9 MOS model 20, level 2002

9.1 Introduction

General Remarks

MOS Model 20 (MM20) is a new compact MOSFET model, intended for analogue circuit simulation in high-voltage MOS technologies. MOS Model 20 describes the electrical behaviour of the region under the thin gate oxide of a high-voltage MOS device, like a Lateral Double-diffused MOS (LDMOS) device or an extended-drain MOSFET; see Figure 1. It thus combines the MOSFET-operation of the channel region with that of the drift region under the thin gate oxide in a high-voltage MOS device. As such, MOS Model 20 is aimed as a successor of the combination of MOS Model 9 (MM9) [1] for the channel region in series with MOS Model 31 (MM31) [1] for the drift region under the thin gate oxide, in macro models of various high-voltage MOS devices.

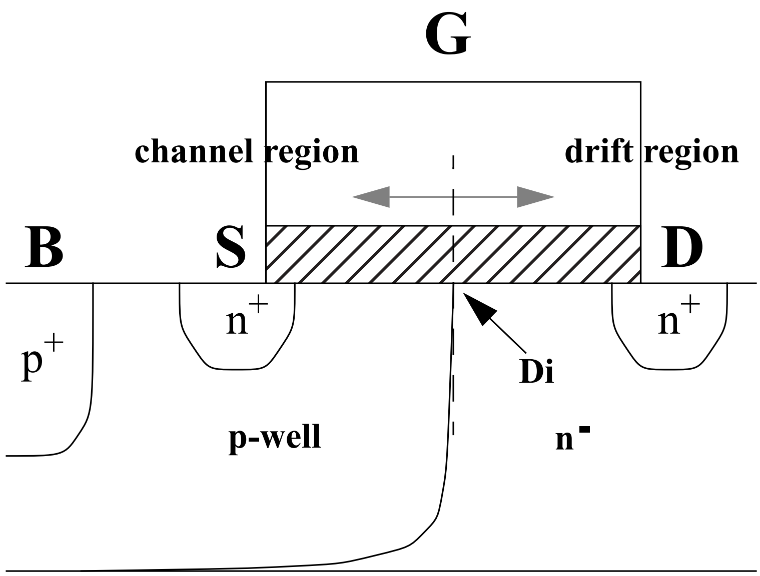


Figure 1: The region under the thin gate oxide of an n-channel LDMOS device, described by MOS Model 20.

The model is based on the Silicon-on-Insulator (SOI)-LDMOS model developed by the University of Southampton [2]. MOS Model 20 has especially been developed to improve the convergence behaviour during circuit simulation, by having the voltage at the transition Di from the channel region to the drift region calculated inside the model itself.

MOS Model 20 gives a complete description of all transistor-action related quantities: nodal currents, nodal charges and noise-power spectral densities. The equations describing these quantities are based on surface-potential formulations, resulting in equations valid over all operation regimes (i.e. accumulation, depletion and inversion in both the channel region and the drift region). The surface potential as function of the terminal voltages is obtained by the explicit expression as derived in [3] and used in MOS Model 11 (MM11), level 1101 [4]. Additionally, several important physical effects have been included in the model: mobility reduction, velocity saturation, drain-induced barrier lowering, static feedback, channel length modulation and weak-avalanche (or impact ionization).

MOS Model 20 only provides a model for the intrinsic MOSFET behaviour of the region under the thin gate oxide of a high-voltage MOS device, as well as the gate/source- and gate/drain overlap regions. Junction charges, junction leakage currents, interconnect capacitances and parasitic bipolar transistors are not included; they should be covered by separate models. For instance, to describe the electrical behaviour due to the pn-junction between the backgate (B) and drain (D), an additional diode model for this pn-junction has to be added; see Figure 2. Furthermore, for very high-voltage MOS transistors with an additional thick field oxide, like in Figure 3, MOS Model 20 can be used in series with a separate model for the drift region under the thick field oxide. In the case of the SOI-LDMOS transistor in Figure 3, MOS Model 40 (MM40) [1] has been used to model the part of the drift region underneath the thick oxide. Finally, self-heating of the device, which may significantly affect the electrical behaviour, should be incorporated externally via a thermal network.

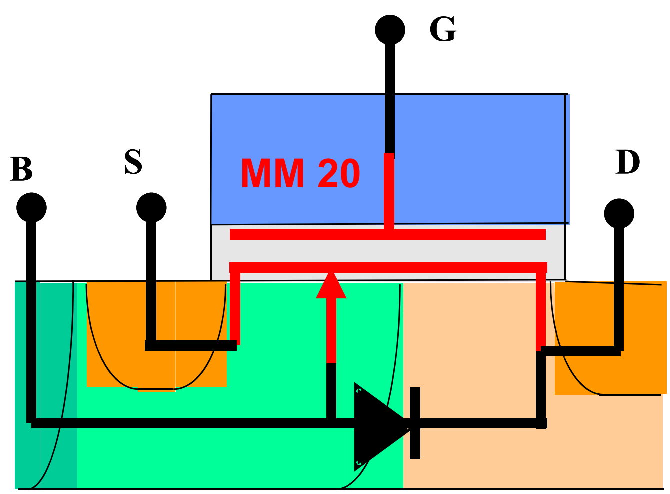


Figure 2: Macro model for an LDMOS transistor.

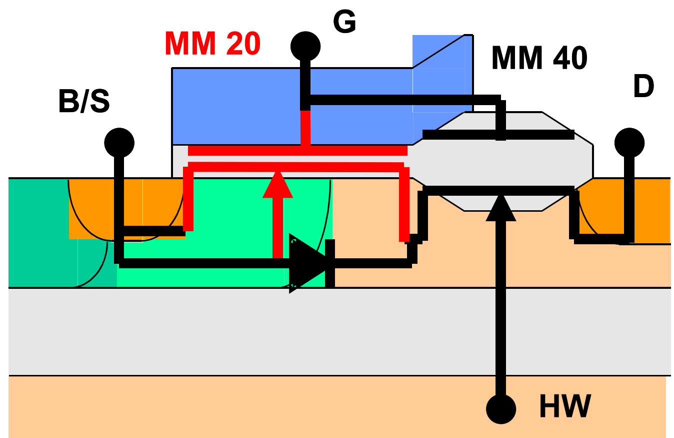


Figure 3: Macro model for an SOI-LDMOS transistor with a thick field oxide.

- Structural Elements of MOS Model 20

The structure of MOS Model 20 is the same as the structure of MOS Model 9 and MOS Model 11. This structure can be divided into:

- **Model embedding**

It is convenient to use one single model for both *n*- and *p*-channel devices. For this reason, any *p*-channel device and its bias conditions are mapped onto those of an equivalent *n*-channel transistor. This mapping comprises a number of sign changes. Since a DMOS transistor in an asymmetric device, no source drain interchange is applied in case the external voltage mapped onto an n-channel transistor is negative. Thus, in MOS Model 20, the dc-currents and charges are calculated by use of the externally applied voltages mapped onto an equivalent *n*-channel transistor.

- **Preprocessing**

The complete set of all the parameters, as they occur in the equations for the various electrical quantities, is denoted as the set of actual parameters. Since most of these actual parameters scale with temperature and since self-heating is significant for high-voltage devices, each of them can be determined by electrical measurements over a range of temperatures. The set of electrical parameters at a reference temperature including the temperature scaling parameters and reference temperature itself, is denoted by the “miniset”. This miniset forms the input for the so-called electrical model, from which the actual parameters for an arbitrary temperature are obtained by applying the temperature scaling rules. These temperature scaling rules thus describe the dependencies of the actual parameters on the temperature of the device.

Since most of the electrical parameters also scale with geometry, the process as a whole is characterized by an enlarged set of parameters, usually called the “maxiset”. This “maxiset” consists of the transistor dimensions, the electrical parameters for certain device dimensions at a reference temperature, the reference temperature itself, and all temperature- and geometry scaling parameters. Together they form the input for the so-called geometrical model. From the maxiset parameters the actual parameters for an arbitrary transistor are obtained by applying the temperature and geometry scaling rules. These scaling rules thus describe the dependencies of the actual parameters on the drift region length, device width, and temperature of the device.

Since the application of the scaling rules is done only once, i.e. prior to the actual electrical simulation, this procedure is called preprocessing.

- **Clipping**

To prevent the scaling rules from generating actual parameters that are outside a physically realistic range or that create numerical difficulties, like division by zero, the actual parameters may be clipped to a pre-specified range. This clipping of actual parameters is done after the preprocessing. The pre-specified clipping range for the actual parameters is taken as in the electrical model parameter list in Section 9.3.3.

Furthermore, in order to prevent numerical difficulties in the preprocessing procedure, the model parameters of both the electrical and geometrical model may also be clipped to a pre-specified range. This clipping of model parameters is done *before* the preprocessing. The pre-specified clipping ranges for both the electrical and geometrical model parameters are taken as in the geometrical model parameter list in Section 9.3.2.

- **Current equations**

These are all expressions needed to obtain the DC nodal currents as a function of the bias conditions. They are segmentable in equations for the channel current, and the avalanche current.

- **Charge equations**

These are all the equations that are used to calculate both the intrinsic and extrinsic charge quantities, which are assigned to the nodes. They are segmentable in equations for the channel region charges, and the drift region charges.

- **Noise equations**

The total noise output of a transistor consists of a thermal noise and a flicker noise part, which create fluctuations in the channel current. Owing to the capacitive coupling between gate and channel region, current fluctuations in the gate current are induced as well, which are referred to as induced gate noise.

9.2 Physics

9.3 Symbols, parameters and constants

9.3.1 Input Variables and Quantities

List of Numerical Constants

Constant	Prog. Name	Value
A	LN_MINDOUBLE	-800

List of Physical Constants

Constant	Program Name	Value	Units
T_0	KELVIN_CONVERSION	273.15	K
Offset for conversion from Celcius to Kelvin temperature scale			
k_B	K_BOLTZMANN	$1.3806226 \cdot 10^{-23}$	JK^{-1}
Boltzmann constant			
q	Q_ELECTRON	$1.6021918 \cdot 10^{-19}$	C
Elementary unit charge			
ε_{ox}	PHY_EPSOX	$3.4531438 \cdot 10^{-11}$	Fm^{-1}
Absolute permittivity of the oxide layer			

List of circuit simulator variables

Symbol	Prog. Name	Units	Description
T_a	TA	°C	Ambient circuit temperature
f	F	Hz	Operation frequency

9.3.2 Geometrical Model

To characterize a high-voltage MOS process as a whole, the geometrical model can be used. This model uses as input the actual transistor dimensions, the electrical parameters for a reference device dimension and temperature, the reference temperature, and all temperature- and geometry scaling parameters, together referred to as the “maxiset”. The model parameters of the geometrical model and the scaling rules are listed in this section. For simplicity, in the geometrical MOS Model 20 both the *n*-channel and *p*-channel devices have been assigned the same default parameter values.

