5

MOS Model, level 3002 (Used for DMOS)

5.1 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. [1]

5.1.1 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

Not included in the model

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

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[1] 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.

5.2 Symbols, parameters and constants

The parameters are listed below .

No.	Parameter	Units	Description
1	*LEVEL*	-	Model level, must be set to 3002
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=0 no depletion and/or accumulation in the channel
7	*TOX*	cm	Gate oxide thickness $TOX > 0$ MOSFET device $TOX \leq 0$ No depletion and/or accumulation at the surface
8	*DCH*	cm^{-3}	Doping level channel
9	*DSUB*	cm^{-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	*KF*	–	Flickernoise coefficient
17	*AF*	–	Flickernoise exponent
18	*TREF*	°C	Reference temperature
19	*DTA*	°C	Difference of the device temperature to the ambient temperature $(T_{DEVICE} = T_{AMBIENT} + DTA)$
20	*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*

Divided by *MULT* are:

RON *RSAT*

Default and clipping values

The default values and clipping values as used for the MOS level 3002 model are listed below.

Position in list	Parameter name	Units	Default	Clip low	Clip high
1	*LEVEL*	-	3002	-	-
2	*RON*	Ω	1.00	1.00×10^{-6}	-
3	*RSAT*	Ω	1.00	1.00×10^{-6}	-
4	*VSAT*	V	10.00	1.00×10^{-6}	-
5	*PSAT*	–	1.00	0.0	-
6	*VP*	V	-1.00	-1.0	-
7	*TOX*	cm	-1.00	-1.0	0.01
8	*DCH*	cm^{-3}	1.00×10^{15}	1.00×10^{5}	1.00×10^{23}
9	*DSUB*	cm^{-3}	1.00×10^{15}	-1.0	1.00×10^{23}
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	*KF*	–	0.00	0.0	-
17	*AF*	–	1.00	0.1	-

Position in list	Parameter name	Units	Default	Clip low	Clip high
18	*TREF*	°C	25	-273.15	-
19	*DTA*	°C	0.00	-	-
20	*MULT*	–	1.00	0.0	-

