEL*	-	Model level, must be set to 3100
2	*RON*	Ω	Ohmic resistance at zero bias
3	*RSAT*	Ω	Space charge resistance at zero bias
4	*VSAT*	V	Critical drain-source voltage for hot carriers
5	*PSAT*	–	Velocity saturation coefficient
6	*VP*	V	Pinch off voltage at zero gate and substrate voltages $VP \leq 0$: no depletion and/or accumulation in the channel
7	*TOX*	m	Gate oxide thickness $TOX > 0$: MOSFET device $TOX \leq 0$: No accumulation and/or depletion at the surface
8	*DCH*	m^{-3}	Doping level channel
9	*DSUB*	m^{-3}	Doping level substrate $DSUB \leq 0$: No depletion from the substrate
10	*VSUB*	V	Substrate diffusion voltage
11	*VGAP*	V	Bandgap voltage channel
12	*CGATE*	F	Gate capacitance at zero bias
13	*CSUB*	F	Substrate capacitance at zero bias
14	*TAUSC*	s	Space charge transit time of the channel
15	*ACH*	–	Temperature coefficient restivity of the channel
16	*ACHMOD*	–	Parameter to switch to extended temperature scaling
17	*ACHRON*	–	Temperature coefficient of ohmic resistance at zero bias
18	*ACHVSAT*	–	Temperature coefficient of critical drain-source voltage for hot carriers
19	*ACHRSAT*	–	Temperature coefficient of space charge resistance at zero bias
20	*TREF*	°C	Reference temperature

No.	Parameter	Units	Description
21	*DTA*	°C	Temperature offset to the ambient temperature

The additional operating point output for the model including self-heating (see section 6.4) is listed in the table below.

No.	Parameter	Units	Description
22	*RTH*	°C/W	Thermal resistance
23	*CTH*	J/°C	Thermal capacitance
24	*ATH*	–	Temperature coefficient of the thermal resistance.

The *MULT* parameter is listed in the table below.

No.	Parameter	Units	Description
25	*MULT*	–	Multiplication factor

Parameter *MULT*

This parameter may be used to put several devices in parallel. The following parameters are multiplied by *MULT* :

CGATE *CSUB* *CTH*

Divided by *MULT* are:

RON *RSAT* *RTH*

Default and clipping values

The default values and clipping values as usedfor the MOS level 3100 model are listed below.

Position in list	Parameter name	Units	Default	Clip low	Clip high
1	*LEVEL*	-	3100	-	-
2	*RON*	Ω	1.00	1e-2	-
3	*RSAT*	Ω	1.00	1e-2	-
4	*VSAT*	V	10.00	1.00×10^{-6}	-

Position in list	Parameter name	Units	Default	Clip low	Clip high
5	*PSAT*	–	1.00	0.1	-
6	*VP*	V	-1.00	-1.0	-
7	*TOX*	m	-1.00	-1.0	0.0001
8	*DCH*	m^{-3}	1.00×10^{21}	1.00×10^{11}	1.00×10^{29}
9	*DSUB*	m^{-3}	1.00×10^{21}	-1.0	1.00×10^{29}
10	*VSUB*	V	0.60	0.05	-
11	*VGAP*	V	1.20	0.1	-
12	*CGATE*	F	0.00	0.0	-
13	*CSUB*	F	0.00	0.0	-
14	*TAUSC*	s	0.00	0.0	-
15	*ACH*	–	0.00	-	-
16	*ACHMOD*	–	0.00	0	1
17	*ACHRON*	–	0.00	-	-
18	*ACHVSAT*	–	0.00	-	-
19	*ACHRSAT*	–	0.00	-	-
20	*TREF*	°C	25	-273.0	-
21	*DTA*	°C	0.00	-	-

The default values and clipping values of the additional parameters for the model including self-heating (see section 6.4) is listed in the table below.

Position in list	Parameter Name	Units	Default	Clip low	Clip high
22	*RTH*	^{o}C/W	300.0	0.000	-
23	*CTH*	J/^{o}C	3.0×10^{-9}	0.000	-
24	*ATH*	–	0.0	-	-

The *MULT* parameter is listed in the table below.

Position in list	Parameter Name	Units	Default	Clip low	Clip high
25	*MULT*	-	1.000	0.000	-

6.3 Model equations

A full description of the long channel JFET/MOSFET model is given below.

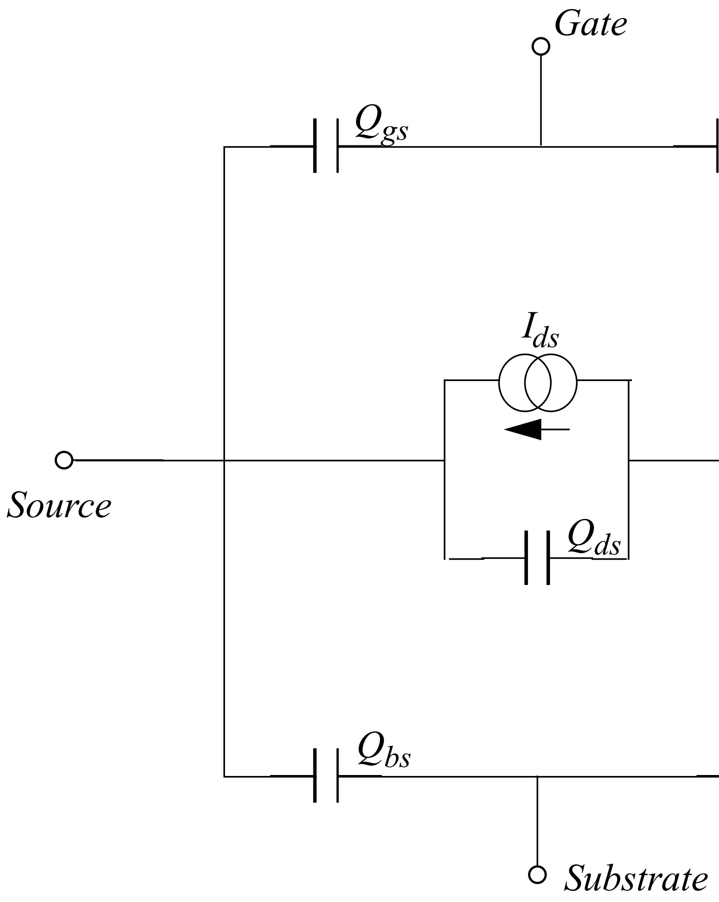


Figure 15: Equivalent Circuit of an JFET/MOSFET

6.3.1 Model constants

$$q = 1.6021918 \cdot 10^{-19}\mathrm{C}$$

$$\varepsilon_{si} = 1.036 \cdot 10^{-10}\mathrm{C/V \cdot m} \tag{6.1}$$

$$\varepsilon_{ox} = 3.453 \cdot 10^{-11}\mathrm{C/V \cdot m} \tag{6.2}$$

$$\left(\frac{k}{q}\right) = 0.86171 \times 10^{-4}\mathrm{V/K} \tag{6.3}$$

$$\delta_v = 10^{-8} \tag{6.4}$$

$$V_0 = 10^{-3} \tag{6.5}$$

$$\varepsilon = 10^{-2} \tag{6.6}$$

The default reference temperature *TREF* for parameter determination is 25 °C.