List of Geometrical Model Parameters

Parameter	Symbol	Units	Meaning
LEVEL	level	-	Must be 2002
PARAMCHK	-	-	Level of clip warning info *)
W	W	m	Drawn width of the channel region
WVAR	ΔW	m	Width offset of the channel region
WD	W_D	m	Drawn width of the drift region
WDVAR	ΔW_D	m	Width offset of the drift region
TREF	T_{ref}	°C	Reference temperature
VFB	V_{FB}	V	Flatband voltage of the channel region, at reference temperature
STVFB	$S_{T;V_{FB}}$	VK^{-1}	Temperature scaling coefficient for V_{FB}
VFBD	V_{FBD}	V	Flatband voltage of the drift region, at reference temperature
STVFBD	$S_{T;V_{FBD}}$	VK^{-1}	Temperature scaling coefficient for V_{FBD}
KOR	k_{0R}	$V^{1/2}$	Body factor of the channel region of an infinitely wide transistor
SWKO	$S_{W;k_0}$	-	Width scaling coefficient for k_0
KODR	k_{0DR}	$V^{1/2}$	Body factor of the drift region of an infinitely wide transistor
SWKOD	$S_{W;k_{0D}}$	-	Width scaling coefficient for k_{0D}
PHIB	ϕ_B	V	Surface potential at the onset of strong inversion in the channel region, at reference temperature
STPHIB	$S_{T;\phi_B}$	VK^{-1}	Temperature scaling coefficient for ϕ_B
PHIBD	ϕ_{BD}	V	Surface potential at the onset of strong inversion in the drift region, at reference temperature

Parameter	Symbol	Units	Meaning
STPHIBD	$S_{T;\phi_{BD}}$	VK^{-1}	Temperature scaling coefficient for ϕ_{BD}
BETW	β_W	AV^{-2}	Gain factor of a channel region of $1\,\mu m$ wide, at reference temperature
ETABET	η_β	-	Temperature scaling exponent for β
BETACCW	β_{acc_W}	AV^{-2}	Gain factor of a drift region of $1\,\mu m$ wide, at reference temperature
ETABETACC	$\eta_{\beta_{acc}}$	-	Temperature scaling exponent for β_{acc}
RDW	R_{DW}	Ω	On-resistance of a drift region of $1\,\mu m$ wide, at reference temperature
ETARD	η_{R_D}	-	Temperature scaling exponent for R_D
LAMD	λ_D	-	Quotient of the depletion layer thickness to the effective thickness of the drift region at $V_{SB} = 0V$
THEIR	θ_{1R}	V^{-1}	Mobility reduction coefficient of an infinitly wide transistor, due to vertical strong-inversion field in channel region
SWTHE1	$S_{W;\theta_1}$	-	Width scaling coefficient for θ_1
THE1ACC	θ_{1acc}	V^{-1}	Mobility reduction coefficient in the drift region due to the vertical electrical field caused by accumulation
THE2R	θ_{2R}	$V^{-1/2}$	Mobility reduction coefficient for $V_{SB} > 0$ of an infinitly wide transistor, due to the vertical depletion field in the channel region
SWTHE2	$S_{W;\theta_2}$	-	Width scaling coefficient for θ_2
THE3R	θ_{3R}	V^{-1}	Mobility reduction coefficient in a channel region of an infinitly wide transistor, due to velocity saturation
ETATHE3	η_{θ_3}	-	Temperature scaling coefficient for θ_3

Parameter	Symbol	Units	Meaning
SWTHE3	$S_{W;\theta_3}$	-	Width scaling coefficient for θ_3
MEXP	m	-	Smoothing factor for transition from linear to saturation regime
THE3DR	θ_{3DR}	V^{-1}	Mobility reduction coefficient in the drift region of an infinitly wide transistor, due to velocity saturation
ETATHE3D	$\eta_{\theta_{3D}}$	-	Temperature scaling coefficient for θ_{3D}
SWTHE3D	$S_{W;\theta_{3D}}$	-	Width scaling coefficient for θ_{3D}
MEXPD	m_D	-	Smoothing factor for transition from linear to quasi-saturation regime
ALP	α	-	Factor for channel length modulation
VP	V_p	V	Characteristic voltage of channel length modulation
SDIBL	σ_{dibl}	$V^{-1/2}$	Factor for drain-induced barrier lowering
MSDIBL	$m_{\sigma_{dibl}}$	-	Exponent for the drain-induced barrier lowering dependence on the backgate bias
MO	m_0	V	Parameter for the (short-channel) sub-threshold slope
SSF	σ_{sf}	$V^{-1/2}$	Factor for static feedback
A1CHR	a_{1chR}	-	Factor of weak avalanche current of an infinitely wide transistor, at reference temperature, accounting for contribution of channel region to the total avalanche current
STA1CH	$S_{T;a_{1ch}}$	K^{-1}	Temperature scaling coefficient for a_{1ch}
SWA1CH	$S_{W;a_{1ch}}$	-	Width scaling coefficient for a_{1ch}
A2CH	a_{2ch}	V	Exponent of weak avalanche current, related to channel
A3CH	a_{3ch}	-	Factor of the internal drain-source voltage above which weak avalanche occurs

Parameter	**Symbol**	**Units**	**Meaning**
A1DRR	$a_{1dr\mathrm{R}}$	-	Factor of weak avalanche current of an infinitely wide transistor, at reference temperature, accounting for contribution of drift region to the total avalanche current
STA1DR	$S_{T;a_{1dr}}$	K^{-1}	Temperature scaling coefficient for a_{1dr}
SWA1DR	$S_{W;a_{1dr}}$	-	Width scaling coefficient for a_{1dr}
A2DR	a_{2dr}	V	Exponent of weak avalanche current, related to drift
A3DR	a_{3dr}	-	Factor of the drain-source voltage above which weak avalanche occurs
COXW	C_{oxW}	F	Oxide capacitance for an intrinsic channel region of $1\,\mu m$ wide
COXDW	C_{oxDW}	F	Oxide capacitance for an intrinsic drift region of $1\,\mu m$ wide
CGDOW	C_{GDOW}	F	Gate-to-drain overlap capacitance for a drift region of $1\,\mu m$ wide
CGSOW	C_{GSOW}	F	Gate-to-source overlap capacitance for a drift region of $1\,\mu m$ wide
NT	N_T	J	Coefficient of thermal noise, at reference temperature
NFAW	N_{fA_W}	$V^{-1}m^{-4}$	First coefficient of flicker noise for a channel region of $1\,\mu m$ wide
NFBW	N_{fB_W}	$V^{-1}m^{-2}$	Second coefficient of flicker noise for a channel region of $1\,\mu m$ wide
NFCW	N_{fC_W}	V^{-1}	Third coefficient of flicker noise for a channel region of $1\,\mu m$ wide
TOX	t_{ox}	m	Thickness of the oxide above the channel region
DTA	ΔT_a	K	Temperature offset to the ambient temperature

The additional parameters for the model including self-heating are listed below.

No.	Parameter	Symbol	Units	Meaning
64	RTH	R_{TH}	^{o}C/W	Thermal resistance
65	CTH	C_{TH}	J/^{o}C	Thermal capacitance
66	ATH	A_{TH}	-	Thermal coefficient of the thermal resistance

The additional parameter MULT for all level - 2002 models is listed in the table below.

No.	Parameter	Symbol	Units	Meaning
67	MULT	M	-	Number of devices in parallel

*) See Appendix D for the definition of PARAMCHK.

Default and Clipping Values of Geometrical Model Parameters

Parameter	Symbol	Units	Default	Clip low	Clip high
LEVEL	level	-	2002	-	-
PARAMCHK	-	-	0	-	-
W	W	m	20×10^{-6}	1.0×10^{-9}	-
WVAR	ΔW	m	0	-	-
WD	W_D	m	20×10^{-6}	1.0×10^{-9}	-
WDVAR	ΔW_D	m	0	-	-
TREF	T_{ref}	°C	25	-273	-
VFB	V_{FB}	V	-1.0	-	-
STVFB	$S_{T;V_{FB}}$	VK^{-1}	0	-	-
VFBD	V_{FBD}	V	-0.1	-	-
STVFBD	$S_{T;V_{FBD}}$	VK^{-1}	0	-	-
KOR	k_{0R}	$V^{1/2}$	1.6	-	-
SWKO	$S_{W;k_0}$	-	0	-	-
KODR	k_{0DR}	$V^{1/2}$	1.0	-	-
SWKOD	$S_{W;k_{0D}}$	-	0	-	-
PHIB	ϕ_B	V	0.86	-	-
STPHIB	$S_{T;\phi_B}$	VK^{-1}	-1.2×10^{-3}	-	-
PHIBD	ϕ_{BD}	V	0.78	-	-
STPHIBD	$S_{T;\phi_{BD}}$	VK^{-1}	-1.2×10^{-3}	-	-
BETW	β_W	AV^{-2}	7.0×10^{-5}	-	-
ETABET	η_β	-	1.6	-	-