5.2.1 Model constants

$$q = 1.6021918 \cdot 10^{-19}\mathrm{C} \tag{5.1}$$

$$\varepsilon_{si} = 1.036 \cdot 10^{-12}\mathrm{C/V \cdot cm} \tag{5.2}$$

$$\varepsilon_{ox} = 3.453 \cdot 10^{-13}\mathrm{C/V \cdot cm} \tag{5.3}$$

$$\left(\frac{k}{q}\right) = 0.86171 \times 10^{-4}\mathrm{V/K} \tag{5.4}$$

$$g_{min} = 10^{-15}\mathrm{A/V} \tag{5.5}$$

$$\delta_v = 10^{-8} \tag{5.6}$$

$$\delta_y = 10^{-5} \tag{5.7}$$

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

5.3 Model equations

5.3.1 Equivalent circuit and equations

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

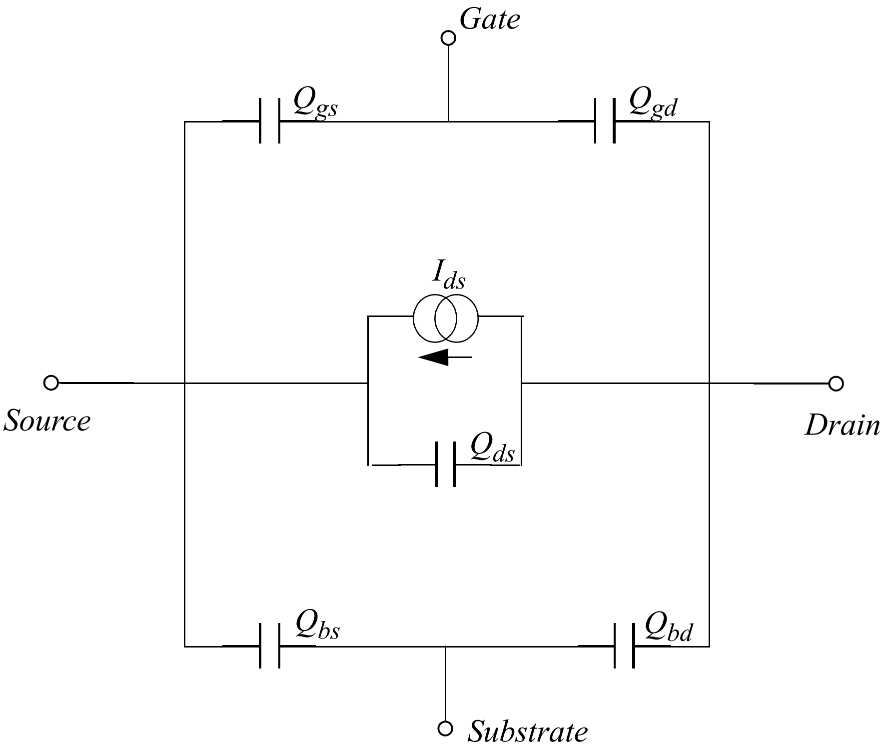

Figure 14: Equivalent Circuit of an JFET/MOSFET

5.3.2 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

$$T_K = TEMP + DTA + 273.15 \tag{5.8}$$

$$T_{RK} = TREF + 273.15 \tag{5.9}$$

$$T_N = \frac{T_K}{T_{RK}} \tag{5.10}$$

- Thermal Voltage

$$V_T = \left(\frac{k}{q}\right) \cdot T_K \tag{5.11}$$

- On resistance and saturation voltage

$$RON_T = RON \cdot T_N{}^{ACH} \tag{5.12}$$

$$VSAT_T = VSAT \cdot T_N{}^{ACH} \tag{5.13}$$

- Substrate depletion capacitance.

$$VSUB_T = -3 \cdot \left(\frac{k}{q}\right) \cdot T_K \cdot ln(T_N) + VSUB \cdot T_N + (1 - T_N) \cdot VGAP \tag{5.14}$$

$$CSUB_T = CSUB \cdot \left(\frac{VSUB}{VSUB_T}\right)^{0.5} \tag{5.15}$$

5.3.3 Model preprocessing

- Parameter dependent constants DC part

When $VP \le 0$ only equations 5.33, 5.59, 5.58, 5.67, 5.68, 5.110 and 5.111 are used. In this case the charges Q_b and Q_g are equal zero.

$DSUB > 0$

$$k_b = \sqrt{\frac{2 \cdot \varepsilon_{si} \cdot q \cdot DSUB \cdot DCH}{DSUB + DCH}} \tag{5.16}$$

$DSUB \le 0$

$$k_b = 0 \tag{5.17}$$

$$Q_{bp} = k_b \cdot (\sqrt{VP + VSUB_T} - \sqrt{VSUB_T}) \tag{5.18}$$

$$V_{si} = \frac{\varepsilon_{si} \cdot q \cdot DCH}{2} \cdot \left(\frac{TOX}{\varepsilon_{ox}}\right)^2 \tag{5.19}$$