6.3.2 Temperature effects

The actual simulation temperature is denoted by *TEMP* (in ^{o}C). The temperature at which the parameters are determined is *TREF* (in ^{o}C).

- Conversions to Kelvins

3 Note

Note the addition of the voltage V_{dT} of the thermal node in order to include self-heating, see section 6.7.

$$T_K = TEMP + DTA + 273.15 + V_{dT} \tag{6.7}$$

$$T_{amb} = TEMP + DTA + 273.15 \tag{6.8}$$

$$T_{RK} = TREF + 273.15 \tag{6.9}$$

$$T_N = \frac{T_K}{T_{RK}} \tag{6.10}$$

- Thermal Voltage

$$V_T = \left(\frac{k}{q}\right) \cdot T_K \tag{6.11}$$

- On resistance and saturation voltage

$$RON_T = RON \cdot T^{ACHRON} \tag{6.12}$$

$$VSAT_T = VSAT \cdot T^{ACHVSAT} \tag{6.13}$$

$$RSAT_T = RSAT \cdot T^{ACHRSAT} \tag{6.14}$$

- Substrate depletion capacitance.

$$VSUB_T = -3 \cdot \left(\frac{k}{q}\right) \cdot T_K \cdot ln(T_N) + VSUB \cdot T_N + (1 - T_N) \cdot VGAP \tag{6.15}$$

$$CSUB_T = CSUB \cdot \sqrt{\frac{VSUB}{VSUB_T}} \tag{6.16}$$

- Thermal resistance

$$RTH_T = RTH \cdot \left(\frac{T_{amb}}{T_{RK}}\right)^{ATH} \tag{6.17}$$

6.3.3 Model preprocessing

- Parameter dependent constants DC part

If $TOX \le 0\ CGATE = 0$

If $DSUB \le 0\ \ DSUB = 0$

If $TOX < 0\ \&\ DSUB < 0\ \ VP = 0$

For both *DSUB* and *TOX* less than or equal to zero the pinch off voltage $VP = 0$. When $VP \le 0$ only equations 6.29, 6.47, 6.49, 6.50, 6.62, 6.63, 6.104 and 6.105 are used. In this case the charges Q_b and Q_g are equal zero.

$$DSUB > 0 : k_b = \sqrt{\frac{2 \cdot \varepsilon_{si} \cdot q \cdot DSUB \cdot DCH}{DSUB + DCH}} \tag{6.18}$$

$$DSUB \le 0 : k_b = 0 \tag{6.19}$$

$$Q_{bp} = \frac{k_b \cdot VP}{\sqrt{VP + VSUB_T} + \sqrt{VSUB_T}} \tag{6.20}$$

$$V_{ox} = \frac{\varepsilon_{si} \cdot q \cdot DCH}{2} \cdot \left(\frac{TOX}{\varepsilon_{ox}}\right)^2 \tag{6.21}$$

$$TOX > 0 : k_{ox} = \sqrt{2 \cdot \varepsilon_{si} \cdot q \cdot DCH} \tag{6.22}$$

$$TOX \le 0 : k_{ox} = 0 \tag{6.23}$$

$$Q_{sp} = \frac{k_{ox} \cdot VP}{\sqrt{VP + V_{ox}} + \sqrt{V_{ox}}} \tag{6.24}$$

$$Q_i = Q_{bp} + Q_{sp} \tag{6.25}$$

$$Q_m = k_b \cdot \sqrt{VP + VSUB_T} + k_{ox} \cdot \sqrt{VP + V_{ox}} \tag{6.26}$$

$$T_s = \frac{Q_i}{q \cdot DCH} \tag{6.27}$$

$$TOX > 0 : C_{ox} = \frac{\varepsilon_{ox}}{TOX} \tag{6.28}$$

$$TOX \le 0 : C_{ox} = 0 \tag{6.29}$$

$$C_b = \frac{k_b}{2 \cdot \sqrt{VSUB_T}} \tag{6.30}$$

$$J_{sat} = \frac{VSAT_T}{T_s \cdot RON_T} \tag{6.31}$$

$$VR_{sat} = VSAT_T \cdot \frac{RSAT}{RON_T} \tag{6.32}$$

$$\delta_q = 10^{-2} \cdot Q_i^2 \tag{6.33}$$

6.3.4 Model evaluation

Drain and source voltage

$$V_d \geq V_s \qquad sign = 1$$

$$V_{d1} = V_d$$

$$V_{s1} = V_s$$

$$V_d < V_s \qquad sign = -1$$

$$V_{d1} = V_s$$

$$V_{s1} = V_d$$

Substrate - source voltage < $VSUB_T$

$$DSUB > 0: \begin{aligned} V_{bm} &= VSUB_T + V_{s1} - V_b - \varepsilon^2 / VSUB_T \\ V_{b1} &= VSUB_T + V_{s1} - 0.5 \cdot \left(V_{bm} + \sqrt{V_{bm}^2 + 4 \cdot \varepsilon^2}\right) \end{aligned} \tag{6.34}$$

$$DSUB \leq 0 : V_{b1} = V_b$$

Gate voltage $V_g > V_{b_1} - V_{g_{sw}}$

$$DSUB > 0 \ \& \ TOX > 0 :$$

$$V_{g_{sw}} = VSUB_T - V_{ox} + (Q_m / k_{ox})^2 \tag{6.35}$$

$$V_{gm} = V_g - V_{b_1} + V_{g_{sw}} - \varepsilon^2 \cdot V_{g_{sv}} \tag{6.36}$$

$$V_{g_1} = V_{b_1} - V_{g_{sw}} + 0.5 \cdot \left(V_{gm} + \sqrt{V_{gm}^2 + 4 \cdot \varepsilon^2 \cdot V_{g_{sw}}^2} \right) \tag{6.37}$$

$DSUB \leq 0$ or $TOX \leq 0$:

$$V_{g1} = V_g$$

- Pinch-off voltage

$$DSUB \leq 0 : V_p = VP + V_{g_1} \tag{6.38}$$

$$TOX \leq 0 : V_p = VP + V_{b_1} \tag{6.39}$$

$TOX > 0$ & $DSUB > 0$:

$$V_{b_{sw}} = V_{g_1} - 2 \cdot (Q_i / k_b) \cdot \sqrt{VSUB_T} - (Q_i / k_b)^2 \tag{6.40}$$

$V_{b_1} > V_{b_{sw}}$:

$$b_p = \frac{k_b \cdot Q_m}{k_{ox}^2} \cdot \frac{DSUB + DCH}{DCH} \tag{6.41}$$

$$c_p = \left[\left(\frac{Q_m}{k_{ox}} \right)^2 + (V_{g_1} - V_{b_1} + VSUB_T - V_{ox}) \right] \cdot \frac{DSUB + DCH}{DCH} \tag{6.42}$$

$$V_p = V_{b_1} - VSUB_T + \frac{c_p^2}{2 \cdot b_p^2 + c_p + 2 \cdot b_p \cdot \sqrt{b_p^2 + c}} \tag{6.43}$$