Parameter	**Symbol**	**Units**	**Default**	**Clip low**	**Clip high**
BETACCW	β_{accW}	AV^{-2}	7.0×10^{-5}	-	-
ETABETACC	$\eta_{\beta_{acc}}$	-	1.5	-	-
RDW	R_{DW}	Ω	4.0×10^{3}	-	-
ETARD	η_{R_D}	-	1.5	-	-
LAMD	λ_D	-	0.2	-	-
THE1R	θ_{1R}	V^{-1}	0.09	-	-
SWTHE1	$S_{W;\theta_1}$	-	0	-	-
THE1ACC	θ_{1acc}	V^{-1}	0.02	-	-
THE2R	θ_{2R}	$V^{-1/2}$	0.03	-	-
SWTHE2	$S_{W;\theta_2}$	-	0	-	-
THE3R	θ_{3R}	V^{-1}	0.4	-	-
ETATHE3	η_{θ_3}	-	1.0	-	-
SWTHE3	$S_{W;\theta_3}$	-	0	-	-
MEXP	m	-	2.0	-	-
THE3DR	θ_{3DR}	V^{-1}	0.0	-	-
ETATHE3D	$\eta_{\theta_{3D}}$	-	1.0	-	-
SWTHE3D	$S_{W;\theta_{3D}}$	-	0	-	-
MEXPD	m_D	-	2.0	-	-
ALP	α	-	2.0×10^{-3}	-	-
VP	V_p	V	0.05	-	-
SDIBL	σ_{dibl}	$V^{-1/2}$	1.0×10^{-3}	-	-

Parameter	Symbol	Units	Default	Clip low	Clip high
MSDIBL	$m_{\sigma_{dibl}}$	-	3.0	-	-
MO	m_0	V	0.0	-	-
SSF	σ_{sf}	$V^{-1/2}$	1.0×10^{-12}	-	-
A1CHR	a_{1chR}	-	1.5×10^{1}	-	-
STA1CH	$S_{T;a_{1ch}}$	K^{-1}	0	-	-
SWA1CH	$S_{W;a_{1ch}}$	-	0	-	-
A2CH	a_{2ch}	V	7.3×10^{1}	-	-
A3CH	a_{3ch}	-	0.8	-	-
A1DRR	$a_{1dr\mathrm{R}}$	-	1.5×10^{1}	-	-
STA1DR	$S_{T;a_{1dr}}$	K^{-1}	0	-	-
SWA1DR	$S_{W;a_{1dr}}$	-	0	-	-
A2DR	a_{2dr}	V	7.3×10^{1}	-	-
A3DR	a_{3dr}	-	0.8	-	-
COXW	C_{oxW}	F	0.75×10^{-15}	-	-
COXDW	C_{oxDW}	F	0.75×10^{-15}	-	-
CGDOW	C_{GDOW}	F	0	-	-
CGSOW	C_{GSOW}	F	0	-	-
NT	N_T	J	1.645×10^{-20}	-	-
NFAW	N_{fA_W}	$V^{-1}m^{-4}$	1.4×10^{25}	-	-
NFBW	N_{fB_W}	$V^{-1}m^{-2}$	2.0×10^{8}	-	-
NFCW	N_{fC_W}	V^{-1}	0	-	-

Parameter	Symbol	Units	Default	Clip low	Clip high
TOX	t_{ox}	m	3.8×10^{-8}	-	-
DTA	ΔT_a	K	0	-	-

The additional values and clipping values of the additional parameters for the model including self-heating are listed in the table below.

Parameter	Symbol	Units	Default	Clip low	Clip high
RTH	R_{TH}	^{o}C/W	300.0	0.000	-
CTH	C_{TH}	J/^{o}C	3.0×10^{-9}	0.000	-
ATH	A_{TH}	-	0.0	-	-

The additional parameter MULT for all level - 2001 models is listed in the table below.

Parameter	Symbol	Units	Default	Clip low	Clip high
MULT	M	-	1.0	0	-

Geometery and Temperature scaling

Effective temperature and dimensions:

$$T_{Kamb} = T_0 + T_a + \Delta T_a \tag{9.1}$$

$$T_{Kdev} = T_0 + T_a + \Delta T_a + V_{dT} \tag{9.2}$$

$$T_{Kref} = T_0 + T_{ref} \tag{9.3}$$

$$\Delta T = T_{Kdev} - T_{Kref} \tag{9.4}$$

$$W_E = W + \Delta W \tag{9.5}$$

$$W_{ED} = W_D + \Delta W_D \tag{9.6}$$

$$W_{EN} = 1.0 \times 10^{-6}(m) \tag{9.7}$$

Actual parameters:

$$\phi_T = \frac{k_B \cdot T_{Kdev}}{q} \tag{9.8}$$

$$V_{FBT} = V_{FB} + \Delta T \cdot S_{T;V_{FB}} \tag{9.9}$$

$$V_{FBDT} = V_{FBD} + \Delta T \cdot S_{T;V_{FBD}} \tag{9.10}$$

$$k_0 = k_{0R} \cdot \left(1 + \frac{W_{EN}}{W_E} \cdot S_{W;k_0}\right) \tag{9.11}$$

$$k_{0D} = k_{0DR} \cdot \left(1 + \frac{W_{EN}}{W_{ED}} \cdot S_{W;k_{0D}}\right) \tag{9.12}$$

$$\phi_{BT} = \phi_B + \Delta T \cdot S_{T;\phi_B} \tag{9.13}$$

$$\phi_{BDT} = \phi_{BD} + \Delta T \cdot S_{T;\phi_{BD}} \tag{9.14}$$

$$\beta_T = \beta_W \cdot \frac{W_E}{W_{EN}} \cdot \left(\frac{T_{Kref}}{T_{Kdev}}\right)^{\eta_\beta} \tag{9.15}$$

$$\beta_{acc_T} = \beta_{accW} \cdot \frac{W_{ED}}{W_{EN}} \cdot \left(\frac{T_{Kref}}{T_{Kdev}}\right)^{\eta_{\beta_{acc}}} \tag{9.16}$$

$$R_{DT} = R_{DW} \cdot \frac{W_{EN}}{W_{ED}} \cdot \left(\frac{T_{Kdev}}{T_{Kref}}\right)^{\eta_{R_D}} \tag{9.17}$$

$$\theta_1 = \theta_{1R} \cdot \left(1 + \frac{W_{EN}}{W_E} \cdot S_{W;\theta_1}\right) \tag{9.18}$$

$$\theta_2 = \theta_{2R} \cdot \left(1 + \frac{W_{EN}}{W_E} \cdot S_{W;\theta_2}\right) \tag{9.19}$$

$$\theta_{3T} = \theta_{3R} \cdot \left(\frac{T_{Kref}}{T_{Kdev}}\right)^{\eta_{\theta_3}} \cdot \left(1 + \frac{W_{EN}}{W_E} \cdot S_{W;\theta_3}\right) \tag{9.20}$$

$$\theta_{3DT} = \theta_{3DR} \cdot \left(\frac{T_{Kref}}{T_{Kdev}}\right)^{\eta_{\theta_{3D}}} \cdot \left(1 + \frac{W_{EN}}{W_{ED}} \cdot S_{W;\theta_{3D}}\right) \tag{9.21}$$

$$a_{1chT} = a_{1chR} \cdot (1 + \Delta T \cdot S_{T;a_{1ch}}) \cdot \left(1 + \frac{W_{EN}}{W_E} \cdot S_{W;a_{1ch}}\right) \tag{9.22}$$

$$a_{1drT} = a_{1drR} \cdot (1 + \Delta T \cdot S_{T;a_{1dr}}) \cdot \left(1 + \frac{W_{EN}}{W_{ED}} \cdot S_{W;a_{1dr}}\right) \tag{9.23}$$

$$C_{ox} = C_{oxW} \cdot \frac{W_E}{W_{EN}} \tag{9.24}$$

$$C_{oxD} = C_{oxDW} \cdot \frac{W_{ED}}{W_{EN}} \tag{9.25}$$

$$C_{GDO} = C_{GDOW} \cdot \frac{W_{ED}}{W_{EN}} \tag{9.26}$$

$$C_{GSO} = C_{GSOW} \cdot \frac{W_E}{W_{EN}} \tag{9.27}$$

$$N_{T_T} = N_T \cdot \frac{T_{Kdev}}{T_{Kref}} \tag{9.28}$$

$$N_{fA} = N_{fA_W} \cdot \frac{W_{EN}}{W_E} \tag{9.29}$$

$$N_{fB} = N_{fB_W} \cdot \frac{W_{EN}}{W_E} \tag{9.30}$$

$$N_{fC} = N_{fC_W} \cdot \frac{W_{EN}}{W_E} \tag{9.31}$$

$$R_{TH_T} = R_{TH} \cdot \left(\frac{T_{Kamb}}{T_{Kref}}\right)^{A_{TH}} \tag{9.32}$$

9.3.3 Electrical Model

To characterize a single LDMOS device including self-heating effects, the electrical model can be used. This model uses as input the electrical parameters for a reference temperature, the reference temperature, and all temperature- scaling parameters, together referred to as the “miniset”. The model parameters of the electrical model and the temperature scaling rules are listed in this section. For simplicity, in the electrical MOS Model 20 both the *n*-channel and *p*-channel devices have been assigned the same default parameter values.