$TOX > 0$

$$k_s = \sqrt{2 \cdot \varepsilon_{si} \cdot q \cdot DCH} \tag{5.20}$$

$TOX \le 0$

$$k_s = 0 \tag{5.21}$$

$$Q_{sp} = k_s \cdot (\sqrt{VP + V_{si}} - \sqrt{V_{si}}) \tag{5.22}$$

$$Q_i = Q_{bp} + Q_{sp} \tag{5.23}$$

$$T_s = \frac{Q_i}{q \cdot DCH} \tag{5.24}$$

$$k_{b1} = \frac{k_b \cdot \sqrt{VSUB_T}}{Q_i \cdot RON_T} \tag{5.25}$$

$$k_{b2} = \frac{2 \cdot k_b}{3 \cdot Q_i \cdot RON_T} \tag{5.26}$$

$$k_{s1} = \frac{k_s \cdot \sqrt{V_{si}}}{Q_i \cdot RON_T} \tag{5.27}$$

$$k_{s2} = \frac{2/3 \cdot k_s}{Q_i \cdot RON_T} \tag{5.28}$$

$TOX > 0$

$$k_{s3} = \frac{\varepsilon_{ox}}{TOX} \tag{5.29}$$

$TOX \leq 0$

$$k_{s3} = 0 \tag{5.30}$$

$$k_{s4} = \frac{k_{s3}}{Q_i \cdot RON_T} \tag{5.31}$$

$$J_{sat} = \frac{VSAT_T}{T_s \cdot RON_T} \tag{5.32}$$

$$VR_{sat} = RSAT \cdot J_{sat} \cdot T_s \tag{5.33}$$

$$\delta_q = 10^{-2} \cdot Q_i^2 \tag{5.34}$$

- Parameter dependent constants substrate charge model

$DSUB > 0$

$$kq_{b1} = \frac{2 \cdot \sqrt{VSUB_T}}{RON_T} \tag{5.35}$$

$$kq_{b2} = -kq_{b1} \cdot k_b / Q_i \tag{5.36}$$

$$kq_{b3} = kq_{b1} \cdot k_{s3} / Q_i \tag{5.37}$$

$$kq_{b4} = kq_{b1} \cdot k_s / Q_i \tag{5.38}$$

- Parameter dependent constants gate charge model

$TOX > 0$

$$kq_{g1} = \frac{CGATE}{RON_T} \tag{5.39}$$

$$kq_{g2} = \frac{-CGATE \cdot k_s}{RON_T \cdot k_{s3}} \tag{5.40}$$

$$kq_{g3} = \frac{CGATE \cdot k_b}{RON_T \cdot Q_i} \tag{5.41}$$

$$kq_{g4} = \frac{CGATE \cdot k_b \cdot k_s}{RON_T \cdot Q_i \cdot k_{s3}} \tag{5.42}$$

$$kq_{g5} = \frac{CGATE \cdot k_{s3}}{3 \cdot RON_T \cdot Q_i} \tag{5.43}$$

$$kq_{g6} = \frac{-CGATE \cdot k_s^2}{RON_T \cdot Q_i \cdot k_{s3}} \tag{5.44}$$

5.3.4 Model evaluation

Drain and source voltage

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

$$V_{d1} = V_d$$

$$V_{s1} = V_s$$

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

$$V_{d1} = V_s$$

$$V_{s1} = V_d$$

- Pinch-off voltage

$DSUB \leq 0$ $\quad V_p = VP + V_g \quad (5.45)$

$TOX \leq 0$ $\quad V_p = VP + V_b \quad (5.46)$

$TOX > 0 \text{ \& } DSUB > 0$

$$V_{b_{sw}} = V_g + VSUB_T - (Q_i / k_b + \sqrt{VSUB_T})^2 \quad (5.47)$$

$$Q_m = Q_i + k_s \cdot \sqrt{V_{si}} + k_b \cdot \sqrt{VSUB_T} \quad (5.48)$$

$$V_{g_{SW}} = V_b - VSUB_T + V_{si} - (Q_m / k_s)^2 \quad (5.49)$$

$V_b > V_{b_{sw}} \text{ \& } V_g > V_{g_{SW}}$

$$b_p = \frac{k_b \cdot Q_m}{k_s^2 - k_b^2} \quad (5.50)$$

$$c_p = \frac{Q_m^2 + k_s^2 \cdot (V_g - V_b + VSUB_T - V_{si})}{k_s^2 - k_b^2} \tag{5.51}$$

$$V_p = V_b - VSUB_T + 2 \cdot b_p^2 + c_p - 2 \cdot b_p \cdot \sqrt{b_p^2 + c_p}$$