$V_{b_1} \leq V_{b_{SW}}$:

$$b_{ac} = V_{g_1} + (Q_i + k_b \cdot \sqrt{VSUB_T})/C_{ox} + \left(\frac{k_b}{2 \cdot C_{ox}}\right)^2 \tag{6.44}$$

$$V_p = b_{ac} + \left(\frac{k_b}{2 \cdot C_{ox}}\right)^2 - \frac{k_b}{C_{ox}} \cdot \sqrt{b_{ac} + VSUB_T - V_{b_1}} \tag{6.45}$$

- Source and drain voltage including pinch-off and velocity saturation

$$VP > 0: V_{sp} = 1/2 \cdot \left[V_{s_1} + V_p - \sqrt{(V_{s_1} - V_p)^2 + \delta_v}\right] \tag{6.46}$$

$$VP \leq 0: V_{sp} = V_{s_1} \tag{6.47}$$

$$VP > 0: V_c = \frac{2 \cdot VSAT_T \cdot (V_p - V_{sp})}{VSAT_T + V_p - V_{sp} + \sqrt{VSAT_T^2 + (V_p - V_{sp})^2}} \tag{6.48}$$

$$VP \leq 0: V_c = VSAT_T \tag{6.49}$$

$$V_{dp} = V_{sp} + \frac{(V_{d_1} - V_{s_1}) \cdot V_c}{\sqrt[PSAT]{(V_{d_1} - V_{s_1})^{PSAT} + V_c^{PSAT}}} \tag{6.50}$$

- Integration boundary voltage V_{ad}

$V_{sp} < V_{g_1}$: $V_{dp} < V_{g_1}\ V_{ad} = V_{dp}$

$V_{dp} \geq V_{g_1}\ V_{ad} = V_{g_1}$

$V_{sp} \geq V_{g_1}$: $V_{ad} = V_{sp}$

- Transformation of voltages

$V_{sp} - V_{b_1} + VSUB_T$

$$S_{spb} = \frac{V_{sp} - V_{b_1}}{VSUB_T}, Y_{spb} = \frac{S_{spb}}{1 + \sqrt{1 + S_{spb}}}$$

(6.51)

$V_{dp} - V_{b_1} + VSUB_T$

$$S_{dpb} = \frac{V_{dp} - V_{b_1}}{VSUB_T}, Y_{dpb} = \frac{S_{dpb}}{1 + \sqrt{1 + S_{dpb}}}$$

(6.52)

$V_{ad} - V_{b_1} + VSUB_T$

$$S_{adb} = \frac{V_{ad} - V_{b_1}}{VSUB_T}, Y_{adb} = \frac{S_{adb}}{1 + \sqrt{1 + S_{adb}}}$$

(6.53)

$V_{sp} - V_{g_1} + V_{ox}$

$$S_{spg} = \frac{V_{sp} - V_{g_1}}{V_{ox}},$$

$$V_{sp} \geq V_{g_1}: \ Y_{spg} = \frac{S_{spg}}{1 + \sqrt{1 + S_{spg}}}$$

(6.54)

$V_{dp} - V_{g_1} + V_{ox}$

$$S_{dpg} = \frac{V_{dp} - V_{g_1}}{V_{ox}},$$

$$V_{dp} \geq V_{g_1}: Y_{dpg} = \frac{S_{dpg}}{1 + \sqrt{1 + S_{dpg}}}$$

(6.55)

$$V_{ad} - V_{g_1} + V_{ox} \qquad S_{adg} = \frac{V_{ad} - V_{g_1}}{V_{ox}},$$

$$V_{ad} \geq V_{g_1} : Y_{adg} = \frac{S_{adg}}{1 + \sqrt{1 + S_{adg}}}$$

(6.56)

- Current reduction due to substrate effect

$$I_{bd} = \frac{-4 \cdot C_b \cdot VSUB_T^2}{Q_i \cdot RON_T} \cdot \left(\frac{Y_{dpb}^2 - Y_{spb}^2}{2} + \frac{Y_{dpb}^3 - Y_{spb}^3}{3} \right) \tag{6.57}$$

- Current increase due to accumulation

$$V_{sp} < V_{g_1} \qquad I_{sa} = \frac{C_{ox} \cdot V_{ox}^2}{Q_i \cdot RON_T} \cdot \left(\frac{S_{spg}^2 - S_{adg}^2}{2} \right) \tag{6.58}$$

$$V_{sp} \geq V_{g_1} \qquad I_{sa} = 0 \tag{6.59}$$

- Current reduction due to depletion at the surface

$$V_{dp} \geq V_{g_1} : \quad I_{sd} = \frac{-4 \cdot C_{ox} \cdot V_{ox}^2}{Q_i \cdot RON_T} \cdot \left(\frac{Y_{dpg}^2 - Y_{adg}^2}{2} + \frac{Y_{dpg}^3 - Y_{adg}^3}{3} \right) \tag{6.60}$$

$$V_{dp} < V_{g_1} : \quad I_{sd} = 0$$

- Total ohmic current

$$VP > 0 : \qquad I_{ohm} = \frac{V_{dp} - V_{sp}}{RON_T} + I_{bd} + I_{sa} + I_{sd} \tag{6.61}$$

$$VP \le 0: \qquad I_{ohm} = \frac{V_{dp} - V_{sp}}{RON_T} \tag{6.62}$$

- Total current including velocity saturation

$$I_{ds} = sign \cdot I_{ohm} \cdot \left(1 + \frac{V_{d_1} - V_{dp}}{VR_{sat}}\right) \tag{6.63}$$

6.3.5 Substrate charge model

$$F_c = \frac{(V_p - V_{sp})^4}{(V_p - V_{sp})^4 + (VP/100)^4} \cdot \frac{V_{dp} - V_{sp}}{V_0 + V_{dp} - V_{sp}} \tag{6.64}$$

$$Vb_1 = \frac{4 \cdot VSUB_T^2}{RON_T \cdot I_{ohm}} \cdot \left(\frac{Y_{dpb}^2 - Y_{spb}^2}{2} + \frac{Y_{dpb}^3 - Y_{spb}^3}{3}\right) \tag{6.65}$$

$$Vb_2 = \frac{-8 \cdot C_b \cdot VSUB_T^3}{Q_i \cdot RON_T \cdot I_{ohm}} \cdot \left(\frac{Y_{dpb}^3 - Y_{spb}^3}{3} + \frac{Y_{dpb}^4 - Y_{spb}^4}{4}\right) \tag{6.66}$$

$$Vb_2 = \frac{-8 \cdot C_b \cdot VSUB_T^3}{Q_i \cdot RON_T \cdot I_{ohm}} \cdot \left(\frac{Y_{dpb}^3 - Y_{spb}^3}{3} + \frac{Y_{dpb}^4 - Y_{spb}^4}{4}\right) \tag{6.67}$$

For $TOX \leq 0 : V_{b3} = V_{b4} = 0$ (6.68)

$$V_{sp} < V_{g_1}$$

$$V_{b_3} = \frac{4 \cdot C_{ox} \cdot VSUB_T^3}{Q_i \cdot RON_T \cdot I_{ohm}} \cdot \left[\begin{array}{c} \frac{V_{g_1} - V_{b_1}}{VSUB_T} \cdot \left(\frac{Y_{adb}^2 - Y_{spb}^2}{2} + \frac{Y_{adb}^3 - Y_{spb}^3}{3} \right) - \\ \left(2 \cdot \frac{Y_{adb}^3 - Y_{spb}^3}{3} + 3 \cdot \frac{Y_{adb}^4 - Y_{spb}^4}{4} + \frac{Y_{adb}^5 - Y_{spb}^5}{5} \right) \end{array} \right]$$