List of Electrical Model Parameters

Parameter	Symbol	Units	Meaning
LEVEL	level	-	Must be 2002
PARAMCHK	-	-	Level of clip warning info *)
TREF	T_{ref}	°C	Reference temperature
VFB	V_{FB}	V	Flatband voltage of the channel region, at reference temperature
STVFB	$S_{T;V_{FB}}$	VK^{-1}	Temperature scaling coefficient for V_{FB}
VFBD	V_{FBD}	V	Flatband voltage of the drift region, at reference temperature
STVFBD	$S_{T;V_{FBD}}$	VK^{-1}	Temperature scaling coefficient for V_{FBD}
KO	k_0	$V^{1/2}$	Body factor of the channel region
KOD	k_{0D}	$V^{1/2}$	Body factor of the drift region
PHIB	ϕ_B	V	Surface potential at the onset of strong inversion in the channel region, at reference temperature
STPHIB	$S_{T;\phi_B}$	VK^{-1}	Temperature scaling coefficient for ϕ_B
PHIBD	ϕ_{BD}	V	Surface potential at the onset of strong inversion in the drift region, at reference temperature
STPHIBD	$S_{T;\phi_{BD}}$	VK^{-1}	Temperature scaling coefficient for ϕ_{BD}
BET	β	AV^{-2}	Gain factor of the channel region, at reference temperature
ETABET	η_β	-	Temperature scaling exponent for β
BETACC	β_{acc}	AV^{-2}	Gain factor for accumulation in the drift region, at reference temperature
ETABETACC	$\eta_{\beta_{acc}}$	-	Temperature scaling exponent for β_{acc}
RD	R_D	Ω	On-resistance of the drift region, at reference temperature

Parameter	**Symbol**	**Units**	**Meaning**
ETARD	η_{R_D}	-	Temperature scaling exponent for R_D
LAMD	λ_D	-	Quotient of the depletion layer thickness at $V_{SB} > 0$, to the effective thickness of the drift region at $V_{SB} = 0V$
THE1	θ_1	V^{-1}	Mobility reduction coefficient in channel region due to vertical electrical field caused by strong inversion
THE1ACC	θ_{1acc}	V^{-1}	Mobility reduction coefficient in the drift region due to the vertical electrical field caused by accumulation
THE2	θ_2	$V^{-1/2}$	Mobility reduction coefficient at $V_{SB} > 0$ in the channel region due to the vertical electical field caused by depletion
THE3	θ_3	V^{-1}	Mobility reduction coefficient in the channel region due to the horizontal electical field caused by velocity saturation
ETATHE3	η_{θ_3}	-	Temperature scaling coefficient for θ_3
MEXP	m	-	Smoothing factor for transition from linear to saturation regime
THE3D	θ_{3D}	V^{-1}	Mobility reduction coefficient in the drift region due to the horizontal electical field caused by velocity saturation
ETATHE3D	$\eta_{\theta_{3D}}$	-	Temperature scaling coefficient for θ_{3D}
MEXPD	m_D	-	Smoothing factor for transition from linear to quasi-saturation regime
ALP	α	-	Factor for channel length modulation
VP	V_p	V	Characteristic voltage of channel length modulation
SDIBL	σ_{dibl}	$V^{-1/2}$	Factor for drain-induced barrier lowering
MSDIBL	$m_{\sigma_{dibl}}$	-	Exponent for the drain-induced barrier lowering dependence on the backgate bias

Parameter	Symbol	Units	Meaning
MO	m_0	V	Parameter for the (short-channel) sub-threshold slope
SSF	σ_{sf}	$V^{-1/2}$	Factor for static feedback
A1CH	a_{1ch}	-	Factor of weak avalanche current, at reference temperature, accounting for contribution of channel region to the total avalanche current
STA1CH	$S_{T;a_{1ch}}$	K^{-1}	Temperature scaling coefficient for a_{1ch}
A2CH	a_{2ch}	V	Exponent of weak avalanche current, related to channel
A3CH	a_{3ch}	-	Factor of the internal drain-source voltage above which weak avalanche occurs
A1DR	a_{1dr}	-	Factor of weak avalanche current, at reference temperature, accounting for contribution of channel region to the total avalanche current
STA1DR	$S_{T;a_{1dr}}$	K^{-1}	Temperature scaling coefficient for a_{1dr}
A2DR	a_{2dr}	V	Exponent of weak avalanche current, related to drift
A3DR	a_{3dr}	-	Factor of the internal drain-source voltage above which weak avalanche occurs
COX	C_{ox}	F	Oxide capacitance for the intrinsic channel region
COXD	C_{oxD}	F	Oxide capacitance for the intrinsic drift region
CGDO	C_{GDO}	F	Gate to drain overlap capacitance
CGSO	C_{GSO}	F	Gate to source overlap capacitance
NT	N_T	J	Coefficient of thermal noise, at reference temperature
NFA	N_{fA}	$V^{-1}m^{-4}$	First coefficient of flicker noise

Parameter	Symbol	Units	Meaning
NFB	N_{fB}	$V^{-1}m^{-2}$	Second coefficient of flicker noise
NFC	N_{fC}	V^{-1}	Third coefficient of flicker noise
TOX	t_{ox}	m	Thickness of the oxide above the channel region
DTA	ΔT_a	K	Temperature offset to the ambient temperature

The additional parameters for the model including self-heating are listed in the table below.

Parameter	Symbol	Units	Meaning
RTH	R_{TH}	$^oC/W$	Thermal resistance
CTH	C_{TH}	$J/^oC$	Thermal capacitance
ATH	A_{TH}	-	Thermal coefficient of the thermal resistance

The additional parameter MULT for all level - 2002 models is listed in the table below.

Parameter	Symbol	Units	Meaning
MULT	M	-	Number of devices in parallel

*) See Appendix D for the definition of PARAMCHK.

Default and Clipping Values of Electrical Model Parameters

Parameter	Symbol	Units	Default	Clip low	Clip high
LEVEL	level	-	2002	-	-
PARAMCHK	-	-	0	-	-
TREF	T_{ref}	°C	25	-273	-
VFB	V_{FB}	V	-1.0	-	-
STVFB	$S_{T;V_{FB}}$	VK^{-1}	0	-	-
VFBD	V_{FBD}	V	-0.1	-	-
STVFBD	$S_{T;V_{FBD}}$	VK^{-1}	0	-	-
KO	k_0	$V^{1/2}$	1.6	1.0×10^{-12}	-
KOD	k_{0D}	$V^{1/2}$	1.0	1.0×10^{-12}	-
PHIB	ϕ_B	V	0.86	1.0×10^{-12}	-
STPHIB	$S_{T;\phi_B}$	VK^{-1}	-1.2×10^{-3}	-	-
PHIBD	ϕ_{BD}	V	0.78	1.0×10^{-12}	-
STPHIBD	$S_{T;\phi_{BD}}$	VK^{-1}	-1.2×10^{-3}	-	-
BET	β	AV^{-2}	1.4×10^{-3}	1.0×10^{-12}	-
ETABET	η_β	-	1.6	-	-
BETACC	β_{acc}	AV^{-2}	1.4×10^{-3}	1.0×10^{-12}	-
ETABETACC	$\eta_{\beta_{acc}}$	-	1.5	-	-
RD	R_D	Ω	2.0×10^{2}	1.0×10^{-12}	-
ETARD	η_{R_D}	-	1.5	-	-
LAMD	λ_D	-	0.2	1.0×10^{-12}	-
THE1	θ_1	V^{-1}	0.09	0	-

Parameter	Symbol	Units	Default	Clip low	Clip high
THE1ACC	θ_{1acc}	V^{-1}	0.02	0	-
THE2	θ_2	$V^{-1/2}$	0.03	0	-
THE3	θ_3	V^{-1}	0.4	0	-
ETATHE3	η_{θ_3}	-	1.0	-	-
MEXP	m	-	2.0	0.05	-
THE3D	θ_{3D}	V^{-1}	0.0	0	-
ETATHE3D	$\eta_{\theta_{3D}}$	-	1.0	-	-
MEXPD	m_D	-	2.0	0.05	-
ALP	α	-	2.0×10^{-3}	0	-
VP	V_p	V	0.05	1.0×10^{-12}	-
SDIBL	σ_{dibl}	$V^{-1/2}$	1.0×10^{-3}	0	-
MSDIBL	$m_{\sigma_{dibl}}$	-	3.0	0	-
MO	m_0	V	0.0	0	0.5
SSF	σ_{sf}	$V^{-1/2}$	1.0×10^{-12}	1.0×10^{-12}	-
A1CH	a_{1ch}	-	1.5×10^{1}	0	-
STA1CH	$S_{T;a_{1ch}}$	K^{-1}	0	-	-
A2CH	a_{2ch}	V	7.3×10^{1}	1.0×10^{-12}	-
A3CH	a_{3ch}	-	0.8	0	-
A1DR	a_{1dr}	-	1.5×10^{1}	0	-
STA1DR	$S_{T;a_{1dr}}$	K^{-1}	0	-	-
A2DR	a_{2dr}	V	7.3×10^{1}	1.0×10^{-12}	-

Parameter	Symbol	Units	Default	Clip low	Clip high
A3DR	a_{3dr}	-	0.8	0	-
COX	C_{ox}	F	15×10^{-15}	0	-
COXD	C_{oxD}	F	15×10^{-15}	0	-
CGDO	C_{GDO}	F	0	0	-
CGSO	C_{GSO}	F	0	0	-
NT	N_T	J	1.645×10^{-20}	0	-
NFA	N_{fA}	$V^{-1}m^{-4}$	7.0×10^{23}	0	-
NFB	N_{fB}	$V^{-1}m^{-2}$	1.0×10^{7}	0	-
NFC	N_{fC}	V^{-1}	0	0	-
TOX	t_{ox}	m	3.8×10^{-8}	1.0×10^{-12}	-
DTA	ΔT_a	K	0	-	-

The additional values and clipping values of the additional parameters for the model including self-heating are listed in the table below.

Parameter	Symbol	Units	Default	Clip low	Clip high
RTH	R_{TH}	$^oC/W$	300.0	0.000	-
CTH	C_{TH}	$J/^oC$	3.0×10^{-9}	0.000	-
ATH	A_{TH}	-	0.0	-	-

The additional parameter MULT for all level - 2002 models is listed in the table below.