(5.52)

$$V_b > V_{b_{sw}} \ \& \ V_g \le V_{g_{SW}}$$

$$V_p = V_g - V_{s_i} + (Q_m / k_s)^2 \tag{5.53}$$

$$V_b \le V_{b_{sw}}$$

$$b_{ac} = V_g + (Q_i + k_b \cdot \sqrt{VSUB_T}) / k_{s_3} + \left(\frac{k_b}{2 \cdot k_{s3}}\right)^2 \tag{5.54}$$

$$V_p = b_{ac} + \left(\frac{k_b}{2 \cdot k_{s3}}\right)^2 - \frac{k_b}{k_{s3}} \cdot \sqrt{b_{ac} + VSUB_T - V_b} \tag{5.55}$$

- Source and drain voltage including pinch-off

$$VP > 0\text{:}\ V_{sp} = 1/2 \cdot [V_{s1} + V_p - \sqrt{(V_{s1} - V_p)^2 + \delta_v}] \tag{5.56}$$

$$VP \le 0\text{:}\ V_{sp} = V_{s1} \tag{5.57}$$

$$VP > 0\text{: } V_c = VSAT_T + V_p - V_{sp} - \sqrt{{VSAT_T}^2 + (V_p - V_{sp})^2} \tag{5.58}$$

$$VP \leq 0\text{: } V_c = VSAT_T \tag{5.59}$$

$$V_{dp} = V_{sp} + \frac{(V_{d1} - \dot{V}_{s1}) \cdot V_c}{\sqrt[PSAT]{(V_{d1} - V_{s1})^{PSAT} + V_c^{PSAT}}} \tag{5.60}$$

Current reduction due to substrate effect

$$V_{db} = \frac{1}{2} \cdot [V_{dp} + VSUB_T - V_b + \sqrt{(V_{dp} + VSUB_T - V_b)^2 + \delta_v}] \tag{5.61}$$

$$V_{sb} = \frac{1}{2} \cdot [V_{sp} + VSUB_T - V_b + \sqrt{(V_{sp} + VSUB_T - V_b)^2 + \delta_v}] \tag{5.62}$$

$$I_{bd} = k_{b1} \cdot (V_{dp} - V_{sp}) - k_{b2} \cdot ({V_{db}^{3/2}} - {V_{sb}^{3/2}}) \tag{5.63}$$

- Current increase due to accumulation

$$V_{sp} < V_g: \qquad \begin{array}{l} V_{dp} < V_g \;\; V_{ad} = V_{dp} \\ V_{dp} \geq V_g \;\; V_{ad} = V_g \end{array}$$

$$I_{sa} = k_{s4} \cdot \left(V_g(V_{ad} - V_{sp}) - \frac{1}{2} \cdot (V_{ad}^2 - V_{sp}^2) \right) \tag{5.64}$$

$$V_{sp} \geq V_g: \qquad \begin{array}{l} V_{ad} = V_{sp} \\ I_{sa} = 0 \end{array}$$

- Current reduction due to depletion at the surface

$$V_{dp} \geq V_g: \quad I_{sd} = k_{s1} \cdot (V_{dp} - V_{ad}) - k_{s2} \cdot [(V_{si} + V_{dp} - V_g)^{3/2} - (V_{si} + V_{ad} - V_g)^{3/2}] \tag{5.65}$$

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

- Total ohmic current

$$VP > 0: \quad I_{ohm} = \frac{V_{dp} - V_{sp}}{RON_T} + I_{bd} + I_{sa} + I_{sd} \tag{5.66}$$

$$VP \leq 0: \quad I_{ohm} = \frac{V_{dp} - V_{sp}}{RON_T} \tag{5.67}$$

- Total current including velocity saturation

$$I_{ds} = sign \cdot I_{ohm} \cdot \left(1 + \frac{V_{d1} - V_{dp}}{VR_{sat}}\right) + g_{min} \cdot (V_d - V_s) \tag{5.68}$$