(6.69)

$$V_{sp} \geq V_{g_1} : V_{b_3} = 0$$

$$V_{dp} \geq V_{g_1} : z_0 = (V_{g_1} - V_{b_1} - V_{ox} + VSUB_T)/2 \tag{6.70}$$

$$
Vb_4^{exact} = \frac{-k_{ox}\cdot k_b}{Q_i\cdot RON_T\cdot C_b\cdot I_{ohm}}\cdot
\left[\begin{array}{l}
\frac{1}{4}\cdot\sqrt{VSUB_T\cdot V_{ox}}\cdot\left\{\begin{array}{l}
(V_{ox}-VSUB_T)\cdot[(Y_{dpb}-Y_{dpg})-(Y_{adb}-Y_{adg})] \\
\quad + VSUB_T\cdot Y_{dpb}\cdot[Y_{dpb}\cdot(1+Y_{dpb})+Y_{dpg}\cdot(3+3\cdot Y_{dpb}+Y_{dpb}^2)] \\
\quad - VSUB_T\cdot Y_{adb}\cdot[Y_{adb}\cdot(1+Y_{adb})+Y_{adg}\cdot(3+3\cdot Y_{adb}+Y_{adb}^2)] \\
\quad + V_{ox}\cdot Y_{dpg}\cdot[Y_{dpg}\cdot(1+Y_{dpg})+Y_{dpb}\cdot(3+3\cdot Y_{dpg}+Y_{dpg}^2)] \\
\quad - V_{ox}\cdot Y_{adg}\cdot[Y_{adg}\cdot(1+Y_{adg})+Y_{adb}\cdot(3+3\cdot Y_{adg}+Y_{adg}^2)]
\end{array}\right\} \\
-z_0^2\cdot ln\frac{\sqrt{VSUB_T}\cdot(1+Y_{dpb})+\sqrt{V_{ox}}\cdot(1+Y_{dpg})}{\sqrt{VSUB_T}\cdot(1+Y_{adb})+\sqrt{V_{ox}}\cdot(1+Y_{adg})} \\
-2\cdot VSUB_T^{3/2}\cdot\sqrt{V_{ox}}\cdot\left(\frac{Y_{dpb}^2-Y_{adb}^2}{2}+\frac{Y_{dpb}^3-Y_{adb}^3}{3}\right) \\
-2\cdot V_{ox}^{3/2}\cdot\sqrt{VSUB_T}\cdot\left(\frac{Y_{dpg}^2-Y_{adg}^2}{2}+\frac{Y_{dpg}^3-Y_{adg}^3}{3}\right)
\end{array}\right]
\tag{6.71}
$$

$$
\begin{aligned}
& \frac{-k_{ox} \cdot k_b}{Q_i \cdot RON_T \cdot C_b \cdot I_{ohm}} \cdot \\
Vb_4^{appro} = & \left[\begin{aligned}
& \frac{1}{4 \cdot \sqrt{VSUB_T \cdot V_{ox}}} \cdot \left\{ (V_{dp} - V_{ad}) \cdot [V_{b_1} \cdot V_{g_1}] - \frac{V_{dp}^2 - V_{ad}^2}{2} \cdot [V_{g_1} + V_{b_1}] + \frac{V_{dp}^3 - V_{ad}^3}{3} \right\} + \\
& \frac{1}{16 \cdot (VSUB_T \cdot V_{ox})^{3/2}} \cdot \left\{ \begin{aligned}
& \{(V_{dp} - V_{ad}) \cdot [V_{b_1} \cdot V_{g_1} \cdot (V_{g_1} \cdot VSUB_T + V_{b_1} \cdot V_{ox})] - \\
& \frac{V_{dp}^2 - V_{ad}^2}{2} \cdot [V_{g_1}^2 \cdot VSUB_T + V_{b_1}^2 \cdot V_{ox} + 2 \cdot V_{b_1} \cdot V_{g_1} \cdot (VSUB_T + V_{ox})] + \\
& \frac{V_{dp}^3 - V_{ad}^3}{3} \cdot [V_{g_1} \cdot (2 \cdot VSUB_T + V_{ox}) + V_{b_1} \cdot (VSUB_T + 2 \cdot V_{ox})] - \\
& \frac{V_{dp}^4 - V_{ad}^4}{4} \cdot [VSUB_T + V_{ox}]
\end{aligned} \right\}
\end{aligned} \right]
\end{aligned}
\tag{6.72}
$$

$$
Y_{sw} = \frac{VSUB_T \cdot (Y_{dpb}^2 + Y_{adb}^2) + V_{ox} \cdot (Y_{dpg}^2 + Y_{adg}^2)}{V_0^2 \cdot (VSUB_T + V_{ox})} \tag{6.73}
$$

$$
Sw = \frac{(1 + 2 \cdot V_o) \cdot Y_{sw}^2}{1 + Y_{sw}^2} - V_o \tag{6.74}
$$

$$
Sw \geq 1 \qquad V_{b_4} = Vb_4^{exact} \tag{6.75}
$$

$$
Sw \leq 0 \qquad V_{b_4} = Vb_4^{appr} \tag{6.76}
$$

$$
Sw > 0 \,\&\, Sw < 1 \qquad Vb_4 = Sw \cdot Vb_4^{exact} + (1 - Sw) \cdot Vb_4^{appr} \tag{6.77}
$$

$$
V_{dp} \leq V_{g_1} \qquad Vb_4 = 0 \tag{6.78}
$$

$$Q_{b_x} = -CSUB_T \cdot (Vb_1 + Vb_2 + Vb_3 + Vb_4) \tag{6.79}$$

$$Q_{b_y} = -CSUB_T \cdot VSUB_T \cdot (Y_{dpb} + Y_{spb}) \tag{6.80}$$

$$Cb_{fix} = 0.01 \cdot CSUB + MULT \cdot 10^{-17} \tag{6.81}$$

$$Qb = 0.99 \cdot \{F_c \cdot Q_{b_x} + (1 - F_c) \cdot Q_{b_y}\} + Cb_{fix} \cdot \{Vb_1 - (V_d + V_s)/2\} \tag{6.82}$$