Parameter	Symbol	Units	Default	Clip low	Clip high
MULT	M	-	1.0	0	-

9.4 Parameter scaling

Temperature scaling

Effective temperature:

$$T_{Kamb} = T_0 + T_a + \Delta T_a \tag{9.33}$$

$$T_{Kdev} = T_0 + T_a + \Delta T_a + V_{dT} \tag{9.34}$$

$$T_{Kref} = T_0 + T_{ref} \tag{9.35}$$

$$\Delta T = T_{K_{dev}} - T_{K_{ref}} \tag{9.36}$$

Actual parameters:

$$\phi_T = \frac{k_B \cdot T_{K_{dev}}}{q} \tag{9.37}$$

$$V_{FB_T} = V_{FB} + \Delta T \cdot S_{T;V_{FB}} \tag{9.38}$$

$$V_{FBD_T} = V_{FBD} + \Delta T \cdot S_{T;V_{FBD}} \tag{9.39}$$

$$\phi_{B_T} = \phi_B + \Delta T \cdot S_{T;\phi_B} \tag{9.40}$$

$$\phi_{BD_T} = \phi_{BD} + \Delta T \cdot S_{T;\phi_{BD}} \tag{9.41}$$

$$\beta_T = \beta \cdot \left(\frac{T_{Kref}}{T_{Kdev}}\right)^{\eta_\beta} \tag{9.42}$$

$$\beta_{acc_T} = \beta_{acc} \cdot \left(\frac{T_{Kref}}{T_{Kdev}}\right)^{\eta_{\beta_{acc}}} \tag{9.43}$$

$$R_{D_T} = R_D \cdot \left(\frac{T_{Kdev}}{T_{Kref}}\right)^{\eta_{R_D}} \tag{9.44}$$

$$\theta_{3_T} = \theta_3 \cdot \left(\frac{T_{Kref}}{T_{Kdev}}\right)^{\eta_{\theta_3}} \tag{9.45}$$

$$\theta_{3D_T} = \theta_{3D} \cdot \left(\frac{T_{Kref}}{T_{Kdev}}\right)^{\eta_{\theta_{3D}}} \tag{9.46}$$

$$a_{1ch_T} = a_{1ch} \cdot (1 + \Delta T \cdot S_{T;a_{1ch}}) \tag{9.47}$$

$$a_{1dr_T} = a_{1dr} \cdot (1 + \Delta T \cdot S_{T;a_{1dr}}) \tag{9.48}$$

$$N_{T_T} = N_T \cdot \left(\frac{T_{Kdev}}{T_{Kref}}\right) \tag{9.49}$$

$$R_{TH_T} = R_{TH} \cdot \left(\frac{T_{Kamb}}{T_{Kref}}\right)^{A_{TH}} \tag{9.50}$$

Mult Scaling

Since in circuit design equal parallel circuited transistors are frequently applied, the specification of one transistor together with a multiplication factor MULT (M) in the circuit description is convenient and saves computation time. In MOS Model 20 the simulation of currents, charges and noise spectral densities for these equal parallel circuited transistors is implemented by adjusting the following parameters, according to:

$$\beta_T \to \beta_T \cdot M \tag{9.51}$$

$$\beta_{accT} \to \beta_{accT} \cdot M \tag{9.52}$$

$$R_{DT} \to R_{DT} \cdot \frac{1}{M} \tag{9.53}$$

$$C_{ox} \to C_{ox} \cdot M \tag{9.54}$$

$$C_{oxD} \to C_{oxD} \cdot M \tag{9.55}$$

$$C_{GDO} \to C_{GDO} \cdot M \tag{9.56}$$

$$C_{GSO} \to C_{GSO} \cdot M \tag{9.57}$$

$$N_{fA} \to N_{fA} \cdot \frac{1}{M} \tag{9.58}$$

$$N_{fB} \to N_{fB} \cdot \frac{1}{M} \tag{9.59}$$

$$N_{fC} \to N_{fC} \cdot \frac{1}{M} \tag{9.60}$$

Clipping of Actual Parameters

After the geometry, temperature and multi-scaling, the actual parameters are clipped. The clipping values of these parameters are the same as the ones for the electrical model parameters as listed in the section titled, Default and Clipping Values of Electrical Model Parameters on page 28.

9.5 Model equations

In the following sections a function is denoted by *F[variable,...]*, where *F* denotes the function name and the function variables are enclosed by braces []. The definitions of the hyp- and hypm functions are found in Appendix *A Hyp functions*.

9.5.1 Internal Parameters

$$G_{min} = 1 \cdot 10^{-15} \tag{9.61}$$

$$\varepsilon_1 = 2 \cdot 10^{-2} \tag{9.62}$$

$$\varepsilon_2 = 1 \cdot 10^{-2} \tag{9.63}$$

$$\varepsilon_3 = 4 \cdot 10^{-2} \tag{9.64}$$

$$\varepsilon_4 = 1 \cdot 10^{-1} \tag{9.65}$$

$$\varepsilon_5 = 1 \cdot 10^{-4} \tag{9.66}$$

$$\varepsilon_6 = 1 \cdot 10^{-5} \tag{9.67}$$

$$\varepsilon_7 = 2 \cdot 10^{-1} \tag{9.68}$$

$$\varepsilon_8 = 3 \cdot 10^{-2} \tag{9.69}$$

$$V_1 = 1 \tag{9.70}$$

$$V_{limit} = 4 \cdot \phi_T \tag{9.71}$$

$$\phi_0 = \frac{1}{2}(\phi_{B_T} + \phi_{BD_T}) \tag{9.72}$$

$$Acc = \frac{1}{1 + k_0 / \sqrt{2 \cdot \phi_T}} \tag{9.73}$$

$$Acc_D = \frac{1}{1 + k_{0D} / \sqrt{2 \cdot \phi_T}} \tag{9.74}$$

$$F_L = \frac{C_{ox}}{C_{ox} + C_{oxD}} \tag{9.75}$$

9.5.2 Current Equations

Effective potentials:

$$V_{GB_{t0}} = V_{GS} + V_{SB} + V_{FBT} \tag{9.76}$$

$$V_{SB_t} = hyp[V_{SB} + 0.9 \cdot \phi_{BT}; \varepsilon_2] + 0.1 \cdot \phi_{BT} \tag{9.77}$$

$$V_{DS_1} = \begin{cases} V_{DS}, & V_{DS} \geq 0 \\ hypm[V_{DS}, V_{SB_t}; m], & V_{DS} < 0 \end{cases} \tag{9.78}$$

$$V_{GS_t} = V_{GS} - V_{FBDT} \tag{9.79}$$

$$V_{GD_t} = V_{GS_t} - V_{DS_1} \tag{9.80}$$

Channel region quantities:

$$V_{inv0} = hyp[V_{GB_{t0}} - V_{SB_t} - k_0 \cdot \sqrt{V_{SB_t}};\varepsilon_2] \tag{9.81}$$

$$\delta = \frac{k_0}{2 \cdot \sqrt{V_1 + V_{SB_t}}} \tag{9.82}$$

$$\xi = 1 + \delta \tag{9.83}$$

$$V_{DiSsat_0} = \frac{V_{inv0}}{\xi} \tag{9.84}$$

$$V_{DiSsat} = \frac{2 \cdot V_{DiSsat_0}}{1 + \sqrt{1 + 2 \cdot \theta_{3T} \cdot V_{DiSsat_0}}} \tag{9.85}$$

$$V_{SB_{t0}} = hyp[0.9 \cdot \phi_{B_T};\varepsilon_2] + 0.1 \cdot \phi_{B_T} \tag{9.86}$$

$$V_{dep0} = k_0 \cdot \sqrt{V_{SB_t}} \tag{9.87}$$

$$V_{dep0_0} = k_0 \cdot \sqrt{V_{SB_{t0}}} \tag{9.88}$$

$$F_{mob} = 1 + \theta_1 \cdot V_{inv0} + \theta_2 \cdot \frac{V_{dep0} - V_{dep0_0}}{k_0} \tag{9.89}$$

Drift region quantities:

$$f_{lin} = hyp\left[1 - \lambda_D \cdot \frac{\sqrt{\phi_0 + hyp[V_{SB};\varepsilon_1]} - \sqrt{\phi_0}}{\sqrt{\phi_0}};\varepsilon_2\right] \tag{9.90}$$

$$V_{oxp} = \frac{f_{lin}}{\beta_{acc_T} \cdot R_{D_T}} \tag{9.91}$$

$$F_{mobacc} = 1 + \frac{1}{2} \cdot \theta_{1acc} \cdot (hyp[V_{GS_t};\varepsilon_2] + hyp[V_{GD_t};\varepsilon_2]) \tag{9.92}$$

Numerical iteration procedure for the internal drain voltage:

$$V_{DiS_{eff}} = \mathrm{hypm}[V_{DiS}, V_{DiS_{sat}};m] \tag{9.93}$$

$$I_{ch}[V_{DiS},\ V_{DiSsat},\ V_{inv0},\ F_{mob}] = \begin{cases} \beta_T \cdot \dfrac{\left(V_{inv0} - \frac{1}{2} \cdot \xi \cdot V_{DiS}\right) \cdot V_{DiS}}{F_{mob} \cdot (1 - \theta_3 \cdot V_{DiS})} + G_{min} \cdot k_0^2 \cdot V_{DiS}, & V_{DiS} < 0 \\ \beta_T \cdot \dfrac{\left(V_{inv0} - \frac{1}{2} \cdot \xi \cdot V_{DiS_{eff}}\right) \cdot V_{DiS_{eff}}}{F_{mob} \cdot (1 + \theta_3 \cdot V_{DiS_{eff}})} + G_{min} \cdot k_0^2 \cdot V_{DiS}, & V_{DiS} \geq 0 \end{cases} \tag{9.94}$$

$$V_{DiB_t} = \mathrm{hyp}[V_{SB} + V_{DiS} + 0.9 \cdot \phi_{BD_T};\varepsilon_2] + 0.1 \cdot \phi_{BD_T} \tag{9.95}$$

$$V_{GDi_{teff}} = \begin{cases} V_{GDi_t}, & V_{GDi_t} \geq 0 \\ \mathrm{hypm}[V_{GDi_t}, V_{DiB_t} + k_{0D} \cdot \sqrt{V_{DiB_t}}; 8], & V_{GDi_t} < 0 \end{cases} \tag{9.96}$$

$$v_q^{dr}[V_{GDi_t}] = V_{oxp} + \begin{cases} V_{GDi_t}, & V_{GDi_t} \geq 0 \\ -k_{0D} \cdot \left(-\frac{k_{0D}}{2} + \sqrt{\left(\frac{k_{0D}}{2}\right)^2 - V_{GDi_t}}\right), & V_{GDi_t} < 0 \end{cases} \tag{9.97}$$

$$V_{q\ eff}^{dr} = \mathrm{hyp}\left[v_q^{dr}[V_{GDi_{teff}}]; \varepsilon_2\right] \tag{9.98}$$

$$V_{DDisat} = \frac{2 \cdot V_{q\ eff}^{dr}}{1 + \sqrt{1 + 2 \cdot \theta_{3DT} \cdot V_{q\ eff}^{dr}}} \tag{9.99}$$

$$V_{DDi} = V_{DS_1} - V_{DiS} \tag{9.100}$$

$$V_{DDi_{eff}} = \mathrm{hypm}[V_{DDi},\ V_{DDisat};\ m_D] \tag{9.101}$$

$$I_{dr}[V_{DiS}, V_{GS_t}, V_{DS_1}, V_{SB}, F_{mobacc}] = \begin{cases} \beta_{accT} \cdot \dfrac{\left(V_{q\ eff}^{dr} - \frac{1}{2} \cdot V_{DDi_{eff}}\right) \cdot V_{DDi_{eff}}}{F_{mobacc} \cdot (1 + \theta_{3D_T} \cdot V_{DDi_{eff}})} \\ \quad + G_{min} \cdot k_{OD}^2 \cdot V_{DDi}, & V_{DDi} \geq 0 \\ \beta_{accT} \cdot \dfrac{\left(V_{q\ eff}^{dr} - \frac{1}{2} \cdot V_{DDi}\right) \cdot V_{DDi}}{F_{mobacc} \cdot (1 + \theta_{3D_T} \cdot V_{DDi})} \\ \quad + G_{min} \cdot k_{OD}^2 \cdot V_{DDi}, & V_{DDi} < 0 \end{cases}$$