- Substrate charge model

$$F_c = \frac{\exp\{(V_p - V_{sp})/V_t\} - 1}{\exp\{(V_p - V_{sp})/V_t\}} \cdot \frac{V_{dp} - V_{sp}}{1 \cdot 10^{-3} + V_{dp} - V_{sp}} \tag{5.69}$$

$$V_{gb} = V_g - V_{sp} + V_{sb} \tag{5.70}$$

Calculation of Q_{bx}

$$Q_{b1} = \frac{kq_{b1}}{I_{ohm}} \cdot \left(\frac{2}{3} \cdot (V_{db}^{3/2} - V_{sb}^{3/2}) - \sqrt{VSUB_T} \cdot (V_{dp} - V_{sp})\right) \tag{5.71}$$

$$Q_{b2} = \frac{kq_{b2}}{I_{ohm}} \cdot \left[\frac{1}{2} \cdot (V_{db}^2 - V_{sb}^2) + VSUB_T \cdot (V_{dp} - V_{sp}) \right. \tag{5.72}$$
$$\left. - \frac{4}{3} \cdot \sqrt{VSUB_T} \cdot (V_{db}^{3/2} - V_{sb}^{3/2})\right]$$

For $TOX \leq 0$: $Qb3 = Qb4 = 0$ (5.73)

For TOX>0:

$V_{sp} < V_g$: $V_{dp} < V_g$ $V_{ab} = V_{db}$

$V_{dp} \geq V_g$ $V_{ab} = V_{gb}$

$$Q_{b3} = \frac{kq_{b3}}{I_{ohm}} \cdot \left[\frac{2}{3} \cdot V_{gb} \cdot (V_{ab}^{3/2} - V_{sb}^{3/2}) - \frac{2}{5} \cdot (V_{ab}^{5/2} - V_{sb}^{5/2}) + \right.$$
$$\left. \frac{1}{2} \cdot \sqrt{VSUB_T} \cdot \{(V_g - V_{ad})^2 - (V_g - V_{sp})^2\}\right] \tag{5.74}$$

$V_{sp} \geq V_g$: $V_{ab} = V_{sb}$

$$Q_{b3} = 0 \tag{5.75}$$

$V_{dp} < V_g$: $Q_{b4} = 0$ (5.76)

$V_{dp} \geq V_g$ $z_0 = 1/4 \cdot (V_{gb} - V_{si})^2$ (5.77)

$$z_{0d} = 1/4 \cdot (V_g - V_{dp} + V_{db} - V_{si})^2 \tag{5.78}$$

$$z_1 = 1/2 \cdot (V_{db} + V_{dp} - V_g + V_{si}) \tag{5.79}$$

$$z_2 = 1/2 \cdot (V_{ab} + V_{ad} - V_g + V_{si}) \tag{5.80}$$

$$f(z,z_0) = \frac{z}{2} \cdot \sqrt{z^2 - z_0} - \frac{z_0}{2} \cdot \ln\left(z + \sqrt{z^2 - z_0}\right) \tag{5.81}$$

$$\begin{aligned} Q_{b4} = {} & \frac{kq_{b4}}{I_{ohm}} \cdot \left[\frac{2}{3} \cdot \sqrt{V_{si}} \cdot \left(V_{db}^{3/2} - V_{ab}^{3/2}\right) - f(z_1,z_{0d}) + f(z_2,z_0) + \right. \\ & \frac{2}{3} \cdot \sqrt{VSUB_T} \cdot \{(V_{dp} - V_g + V_{si})^{3/2} - (V_{ad} - V_g + V_{si})^{3/2}\} - \\ & \left. \sqrt{VSUB_T} \cdot \sqrt{V_{si}} \cdot (V_{dp} - V_{ad})\right] \end{aligned} \tag{5.82}$$