6.3.6 Gate charge model

$$V_{sp} < V_{g_1}: \qquad V_{g_1} = \frac{-V_{ox}^2}{RON_T \cdot I_{ohm}} \cdot \left(\frac{S_{spg}^2 - S_{adg}^2}{2}\right) \tag{6.83}$$

$$V_{sp} \geq V_{g_1}: \qquad V_{g_1} = 0 \tag{6.84}$$

$$V_{dp} \geq V_{g_1}: \qquad V_{g_2} = \frac{4 \cdot V_{ox}^2}{RON_T \cdot I_{ohm}} \cdot \left(\frac{Y_{dpg}^2 - Y_{adg}^2}{2} + \frac{Y_{dpg}^3 - Y_{adg}^3}{3}\right) \tag{6.85}$$

$$V_{dp} < V_{g_1}: \qquad V_{g_2} = 0 \tag{6.86}$$

$$DSUB \leq 0: \qquad V_{g_3} = V_{g_4} = 0 \tag{6.87}$$

$$DSUB > 0: \qquad V_{g_3} = \frac{C_b}{C_{ox}} \cdot V_{b_3} \tag{6.88}$$

$$V_{g_4} = \frac{C_b}{C_{ox}} \cdot V_{b_4} \tag{6.89}$$

$$V_{sp} < V_{g_1}: \qquad V_{g_5} = \frac{C_{ox} \cdot V_{ox}^3}{Q_i \cdot RON_T \cdot I_{ohm}} \cdot \left(\frac{S_{spg}^3 - S_{adg}^3}{3}\right) \tag{6.90}$$

$$V_{sp} \geq V_{g_1}: \qquad V_{g_5} = 0 \tag{6.91}$$

$$V_{dp} \geq V_{g_1}: \qquad V_{g_6} = \frac{-8 \cdot C_{ox} \cdot V_{ox}^3}{Q_i \cdot RON_T \cdot I_{ohm}} \cdot \left(\frac{Y_{dpg}^3 - Y_{adg}^3}{3} + \frac{Y_{dpg}^4 - Y_{adg}^4}{4}\right) \tag{6.92}$$

$$V_{dp} < V_{g_1}: \qquad V_{g_6} = 0 \tag{6.93}$$

$$Q_{g_x} = -CGATE \cdot (V_{g_1} + V_{g_2} + V_{g_3} + V_{g_4} + V_{g_5} + V_{g_6}) \tag{6.94}$$

:

$$V_{g_1} \geq \left(\frac{V_{sp} + V_{dp}}{2}\right) : Q_{gy} = CGATE \cdot \left[V_{g_1} - \left(\frac{V_{sp} + V_{dp}}{2}\right)\right] \tag{6.95}$$

$$V_{g_1} < \left(\frac{V_{sp} + V_{dp}}{2}\right) : Q_{g_y} = \frac{2 \cdot CGATE \cdot [V_{g_1} - (V_{sp} + V_{dp})/2]}{1 + \sqrt{1 - \frac{V_{g_1} - (V_{sp} + V_{dp})/2}{V_{ox}}}} \tag{6.96}$$

$$Cg_{fix} = 0.01 \cdot CGATE + MULT \cdot 10^{-17} \tag{6.97}$$

$$Q_g = 0.99 \cdot \{F_c \cdot Q_{g_x} + (1 - F_c) \cdot Q_{g_y}\} + Cg_{fix} \cdot \{V_{g_1} - (V_d + V_s)/2\} \tag{6.98}$$

6.3.7 Drain and source charge model

$VP > 0$:

$$V_{g_1} \geq V_{sp} : Q_s = -C_{ox} \cdot V_{ox} \cdot S_{spg} \tag{6.99}$$

$$V_{g_1} < V_{sp} : Q_s = -2 \cdot C_{ox} \cdot V_{ox} \cdot Y_{spg} \tag{6.100}$$

$$Q_{spx} = Q_i + Q_s - 2 \cdot C_b \cdot VSUB_T \cdot Y_{spb} \tag{6.101}$$

$$T_{sp} = \frac{Q_{spx} + \sqrt{Q_{spx}^2 + \delta_q}}{2 \cdot q \cdot DCH} \tag{6.102}$$

$$I_{hc} = J_{sat} \cdot T_{sp} \tag{6.103}$$

$VP \leq 0$:

$$I_{hc} = VSAT_T / RON_T \tag{6.104}$$

$$Q_{ds} = sign \cdot TAUSC \cdot I_{hc} \left[\left\{ 1 + \left(\frac{|I_{ds}|}{I_{hc}} \right)^{2 \cdot PSAT} \right\}^{1/(2 \cdot PSAT)} - 1 \right] \tag{6.105}$$

$$Q_d = -0.5 \cdot (Q_g + Q_b + Q_{ds}) \tag{6.106}$$

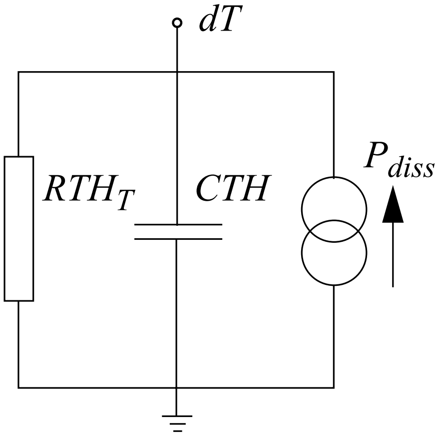
$$Q_s = -0.5 \cdot (Q_g + Q_b - Q_{ds}) \tag{6.107}$$

Numerical Adaptation

To implement MOS Model, level 3100 in a circuit simulator, care must be taken of the numerical stability of the simulation program. The functions as well as their derivatives should be continuous at any bias condition that may occur during the iteration cycle.

6.4 Self-heating

Self-heating is part of the model. It is defined in the usual way by adding a self-heating network (see Figure 16) containing a current source describing the dissipated power and both a thermal resistance R_{TH} and a thermal capacitance C_{TH}.



Material	ATH
Si	1.3
Ge	1.25
GaAs	1.25
AlAs	1.37
InAs	1.1
InP	1.4
GaP	1.4
SiO_2	0.7

Figure 16: On the left, the self-heating network, where the node voltage V_{dT} is used in the temperature scaling relations. Note that for increased flexibility the node dT is available to the user. On the right are parameter values that can be used for A_{th}.

The resistance and capacitance are both connected between ground and the temperature node d_T. The value of the voltage V_{dT} at the temperature node gives the increase in local temperature, which is included in the calculation of the temperature scaling relation (6.4), see section 6.3.2 on page 177.

For the value of *ATH* we recommend using values from literature that describe the temperature scaling of the thermal conductivity. For the most important materials, the values are given in Figure 16, which is largely based on Ref. [1], see also [2].

For example, if the value of V_{dT} is 0.5V, the increase in temperature is 0.5 degrees Celsius.

The total dissipated power is a sum of the dissipated power of each branch of the equivalent circuit and is given by:

$$P_{diss} = I_{DS} \cdot V_{DS}$$

The total dissipation applies for the geometrical model (mnt[1], mpt[2], mos3100t[3]).

Below a *Pstar* example is given to illustrate how self-heating works.

q **Example**

Title: example self-heating 3100;

```
circuit;
mnt_1(Vd, Vg, Vs, 0, dt) level=3100, Rth=1e6,Cth=1e-9;
R_1 ( Vdd, Vd) 100;
R_2 ( Vgg, Vg) 1k;
R_3 ( Vs, 0) 100;
e_SRC_2 (Vgg ,net101) 5;
e_SRC_1 ( Vdd, 0) 1;
e_SRC_3 ( net101, 0) 0;
end;

dc;
print: vn(dt), op(pdiss.mnt_1);
end; run;

result:
DC   Analysis.
VN(DT)               =    24.764E+00
Pdiss.MNT_1          =    24.764E-06
```

The voltage on node *dT* is 24.764e+0 V, which means that the local temperature is increased by 24.764e+0 ^{o}C.

1.*Pstar* model name.
2.*Pstar* model name.
3.*Spectre*/*ADS* model name.