(9.102)

Newton-Raphson/bisection iteration procedure:

$$
\begin{aligned}
&H_0 = I_{ch}[0,\ V_{DiSsat},\ V_{inv0},\ \xi,\ F_{mob}] - I_{dr}[0,\ V_{GS_t},\ V_{DS_1},\ V_{SB},\ F_{mobacc}]\\
&H_1 = I_{ch}[V_{DS_1},\ V_{DiSsat},\ V_{inv0},\ \xi,\ F_{mob}] - I_{dr}[V_{DS_1},\ V_{GS_t},\ V_{DS_1},\ V_{SB},\ F_{mobacc}]\\
&\text{if } H_0 = 0 \ \text{ then } V_{DiS} = 0\\
&\text{if } H_1 = 0 \ \text{ then } V_{DiS} = V_{DS_1}\\
&\text{if } H_0 < 0 \ \text{ then } \{V_{DiSL} = 0;\ V_{DiSH} = V_{DS_1}\}\\
&\qquad\qquad \text{else } \{V_{DiSL} = V_{DS_1};\ V_{DiSH} = 0\}\\
&V_{DiS} = \frac{1}{2}\cdot(V_{DiSL} + V_{DiSH})\\
&H = I_{ch}[V_{DiS},\ V_{DiSsat},\ V_{inv0},\ \xi,\ F_{mob}] - I_{dr}[V_{DiS},\ V_{GS_t},\ V_{DS_1},\ V_{SB},\ F_{mobacc}]\\
&\Delta H = \frac{\partial I_{ch}}{\partial V_{DiS}} - \frac{\partial I_{dr}}{\partial V_{DiS}}\\
&\Delta V_{DiS_0} = |V_{DiSH} - V_{DiSL}|\\
&\Delta V_{DiS} = V_{DiS0}\\
&\text{error} = |\Delta V_{DiS}|\\
&\text{for } (i = 0;\ i < 100 \ \text{ and } \ \text{error} > 1\times 10^{-12};\ i = i+1)\\
&\text{do begin}\\
&\qquad \text{if } \{\ ((V_{DiS} - V_{DiSH})\cdot\Delta H - H)\cdot((V_{DiS} - V_{DiSL})\cdot\Delta H - H) > 0\\
&\qquad\quad \text{or } \ |2\cdot H| > |\Delta V_{DiS0}\cdot\Delta H|\ \}\\
&\qquad \text{then}\\
&\qquad \{\\
&\qquad\qquad \Delta V_{DiS0} = \Delta V_{DiS}\\
&\qquad\qquad \Delta V_{DiS} = \frac{1}{2}\cdot(V_{DiSH} - V_{DiSL})\\
&\qquad\qquad V_{DiS} = V_{DiS_L} + \Delta V_{DiS}\\
&\qquad \}
\end{aligned}
\tag{9.103}
$$

else

{

$\Delta V_{DiS_0} = \Delta V_{DiS}$

$\Delta V_{DiS} = \dfrac{H}{\Delta H}$

$V_{DiS} = V_{DiS} - \Delta V_{DiS}$

}

error $= |\Delta V_{DiS}|$

$H = I_{ch}[V_{DiS},\ V_{DiSsat},\ V_{inv0},\ \xi,\ F_{mob}] - I_{dr}[V_{DiS},\ V_{GS_t},\ V_{DS_1},\ V_{SB},\ F_{mobacc}]$

$\Delta H = \dfrac{\partial I_{ch}}{\partial V_{DiS}} - \dfrac{\partial I_{dr}}{\partial V_{DiS}}$

if $H < 0$ *then* $V_{DiSL} = V_{DiS}$

else $V_{DiSH} = V_{DiS}$

end

$$V_{DDi} = D_{DS1} - V_{DiS} \tag{9.104}$$

Drain-induced barrier lowering and static feedback:

$$V_{GB_{eff0}} = \mathrm{hyp}[V_{GB_{t0}};\varepsilon_1] \tag{9.105}$$

$$\psi_{sat_0} = \left(\frac{V_{GB_{eff0}}}{k_0/2 + \sqrt{V_{GB_{eff0}} + (k_0/2)^2}}\right)^2 \tag{9.106}$$

$$D_{dib1} = \sigma_{dib1} \cdot \sqrt{\phi_{B_T}} \cdot \left(\frac{\sqrt{V_{SB_t}}}{\sqrt{\phi_{BT}}}\right)^{m_{\sigma_{dib1}}} \tag{9.107}$$

$$D_{sf} = \sigma_{sf} \cdot \sqrt{\mathrm{hyp}[\psi_{sat_0} - V_{SB_t};\varepsilon_3]} \tag{9.108}$$

$$D = D_{dib1} + \text{hyp}[D_{sf} - D_{dib1};\varepsilon_4 \cdot \sigma_{sf}] \tag{9.109}$$

$$V_{DS_{eff}} = \frac{V_{DS_1}^{\;4}}{(V_{\text{limit}}^{\;2} + V_{DS_1}^{\;2})^{3/2}} \tag{9.110}$$

$$\Delta V_G = D \cdot V_{DS_{eff}} \tag{9.111}$$

Surface potential at source:

$$V_{GB_t} = V_{GB_{t0}} + \Delta V_G \tag{9.112}$$

$$V_{GB_{eff}} = \text{hyp}[V_{GB_t};\varepsilon_1] \tag{9.113}$$

$$\Delta_{acc} = \phi_T \cdot \left(\exp\left[-\frac{Acc \cdot V_{GB_{eff}} - \varepsilon_1}{\phi_T}\right] - 1\right) \tag{9.114}$$

$$\psi_{sat}[V_{GB_{eff}},\Delta_{acc};k] = \left(\frac{V_{GB_{eff}} + \Delta_{acc}}{k/2 + \sqrt{V_{GB_{eff}} + \Delta_{acc} + (k/2)^2}}\right)^2 - \Delta_{acc} \tag{9.115}$$

$$\psi_{sat} = \psi_{sat}[V_{GB_{eff}},\Delta_{acc};k_0] \tag{9.116}$$

$$f_1[\psi_{sat},V_{CB_t}] = \psi_{sat} - \text{hyp}[\psi_{sat}\text{-}V_{CB_t};\varepsilon_1] \tag{9.117}$$

$$f_2[\psi_{sat}, V_{CB_t}] = f_1[\psi_{sat}, V_{CB_t}] + \frac{\psi_{sat} - f_1[\psi_{sat}, V_{CB_t}]}{\sqrt{1 + \frac{(\psi_{sat} - f_1[\psi_{sat}, V_{CB_t}])^2}{16 \cdot \phi_T^{\ 2}}}} \tag{9.118}$$

$$f_3[\psi_{sat}, V_{CB_t}, V_{GB_{eff}}] = V_{GB_{eff}} - f_2[\psi_{sat}, V_{CB_t}] \tag{9.119}$$

$$\psi_s[V_{GB_{eff}}, \psi_{sat}, \Delta_{acc}, V_{CB_t}; k, m_0] = f_1[\psi_{sat}, V_{CB_t}] + \phi_T \cdot (1 + m_0) \cdot \ln\left[1 + \frac{\left(\frac{f_3[\psi_{sat}, V_{CB_t}, V_{GB_{eff}}]}{k}\right)^2 - f_1[\psi_{sat}, V_{CB_t}] - \Delta_{acc}}{\phi_T}\right] \tag{9.120}$$

$$\psi_{s0} = \Psi_s[V_{GB_{eff}}, \psi_{sat}, \Delta_{acc}, V_{SB_t}; k_0, m_0] \tag{9.121}$$

Recalculation of channel region quantities:

$$\mathcal{V}_{inv}[V_{GB_{eff}}, \psi_s, \Delta_{acc}; k] = \mathrm{hyp}[V_{GB_{eff}} - \psi_s - k \cdot \sqrt{\mathrm{hyp}[\psi_s + \Delta_{acc}; \varepsilon_2]}; \varepsilon_5] \tag{9.122}$$

$$V_{inv0} = \mathcal{V}_{inv}[V_{GB_{eff}}, \psi_{s0}, \Delta_{acc}; k_0] \tag{9.123}$$

$$\mathcal{V}_{dep}[\psi_s, \Delta_{acc}; k, \varepsilon] = k \cdot \sqrt{\mathrm{hyp}[\psi_s + \Delta_{acc}; \varepsilon]} \tag{9.124}$$

$$V_{dep0} = \mathcal{V}_{dep}[\psi_{s0}, \ \Delta_{acc}; \ k_0, \ \varepsilon_2] \tag{9.125}$$

$$\psi_{s0_0} = \psi_s[V_{GB_{eff}}, \psi_{sat}, \Delta_{acc}, V_{SB_{t0}}; k_0, m_0] \tag{9.126}$$

$$V_{dep0_0} = v_{dep}[\psi_{s0_0}, \Delta_{acc}; k_0, \varepsilon_2] \tag{9.127}$$

$$F_{mob} = 1 + \theta_1 \cdot V_{inv0} + \theta_2 \cdot \frac{\text{hyp}[V_{dep0} - V_{dep0_0}; \varepsilon_5]}{k_0} \tag{9.128}$$

$$\delta = \frac{k_0}{2 \cdot \sqrt{V_1 + \text{hyp}[\psi_{s0} + \Delta_{acc}; \varepsilon_5]}} \tag{9.129}$$

$$\xi = 1 + \delta \tag{9.130}$$

$$V_{DiSsat_0} = \frac{V_{inv0}}{\xi} \tag{9.131}$$

$$V_{DiSsat} = \frac{2 \cdot V_{DiSsat_0}}{1 + \sqrt{1 + 2 \cdot \theta_{3_T} \cdot V_{DiSsat_0}}} \tag{9.132}$$

$$V_{DiSsat_{eff}} = V_{limit} + \text{hyp}[V_{DiSsat} - V_{limit}; \varepsilon_3] \tag{9.133}$$