$$Q_{bx} = -CSUB_T \cdot (Qb1 + Qb2 + Qb3 + Qb4) \tag{5.83}$$

Calculation of Q_{by}:

$$V_{spy} = 1/2 \cdot \left\{V_{s1} + V_p - \sqrt{(V_{s1} - V_p)^2 + \delta_y}\right\} \tag{5.84}$$

$$V_{dpy} = 1/2 \cdot \left\{V_{d1} + V_p - \sqrt{(V_{d1} - V_p)^2 + \delta_y}\right\} \tag{5.85}$$

$$V_{sby} = 1/2 \cdot \left\{V_{spy} + VSUB_T - V_b + \sqrt{(V_{spy} + VSUB_T - V_b)^2 + \delta_y}\right\} \tag{5.86}$$

$$V_{dby} = 1/2 \cdot \left\{V_{dpy} + VSUB_T - V_b + \sqrt{(V_{dpy} + VSUB_T - V_b)^2 + \delta_y}\right\} \tag{5.87}$$

$$Q_{by} = -2 \cdot CSUB_T \cdot \sqrt{VSUB_T} \cdot \left[\sqrt{\left(\frac{V_{sby} + V_{dby}}{2}\right)} - \sqrt{VSUB_T}\right] \tag{5.88}$$

Calculation of *Q_b*:

$$Q_b = Q_{by} + F_c \cdot (Q_{bx} - Q_{by}) \tag{5.89}$$

$$Qb_s = 1/2 \cdot Qb \tag{5.90}$$

$$Qb_d = 1/2 \cdot Qb \tag{5.91}$$

Gate charge model

$$Qg_1 = kq_{g1} \cdot \frac{(V_g - V_{ad})^2 - (V_g - V_{sp})^2}{2 \cdot I_{ohm}} \tag{5.92}$$

$$\begin{aligned} Qg_2 = {} & kq_{g2} \cdot \frac{\sqrt{V_{si}} \cdot (V_{dp} - V_{ad})}{I_{ohm}} \\ & - kq_{g2} \cdot \frac{2/3 \cdot [(V_{dp} - V_g + V_{si})^{3/2} - (V_{ad} - V_g + V_{si})^{3/2}]}{I_{ohm}} \end{aligned} \tag{5.93}$$

$$DSUB \le 0 \qquad Qg_3 = Qg_4 = 0 \tag{5.94}$$

For $DSUB > 0$:

$$Qg_3 = kq_{g3} \cdot (Qb3)/kq_{b3} \tag{5.95}$$

$$Qg_4 = kq_{g4} \cdot (Qb4)/kq_{b4} \tag{5.96}$$

$$Qg_5 = kq_{g5} \cdot \frac{(V_g - V_{ad})^3 - (V_g - V_{sp})^3}{I_{ohm}} \tag{5.97}$$

$$Qg_6 = \frac{kq_{g6}}{I_{ohm}} \cdot \left[\frac{(2 \cdot V_{si} - V_g + V_{dp})^2 - (2 \cdot V_{si} - V_g + V_{ad})^2}{2}\right.$$

$$\left. - \frac{4 \cdot \sqrt{V_{si}} \cdot \{(V_{dp} - V_g + V_{si})^{3/2} - (V_{ad} - V_g + V_{si})^{3/2}\}}{3}\right] \tag{5.98}$$

$$Q_{gx} = -(Qg_1 + Qg_2 + Qg_3 + Qg_4 + Qg_5 + Qg_6) \tag{5.99}$$

When $V_g \geq \left(\frac{V_{spy} + V_{dpy}}{2}\right)$

$$Q_{gy} = CGATE \cdot \left(V_g - \left(\frac{V_{spy} + V_{dpy}}{2}\right)\right) \tag{5.100}$$