6.5 DC Operating point output

The DC operating point output facility gives information on the state of a device at its operation point. Besides terminal currents and voltages, the magnitudes of linearized internal elements are given. In some cases meaningful quantities can be derived which are then also given (e.g. u). The objective of the DCOP-facility is twofold:

- Calculate small-signal equivalent circuit element values.

- Open a window on the internal bias conditions of the device and its basic capabilities (e.g. u).

Below the printed items are described. C_{xy} indicates the derivate of the charge Q at terminal x to the voltage at terminal y, when all other terminals remain constant.

Quantity	**Equation**	**Description**
Level	3100	Model level
I_{ds}	I_{ds}	Drain Source current
V_{ds}		Drain Source voltage
V_{gs}		Gate Source voltage
V_{bs}		Bulk Source voltage
V_p	V_p	Channel pinch-off voltage
g_m	dI_{ds}/dV_g	Transconductance
g_{mb}	dI_{ds}/dV_b	Bulk transconductance
g_{ds}	dI_{ds}/dV_d	Output conductance
Q_g		Gate charge
C_{gd}	$-dQ_g/dV_d$	Gate charge dependence on drain voltage
C_{gg}	dQ_g/dV_g	Gate charge dependence on gate voltage
C_{gs}	$-dQ_g/dV_s$	Gate charge dependence on source voltage
C_{gb}	$-dQ_g/dV_b$	Gate charge dependence on bulk voltage
Q_b		Bulk charge

C_{bd}	$-dQ_b/dV_d$	Bulk charge dependence on drain voltage
C_{bg}	$-dQ_b/dV_g$	Bulk charge dependence on gate voltage
C_{bs}	$-dQ_b/dV_s$	Bulk charge dependence on source voltage
C_{bb}	dQ_b/dV_b	Bulk charge dependence on bulk voltage
Q_d		Drain charge
C_{dd}	$+dQ_d/dV_d$	Drain charge dependence on drain voltage
C_{dg}	$-dQ_d/dV_g$	Drain charge dependence on gate voltage
C_{ds}	$-dQ_d/dV_s$	Drain charge dependence on source voltage
C_{db}	$-dQ_d/dV_b$	Drain charge dependence on bulk voltage
Q_s		Source charge
C_{sd}	$-dQ_s/dV_d$	Source charge dependence on drain voltage
C_{sg}	$-dQ_s/dV_g$	Source charge dependence on gate voltage
C_{ss}	$+dQ_s/dV_s$	Source charge dependence on source voltage
C_{sb}	$-dQ_s/dV_b$	Source charge dependence on bulk voltage
u	g_m/g_{ds}	Transistor gain
R_{out}	$1/g_{ds}$	Small signal output resistance
V_{early}	$\lvert I_{ds}\rvert/g_{ds}$	Equivalent Early voltage
I_{ohm}	I_{ohm}	Drain source current excluding velocity saturation
I_{hc}	I_{hc}	Critical current for velocity saturation.

The additional operating point output for the model including self-heating (see section 6.4) is listed in the table below.

Quantity	**Equation**	**Description**
T_K	T_K	Actual temperature including self-heating
P_{diss}	P_{diss}	Power dissipation

Remarks:

- When V_{ds}<0, g_m and g_{mb} are calculated with drain and source terminals interchanged (see section on Channel Type Declarations). The terminal voltages and I_{DS} keep their sign.

- The signs of V_p follow the conventions of the model parameter set. The parameter set is always assumed to correspond to an n-channel device.

- *MULT* is a scaling parameter that multiplies all currents and charges by the value of *MULT*. This is equivalent to putting *MULT* (a number) MOS transistors in parallel. And as a consequence *MULT* effects the operating point output.

- A non-existent conductance, G_{min}, is connected between the nodes *DS*. This conductance G_{min} does not influence the DC-operating point.

6.6 Simulator specific items

6.6.1 Pstar syntax

n channel : mn_n (d,g,s,b) level=3100, <parameters>
p channel : mp_n (d,g,s,b) level=3100, <parameters>
n channel self-heating : mnt_n (d,g,s,b, dt) level=3100, <parameters>
p channel self-heating : mpt_n (d,g,s,b, dt) level=3100, <parameters>

n : occurrence indicator
<parameters> : list of model parameters
d,g,s, b and dt are drain, gate, source, bulk and self-heating terminals respectively.

6.6.2 Spectre syntax

n channel : model modelname mos3100 type=n <modpar>
componentname d g s b modelname <inpar>
p channel : model modelname mos3100 type=p <modpar>
componentname d g s b modelname <inpar>
n channel self-heating: model modelname mos3100t type=n <modpar>
componentname d g s b dt modelname <inpar>
p channel self-heating: model modelname mos3100t type=p <modpar>
componentname d g s b dt modelname <inpar>

modelname : name of model, user-defined
componentname : occurrence indicator
<modpar> : list of model parameters
<inpar> : list of instance parameters
d,g,s, b and dt are drain, gate, source, bulk and self-heating terminals respectively.

3 Note

Warning! In Spectre, use only the parameter statements type=n or type=p. Using any other string and/or numbers will result in unpredictable and possibly erroneous results.

6.6.3 ADS syntax

n channel : model modelname mos3100 gender=1 <modpar>
modelname:componentname d g s b <instpar>
p channel : model modelname mos3100 gender=0 <modpar>
modelname:componentname d g s b <instpar>
n channel self-heating: model modelname mos3100t gender=1 <modpar>
modelname:componentname d g s b dt <instpar>
p channel self-heating: model modelname mos3100t gender=0 <modpar>
modelname:componentname d g s b dt <instpar>

modelname : name of model, user-defined
componentname : occurrence indicator
<modpar> : list of model parameters
<instpar> : list of instance parameters
d,g,s, b and dt are drain, gate, source, bulk and self-heating terminals respectively.

6.6.4 The ON/OFF condition for Pstar

The solution for a circuit involves a process of successive calculations. The calculations are started from a set of ‘initial guesses’ for the electrical quantities of the nonlinear elements. A simplified DCAPPROX mechanism for devices using ON/OFF keywords is mentioned in [3]. By default the devices start in the default state.

n-channel			
	Default	ON	OFF
V_{DS}	2.0	2.0	2.0
V_{GS}	-2.0	-2.0	-4.0
V_{SB}	0.0	0.0	2.0

p-channel			
	Default	ON	OFF
V_{DS}	-2.0	-2.0	-2.0
V_{GS}	2.0	2.0	4.0
V_{SB}	0.0	0.0	-2.0

6.6.5 The ON/OFF condition for Spectre

n-channel							
	OFF	Triode	Saturation	Subthreshold	Reverse	Forward	Breakdown
V_{DS}	0.0	0.75	1.25	0.0	0	0	0
V_{GS}	0.0	2.0	1.25	0.0	0	0	0
V_{SB}	0.0	0.0	0.0	0.0	0	0	0

p-channel							
	OFF	Triode	Saturation	Subthreshold	Reverse	Forward	Breakdown
V_{DS}	0.0	-0.75	-1.25	0.0	0	0	0
V_{GS}	0.0	-2.0	-1.25	0.0	0	0	0
V_{SB}	0.0	0.0	0.0	0.0	0	0	0

6.6.6 The ON/OFF condition for ADS

n-channel	
	Default
V_{DS}	0
V_{GS}	0
V_{SB}	0

p-channel	
	Default
V_{DS}	0
V_{GS}	0
V_{SB}	0

6.7 References

[1] V. Palankovski R. Schultheis and S. Selberherr, *Modelling of power heterojunction bipolar transistor on gallium arsenide,*IEEE Trans. Elec. Dev., vol 48, pp. 1264-1269, 2001. Note: the paper uses $\alpha = 1.65$ for Si, but $\alpha = 1.3$ goves a better fit: also, k_{300} for GaAs is closer to 40 than to the published value of 46 (Palankovski, personal communication).