Surface potential at internal drain:

$$V_{DiS_{eff}} = \text{hypm}[V_{DiS}, V_{DiSsat_{eff}}; m] \tag{9.134}$$

$$V_{DiB_{t,eff}} = \text{hyp}[V_{SB} + V_{DiS_{eff}} + 0.9 \cdot \phi_{B_T}; \varepsilon_2] + 0.1 \cdot \phi_{B_T} \tag{9.135}$$

$$\psi_{sL} = \Psi_s[V_{GB_{eff}}, \psi_{sat}, \Delta_{acc}, V_{DiB_{t,eff}}; k_0, m_0] \tag{9.136}$$

Drain-source current:

$$\mathcal{V}_{inv_{ex}}[\psi_s, \Delta_{acc}, V_{CB_t}; k, m_0]$$

$$= k \cdot \frac{\phi_T \cdot \exp\left[\dfrac{\psi_s - V_{CB_t}}{(1+m_0)\cdot\phi_T}\right]}{\sqrt{\mathrm{hyp}[\psi_s + \Delta_{acc}; \varepsilon_8] + \phi_T \cdot \exp\left[\dfrac{\psi_s - V_{CB_t}}{(1+m_0)\cdot\phi_T}\right]} + \sqrt{\mathrm{hyp}[\psi_s + \Delta_{acc}; \varepsilon_8]}}$$

(9.137)

$$V_{inv_{ex0}} = \mathcal{V}_{inv_{ex}}[\psi_{s0}, \Delta_{acc}, V_{SB_t}; k_0, m_0] \quad (9.138)$$

$$V_{inv_{exL}} = \mathcal{V}_{inv_{ex}}[\psi_{sL}, \Delta_{acc}, V_{DiB_{t,eff}}; k_0, m_0] \quad (9.139)$$

$$\Delta\psi_s = \psi_{sL} - \psi_{s0} \quad (9.140)$$

$$\overline{V_{inv}} = V_{inv0} - \frac{1}{2}\cdot\xi\cdot\Delta\psi_s \quad (9.141)$$

$$F_{mobsat} = 1 + \theta_{3_T}\cdot\Delta\psi_s \quad (9.142)$$

$$G_{mob} = F_{mob}\cdot F_{mobsat} \quad (9.143)$$

$$G_{\Delta L} = \mathrm{hyp}\left[1 - \alpha\cdot\ln\left[\frac{V_{DS_1} - V_{DiS_{eff}} + \sqrt{(V_{DS1} - V_{DiS_{eff}})^2 + V_p^2}}{V_p}\right]; \varepsilon_5\right]$$

(9.144)

$$x_0 = 2 \cdot \frac{\psi_{sat} + \phi_T - V_{SB_t}}{\phi_T} \tag{9.145}$$

$$x_L = 2 \cdot \frac{\psi_{sat} + \phi_T - V_{DiB_{t,eff}}}{\phi_T} \tag{9.146}$$

$$G = \begin{cases} \dfrac{\exp[x_0] + \exp[x_L]}{1 + \exp[x_0] + \exp[x_L]} & x_0 \le 80 \wedge x_L \le 80 \\ 1, & x_0 > 80 \vee x_L > 80 \end{cases} \tag{9.147}$$

$$I_{drift} = \beta_T \cdot G \cdot \frac{\overline{V_{inv}} \cdot \Delta\psi_s}{G_{mob} \cdot G_{\Delta L}} \tag{9.148}$$

$$I_{diff} = \beta_T \cdot \phi_T \cdot \frac{V_{inv_{ex0}} - V_{inv_{exL}}}{G_{mob} \cdot G_{\Delta L}} \tag{9.149}$$

$$I_{DS} = I_{drift} + I_{diff} \tag{9.150}$$

Avalanche current:

$$I_{AVL_{ch}} = \begin{cases} a_{1ch_T} \cdot |I_{DS}| \cdot \exp\left[-\dfrac{a_{2ch}}{|V_{DiS}| - a_{3ch} \cdot V_{DiSsat_{eff}}}\right], & |V_{DiS}| - a_{3ch} \cdot V_{DiSsat_{eff}} > -\dfrac{a_{2ch}}{A}, \\ 0, & |V_{DiS}| - a_{3ch} \cdot V_{DiSsat_{eff}} \le -\dfrac{a_{2ch}}{A} \end{cases} \tag{9.151}$$

$$F_{mobsat_{sat}} = 1 + \theta_{3_T} \cdot V_{DiSsat_{eff}} \tag{9.152}$$

$$G_{mob_{sat}} = F_{mob} \cdot F_{mobsat_{sat}} \tag{9.153}$$

$$\overline{V_{inv_{sat}}} = \text{hyp}\left[V_{inv0} - \frac{1}{2} \cdot \xi \cdot V_{DiSsat_{eff}};\ \varepsilon_2\right] \tag{9.154}$$

$$I_{sat} = \beta_T \cdot G \cdot \frac{\overline{V_{inv_{sat}}} \cdot V_{DiSsat_{eff}}}{G_{mob_{sat}}} \tag{9.155}$$

$$V_{ch_{sat}} = R_{D_T} \cdot I_{sat} \tag{9.156}$$

$$f_{acc} = \frac{\beta_{acc_T} \cdot R_{D_T}}{F_{mobacc}} \tag{9.157}$$

$$V_{oxp_{avl}} = \frac{f_{lin}}{f_{acc}} \tag{9.158}$$

$$V_{DS_{sat}} = V_{oxp_{avl}} + V_{GS_t} - \sqrt{\text{hyp}\left[(V_{oxp_{avl}} + V_{GS_t} - V_{DiSsat_{eff}})^2 - \frac{2 \cdot V_{ch_{sat}}}{f_{acc}};\ \varepsilon_5\right]} \tag{9.159}$$

$$V_{DSsat_{eff}} = V_{limit} + \text{hyp}[V_{DSsat} - V_{limit};\varepsilon_5] \tag{9.160}$$

$$I_{AVL_{dr}} = \begin{cases} a_{1dr_T} \cdot |I_{DS}| \cdot \exp\left[-\dfrac{a_{2dr}}{|V_{DS}| - a_{3dr} \cdot V_{DSsat_{eff}}}\right], & |V_{DS}| - a_{3dr} \cdot V_{DSsat_{eff}} > -\dfrac{a_{2dr}}{A}, \\ 0, & |V_{DS}| - a_{3dr} \cdot V_{DSsat_{eff}} \le -\dfrac{a_{2dr}}{A} \end{cases} \tag{9.161}$$

$$I_{AVL} = I_{AVL_{ch}} + I_{AVL_{dr}} \tag{9.162}$$

9.5.3 Charge equations

Surface potential for accumulation in the channel region:

$$f_{1acc}[V_{GB_t}, V_{GB_{eff}}; Acc] = Acc \cdot (V_{GB_t} - V_{GB_{eff}}) \tag{9.163}$$

$$f_{2acc}[V_{GB_t}, V_{GB_{eff}}; Acc] = \frac{f_{1acc}[V_{GB_t}, V_{GB_{eff}}; Acc]}{\sqrt{1 + \dfrac{f^2_{1acc}[V_{GB_t}, V_{GB_{eff}}; Acc]}{16 \cdot \phi_T^2}}} \tag{9.164}$$

$$f_{3acc}[V_{GB_t}, V_{GB_{eff}}; Acc] = V_{GB_t} - V_{GB_{eff}} - f_{2acc}[V_{GB_t}, V_{GB_{eff}}; Acc] \tag{9.165}$$

$$\Psi_{sacc}[V_{GB_t}, V_{GB_{eff}}; k, Acc] = -\phi_T \cdot ln\left[1 + \frac{\left(\dfrac{f_{3acc}[V_{GB_t}, V_{GB_{eff}}; Acc]}{k}\right)^2 - f_{2acc}[V_{GB_t}, V_{GB_{eff}}; Acc]}{\phi_T}\right] \tag{9.166}$$

$$\psi_{sacc} = \Psi_{sacc}[V_{GB_t}, V_{GB_{eff}}; k_0, Acc] \tag{9.167}$$

Charges in the channel region:

$$V_{ox} = V_{GB_t} - \frac{1}{2} \cdot (\psi_{s0} + \psi_{sL}) - \psi_{sacc} \tag{9.168}$$

$$V_{GT0} = v_{inv}[V_{GB_{eff}}, \psi_{s0}, \Delta_{acc}; k_0] \tag{9.169}$$

$$V_{GTL} = v_{inv}[V_{GB_{eff}}, \psi_{sL}, \Delta_{acc}; k_0] \tag{9.170}$$

$$\Delta V_{GT} = V_{GT0} - V_{GTL} \tag{9.171}$$

$$\overline{V_{GT}} = \frac{1}{2} \cdot (V_{GT0} + V_{GTL}) \tag{9.172}$$

$$F_j = \frac{\Delta V_{GT}}{\overline{V_{GT}} + \xi \cdot \phi_T} \tag{9.173}$$

$$Q_{G_{mos}} = C_{ox} \cdot \left(V_{ox} + \frac{F_j}{12 \cdot \xi} \cdot \Delta V_{GT}\right) \tag{9.174}$$

$$Q_{D_{mos}} = -\frac{C_{ox}}{2} \cdot \left(\overline{V_{GT}} - \frac{\Delta V_{GT}}{6} \cdot \left\{1 - \frac{F_j}{2} - \frac{F_j^2}{20}\right\}\right) \tag{9.175}$$

$$Q_{S_{mos}} = -\frac{C_{ox}}{2} \cdot \left(\overline{V_{GT}} + \frac{\Delta V_{GT}}{6} \cdot \left\{1 + \frac{F_j}{2} - \frac{F_j^2}{20}\right\}\right) \tag{9.176}$$