When $V_g < \left(\frac{V_{spy} + V_{dpy}}{2}\right)$

$$Q_{gy} = \frac{CGATE \cdot k_s}{k_{s3}} \cdot \left(\sqrt{V_{si}} - \sqrt{\left(\frac{V_{spy} + V_{dpy}}{2}\right) + V_{si} - V_g}\right) \tag{5.101}$$

$$Q_g = Q_{gy} + F_c \cdot (Q_{gx} - Q_{gy}) \tag{5.102}$$

$$Qg_s = 1/2 \cdot Q_g \tag{5.103}$$

$$Qg_d = 1/2 \cdot Q_g \tag{5.104}$$

Note: if $I_{ohm} \le 0$, then $F_c = 0$ and $Q_g = Q_{gy}$

Space charge in the channel

- Width of the channel at source side

$$VP > 0$$

$$V_g \ge V_{sp}: \qquad Q_s = k_{s3} \cdot (V_g - V_{sp}) \tag{5.105}$$

$$V_g < V_{sp}: \qquad Q_s = -k_s \cdot \sqrt{V_{sp} - V_g + V_{si}} + k_s \cdot \sqrt{V_{si}} \tag{5.106}$$

$$Q_{spx} = Q_i + Q_s - k_b \cdot \sqrt{V_{sb}} + k_b \cdot \sqrt{VSUB_T} \tag{5.107}$$

$$T_{sp} = \frac{Q_{spx} + \sqrt{Q_{spx}^2 + \delta_q}}{2 \cdot q \cdot DCH} \tag{5.108}$$

- Critical current for hot-carriers

$$VP > 0.: \qquad I_{hc} = J_{sat} \cdot T_{sp} \tag{5.109}$$

$$VP \le 0.: \qquad I_{hc} = VSAT_T / RON_T \tag{5.110}$$

$$Q_{ds} = sign \cdot TAUSC \cdot I_{hc}\left[\left\{1 + \left(\frac{|I_{ds}|}{I_{hc}}\right)^{2 \cdot PSAT}\right\}^{1/(2 \cdot PSAT)} - 1\right] \tag{5.111}$$

Numerical Adaptations

To implement MOS Model, level 3002 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.

Numerical Problems and Solutions

- Problem I. Eqs. 5.69.

F_c must be set to zero when I_{ohm} gets close to zero or even negative. This prevents divisions by zero in het substrate charge model.

5.3.5 Numerical Adaptation

To implement the model in a circuit simulator, care must be taken of the numerical stability of the simulation program. A non-existent conductance, G_{min}, is connected between the nodes *DS*. The value of the conductance is 10^{-15} [1/Ω].

5.4 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. $C_{x(y)}$ 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	3002	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
$C_{g(d)}$	$-dQ_g/dV_d$	Gate charge dependence on drain voltage
$C_{g(g)}$	dQ_g/dV_g	Gate charge dependence on gate voltage
$C_{g(b)}$	$-dQ_g/dV_b$	Gate charge dependence on bulk voltage
Q_b		Bulk charge
$C_{b(d)}$	$-dQ_b/dV_d$	Bulk charge dependence on drain voltage

$C_{b(g)}$	$-dQ_b/dV_g$	Bulk charge dependence on gate voltage
$C_{b(b)}$	$+dQ_b/dV_b$	Bulk 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

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.

5.5 Simulator specific items

5.5.1 Pstar syntax

n channel : mn_n(d,g,s,b) level=3002, <parameters>
p channel : mp_n(d,g,s,b) level=3002, <parameters>

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

5.5.2 Spectre syntax

n channel : model modelname mos3002 type=n <modpar>
componentname d g s b modelname <inpar>
p channel : model modelname mos3002 type=p <modpar>
componentname d g s b modelname <inpar>

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

✓ 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.

5.5.3 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 [1]. 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_{BS}	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_{BS}	0.0	0.0	2.0

5.5.4 The ON/OFF condition for Spectre

	OFF	Triode	Saturation	Subthreshold
Gds	0.0	1e-4	1e-4	1e-4

5.6 References

[1] **Pstar** User Manual.