[2] Sze, S.M., *Physics of semiconductor devices*, 2nd edition, John Wiley & Sons, Inc., New York, 1981

[3] **Pstar** User Manual.

A Hyp functions

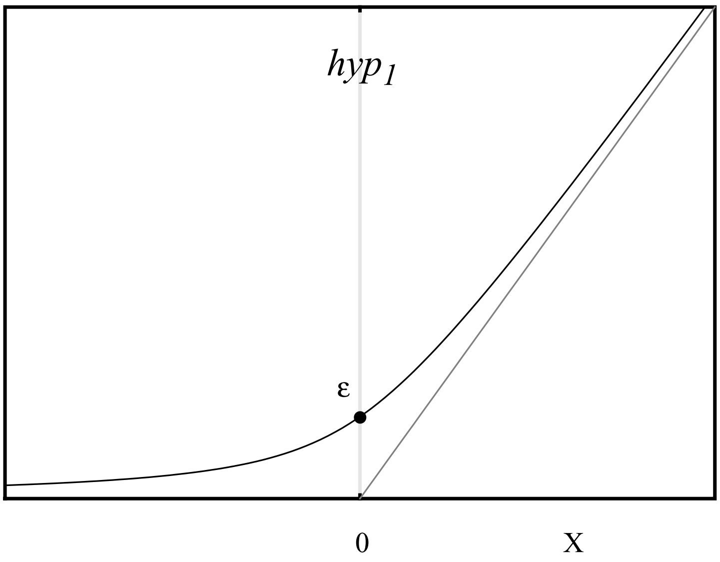


Figure 86: $hyp_1(x;\varepsilon) = \frac{1}{2} \cdot (x + \sqrt{x^2 + 4 \cdot \varepsilon^2})$

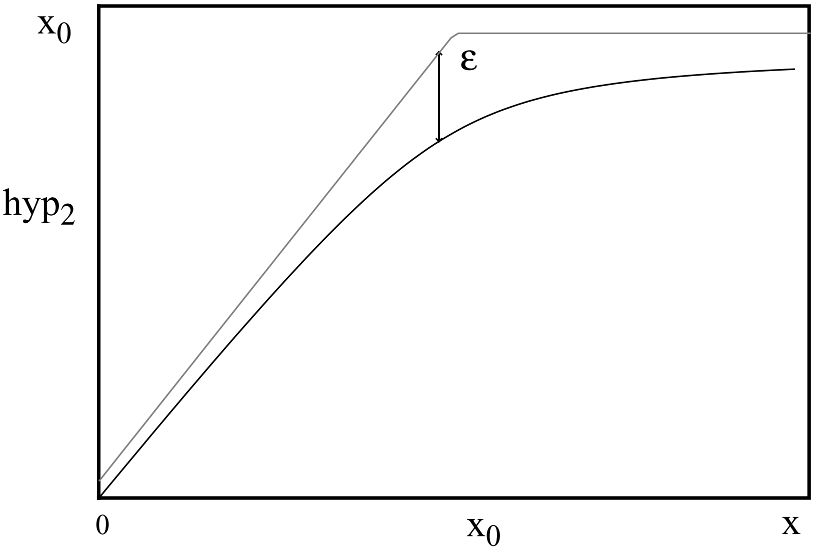


Figure 87: $hyp_2(x;x_0;\varepsilon) = x - hyp_1(x - x_0;\varepsilon)$

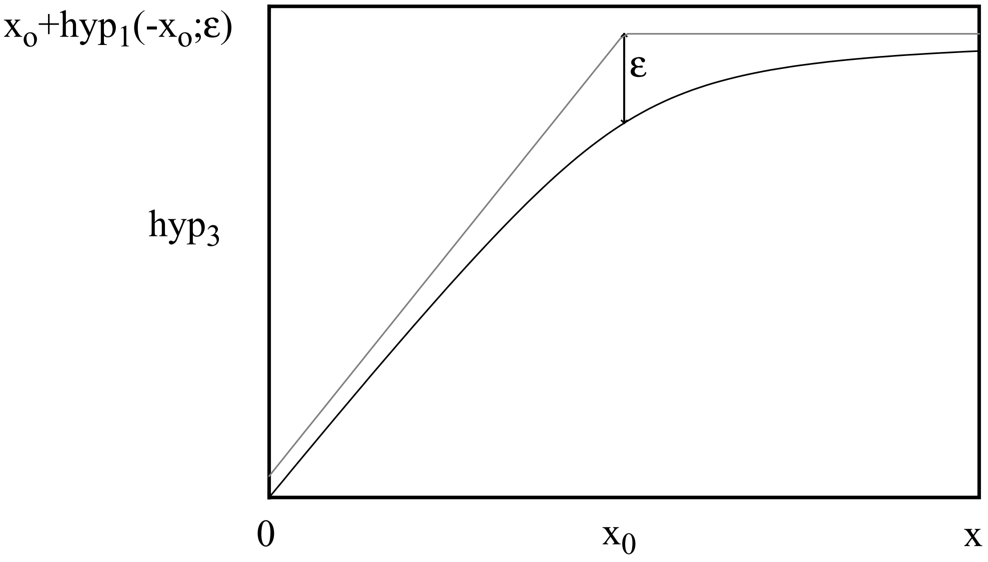


Figure 88: $hyp_3(x;x_0;\varepsilon) = hyp_2(x;x_0;\varepsilon) - hyp_2(0;x_0;\varepsilon) \qquad for\ \varepsilon = \varepsilon(x_0)$

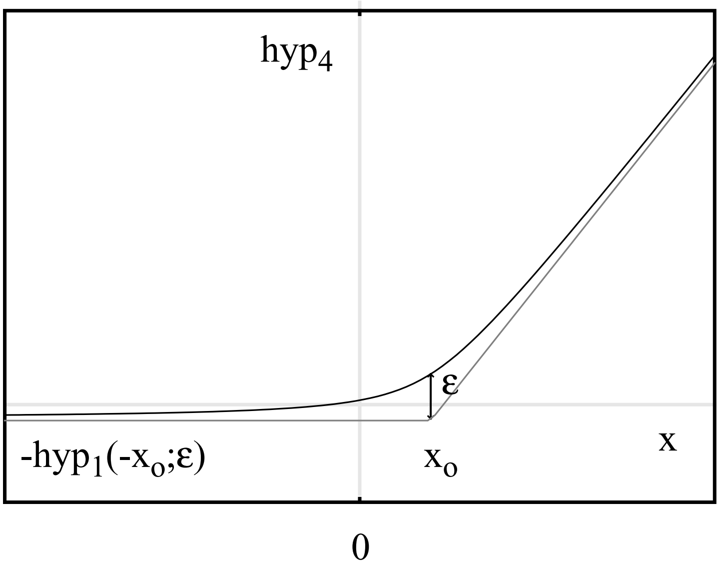


Figure 89: $hyp_4(x;x_0;\varepsilon) = hyp_1(x - x_0;\varepsilon) - hyp_1(-x_0;\varepsilon)$

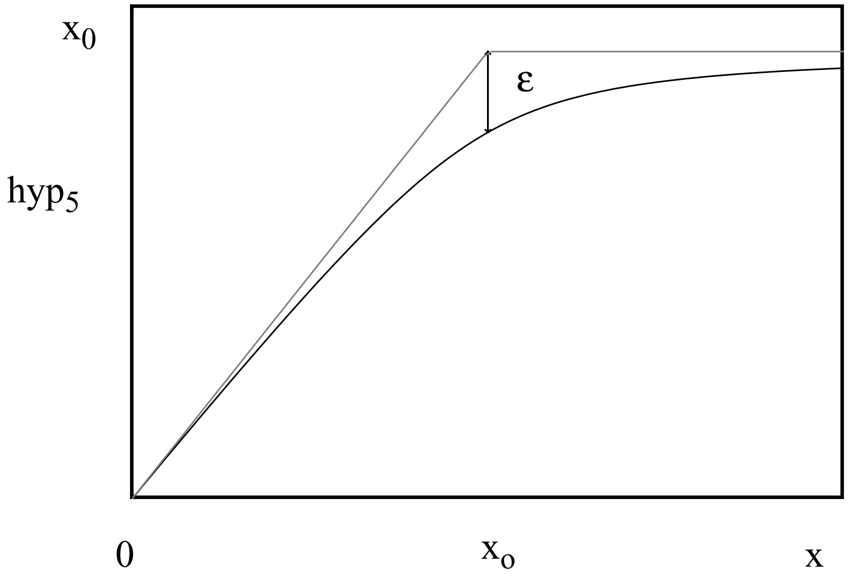


Figure 90: $hyp_5(x;x_0;\varepsilon) = x_0 - hyp_1\left(x_0 - x - \frac{\varepsilon^2}{x_0}, \varepsilon\right) \qquad for\ \varepsilon = \varepsilon(x_0)$

The hypm-function:

$$hypm[x, y; m] = \frac{x \cdot y}{(x^{2 \cdot m} + y^{2 \cdot m})^{1/(2 \cdot m)}} \tag{18.133}$$

B Spectre Specific Information

Imax, Imelt, Jmelt parameters

Introduction

Imax, Imelt and Jmelt are Spectre-specific parameters used to help convergence and to prevent numerical problems. We refer in this text only to the use of Imax model parameter in Spectre with SiMKit devices since the other two parameters, Imelt and Jmelt, are not part of the SiMKit code. For information on Imelt and Jmelt refer to Cadence documentation.

Imax model parameter

Imax is a model parameter present in the following SiMKit models:
– juncap and juncap2
– psp and pspnqs (since they contain juncap models)

In Mextram 504 (bjt504) and Modella (bjt500) SiMKit models, Imax is an internal parameter and its value is set through the adapter via the Spectre-specific parameter Imax.

In models that contain junctions, the junction current can be expressed as:

$$I = I_s \exp\left(\frac{V}{N \cdot \phi_{TD}} - 1\right) \tag{18.134}$$

The exponential formula is used until the junction current reaches a maximum (explosion) current Imax.

$$I_{max} = I_s \exp\left(\frac{V_{\exp l}}{N \cdot \phi_{TD}} - 1\right) \tag{18.135}$$

The corresponding voltage for which this happens is called Vexpl (explosion voltage). The voltage explosion expression can be derived from (1):

$$V_{\exp l} = N \cdot \phi_{TD} \log\left(\frac{I_{max}}{I_s}\right) + 1 \tag{18.136}$$

For $V > V_{\exp l}$ the following linear expression is used for the junction current:

$$I = I_{max} + (V - V_{\exp l})\frac{I_s}{N \cdot \phi_{TD}}\exp\left(\frac{V_{\exp l}}{N \cdot \phi_{TD}}\right) \qquad (18.137)$$

The default value of the Imax model parameter for SiMKit is 1000A. The default value of Imax for Mextram 504 and Modella is 1A. Imax should be set to a value which is large enough so it does not affect the extraction procedure.

Region parameter

Region is an Spectre-specific model parameter used as a convergence aid and gives an estimated DC operating region. The possible values of region depend on the model:

- For Bipolar models:
  - subth: Cut-off or sub-threshold mode
  - fwd: Forward
  - rev: Reverse
  - sat: Saturation.
  - off[1]
  -
- For MOS models:
  - subth: Cut-off or sub-threshold mode;
  - triode: Triode or linear region;
  - sat: Saturation
  - off[1]

For PSP and PSPNQS all regions are allowed, as the PSP(NQS) models both have a MOS part and a juncap (diode). Not all regions are valid for each part, but when e.g. region=forward is set, the initial guesses for the MOS will be set to zero. The same holds for setting a region that is not valid for the JUNCAP.

- For diode models:
  - fwd: Forward
  - rev: Reverse
  - brk: Breakdown
  - off[1]

---

[1] Off is not an electrical region, it just states that the user does not know in what state the device is operating

Model parameters for device reference temperature in Spectre

This text describes the use of the tnom, tref and tr model parameters in Spectre with SiMKit devices to set the device reference temperature.

A Simkit device in Spectre has three model parameter aliases for the model reference temperature, tnom, tref and tr. These three parameters can only be used in a model definition, not as instance parameters.

There is no difference in setting tnom, tref or tr. All three parameters have exactly the same effect. The following three lines are therefore completely equivalent:

```
model nmos11020 mos11020 type=n tnom=30
model nmos11020 mos11020 type=n tref=30
model nmos11020 mos11020 type=n tr=30
```

All three lines set the reference temperature for the mos11020 device to 30 C.

Specifying combinations of tnom, tref and tr in the model definition has no use, only the value of the last parameter in the model definition will be used. E.g.:

```
model nmos11020 mos11020 type=n tnom=30 tref=34
```

will result in the reference temperature for the mos11020 device being set to 34 C, tnom=30 will be overridden by tref=34 which comes after it.

When there is no reference temperature set in the model definition (so no tnom, tref or tr is set), the reference temperature of the model will be set to the value of tnom in the options statement in the Spectre input file. So setting:

```
options1 options tnom=23 gmin=1e-15 reltol=1e-12 \
    vabstol=1e-12 iabstol=1e-16
model nmos11020 mos11020 type=n
```

will set the reference temperature of the mos11020 device to 23 C.

When no tnom is specified in the options statement and no reference temperature is set in the model definition, the default reference temperature is set to 27 C.
So the lines:

```
options1 options gmin=1e-15 reltol=1e-12 vabstol=1e-12 \
    iabstol=1e-16
 model nmos11020 mos11020 type=n
```

will set the reference temperature of the mos11020 device to 27 C.

The default reference temperature set in the SiMKit device itself is in the Spectre simulator never used. It will always be overwritten by either the default "options tnom", an explicitly set option tnom or by a tnom, tref or tr parameter in the model definition.