$$Q_{B_{mos}} = -(Q_{G_{mos}} + Q_{D_{mos}} + Q_{S_{mos}}) \tag{9.177}$$

$$Q_G^{ch} = Q_{G_{mos}} \tag{9.178}$$

$$Q_D^{ch} = F_L \cdot Q_{D_{mos}} \tag{9.179}$$

$$Q_S^{ch} = Q_{S_{mos}} + (1 - F_L) \cdot Q_{D_{mos}} \tag{9.180}$$

$$Q_B^{ch} = -(Q_G^{ch} + Q_D^{ch} + Q_S^{ch}) \tag{9.181}$$

Surface potential at internal drain in the drift region:

$$V_{DiS_{dr.eff}} = V_{DiS} \tag{9.182}$$

$$V_{GDi_{t.eff}} = V_{GS_t} - V_{DiS_{dr.eff}} \tag{9.183}$$

$$V_{DiG_{eff}} = \mathrm{hyp}[-V_{GDi_{t,eff}};\varepsilon_7] \tag{9.184}$$

$$\Delta_{acc_{Di}} = \phi_T \cdot \left(\exp\left[-\frac{A_{cc_D}(V_{DiG_{eff}} - \varepsilon_7)}{\phi_T}\right] - 1\right) \tag{9.185}$$

$$\psi_{sat_{Di}} = \Psi_{sat}[V_{DiG_{eff}},\Delta_{acc_{Di}};k_{0D}] \tag{9.186}$$

$$V_{DiB_t} = \mathrm{hyp}[V_{SB} + V_{DiS_{dr,eff}} + 0.9 \cdot \phi_{BDT};\varepsilon_2] + 0.1 \cdot \phi_{BDT} \tag{9.187}$$

$$\psi_{sDi} = \Psi_s[V_{DiG_{eff}},\psi_{sat_{Di}},\Delta_{acc_{Di}},V_{DiB_t};k_{0D},m_0] \tag{9.188}$$

$$\psi_{sacc_{Di}} = \Psi_{sacc}[-V_{GDi_{t,eff}}, V_{DiG_{eff}}; k_{0D}, Acc_D] \tag{9.189}$$

Drift region charges at internal drain:

$$V_{oxDi}^{dr} = V_{GDi_{t,eff}} + \psi_{sDi} + \psi_{sacc_{Di}} \tag{9.190}$$

$$V_{dep_{Di}} = \mathcal{V}_{dep}[\psi_{sDi},\ \Delta_{acc_{Di}};\ k_{0D},\ \varepsilon_2] \tag{9.191}$$

$$V_{inv_{Di}} = \mathcal{V}_{inv}[V_{DiG_{eff}},\ \psi_{sDi},\ \Delta_{acc_{Di}};\ k_{0D}] \tag{9.192}$$

$$V_{qDi}^{accdep} = V_{oxDi}^{dr} - V_{inv_{Di}} \tag{9.193}$$

$$V_{qDi}^{dr} = V_{oxp} + V_{qDi}^{accdep} \tag{9.194}$$

$$V_{qDi_{eff}}^{dr} = V_{\mathrm{limit}} + \mathrm{hyp}[V_{qDi}^{dr} - V_{limit};\ \varepsilon_7] \tag{9.195}$$

$$V_{DDisat} = \frac{2 \cdot V_{qDi_{eff}}^{dr}}{1 + \sqrt{1 + 2 \cdot \theta_{3D_T} \cdot V_{qDi_{eff}}^{dr}}} \tag{9.196}$$

$$V_{DDi_{eff}} = \mathrm{hypm}[V_{DDi},\ V_{DDisat};\ m_D] \tag{9.197}$$

Surface potential at drain in the drift region:

$$V_{DS_{dr.eff}} = V_{DiS_{dr.eff}} + V_{DDi_{eff}} \tag{9.198}$$

$$V_{GD_{t.eff}} = V_{GS_t} - V_{DS_{dr.eff}} \tag{9.199}$$

$$V_{DG_{eff}} = \text{hyp}[-V_{GD_{t,eff}};\ \varepsilon_7] \tag{9.200}$$

$$\Delta_{acc_D} = \phi_T \cdot \left(\exp\left[-\frac{A_{cc_D}(V_{DG_{eff}} - \varepsilon_7)}{\phi_T}\right] - 1\right) \tag{9.201}$$

$$\psi_{sat_D} = \Psi_{sat}[V_{DG_{eff}},\ \Delta_{acc_D}; k_{0D}] \tag{9.202}$$

$$V_{DB_t} = \text{hyp}[V_{SB} + V_{DS_{dr,eff}} + 0.9 \cdot \phi_{BD_t};\ \varepsilon_2] + 0.1 \cdot \phi_{BD_t} \tag{9.203}$$

$$\psi_{sD} = \Psi_s[V_{DG_{eff}},\ \psi_{sat_D},\ \Delta_{acc_D},\ V_{DB_t};\ k_{0D},\ m_0] \tag{9.204}$$

$$\psi_{sacc_D} = \Psi_{sacc}[-V_{GD_{t,eff}}, V_{DG_{eff}};\ k_{0D},\ Acc_D] \tag{9.205}$$

Drift region charges at drain:

$$V^{dr}_{oxD} = V_{GD_{t,eff}} + \psi_{sD} + \psi_{sacc_D} \tag{9.206}$$

$$V_{dep_D} = \mathcal{V}_{dep}[\psi_{sD},\ \Delta_{acc_D};\ k_{0D},\ \varepsilon_2] \tag{9.207}$$

$$V_{inv_D} = \mathcal{V}_{inv}[V_{DG_{eff}},\ \psi_{sD},\ \Delta_{acc_D};\ k_{0D}] \tag{9.208}$$

$$V^{accdep}_{q_D} = V^{dr}_{oxD} + V_{inv_D} \tag{9.209}$$

$$V^{dr}_{q_D} = V_{oxp} + V^{accdep}_{q_D} \tag{9.210}$$

$$V^{dr}_{q_{D_{eff}}} = V_{\text{limit}} + \text{hyp}[V^{dr}_{q_D} - V_{\text{limit}};\ \varepsilon_7] \tag{9.211}$$

Total charges in the drift region:

$$\overline{V^{dr}_{q}}_{eff} = \frac{1}{2} \cdot (V^{dr}_{q_{Di_{eff}}} + V^{dr}_{q_{D_{eff}}}) \tag{9.212}$$

$$\Delta V^{accdep}_{q} = V^{accdep}_{q_{Di}} - V^{accdep}_{q_D} \tag{9.213}$$

$$F_{j_{dr}} = \frac{\Delta V^{accdep}_{q}}{\overline{V^{dr}_{q}}_{eff}} \tag{9.214}$$

$$Q^{accdep}_{D} = -\frac{C_{oxD}}{2} \cdot \left(\overline{V^{dr}_{q}}_{eff} - \frac{\Delta V^{accdep}_{q}}{6} \cdot \left\{ 1 - \frac{F_{j_{dr}}}{2} - \frac{F^2_{j_{dr}}}{20} \right\} \right) \tag{9.215}$$

$$Q^{accdep}_{S} = -\frac{C_{oxD}}{2} \cdot \left(\overline{V^{dr}_{q}}_{eff} + \frac{\Delta V^{accdep}_{q}}{6} \cdot \left\{ 1 + \frac{F_{j_{dr}}}{2} - \frac{F^2_{j_{dr}}}{20} \right\} \right) \tag{9.216}$$

Inclusion of a-symmetry

$$V_{T_t} = V_{FBT} + \phi_{BT} - V_{FBDT} + k_0 \cdot \sqrt{V_{DiB_{t,eff}}} \tag{9.217}$$

$$V_{GDi_{lim}} = V_{GDi_{teff}} - \text{hyp}[V_{GDi_{teff}} - V_{T_t};\ \varepsilon_7] \tag{9.218}$$

$$V_{GD_{lim}} = V_{GDi_{lim}} - V_{DDi_{eff}} \tag{9.219}$$

$$V_{GD_{acc,lim}} = \text{hyp}[V_{GD_{lim}};\ \varepsilon_7] \quad (9.220)$$

$$V_{GDi_{acc,lim}} = \text{hyp}[V_{GDi_{lim}};\ \varepsilon_7] \quad (9.221)$$

$$\Delta V_{acc,lim} = V_{GDi_{acc,lim}} - V_{GD_{acc,lim}} \quad (9.222)$$

$$\overline{V_{acc,lim}} = \frac{1}{2} \cdot (V_{GDi_{acc,lim}} + V_{GD_{acc,lim}}) \quad (9.223)$$

$$F_{j_{acc,lim}} = \frac{\Delta V_{acc,lim}}{\overline{V_{acc,lim}} + V_{oxp}} \quad (9.224)$$

$$Q_{S_{acc,lim}} = -\frac{C_{oxD}}{2} \cdot \left(\overline{V_{acc,lim}} + \frac{\Delta V_{acc,lim}}{6} \cdot \left\{1 + \frac{F_{j_{acc,lim}}}{2} - \frac{F^2_{j_{acc,lim}}}{20}\right\}\right) \quad (9.225)$$

Total drift region charges

$$Q_D^{dr} = Q_D^{accdep} + F_L \cdot Q_S^{accdep} + (1 - F_L) \cdot Q_{S_{acc,lim}} \quad (9.226)$$

$$Q_S^{dr} = (1 - F_L) \cdot (Q_S^{accdep} - Q_{S_{acc,lim}}) \quad (9.227)$$

$$Q_B^{dr} = \frac{C_{oxD}}{2} \cdot (V_{inv_D} + V_{inv_{Di}}) \quad (9.228)$$

$$Q_G^{dr} = -(Q_S^{dr} + Q_D^{dr} + Q_B^{dr}) \quad (9.229)$$

Total charges:

$$Q_G = Q_G^{ch} + Q_G^{dr} \tag{9.230}$$

$$Q_D = Q_D^{ch} + Q_D^{dr} \tag{9.231}$$

$$Q_S = Q_S^{ch} + Q_S^{dr} \tag{9.232}$$

$$Q_B = -(Q_G + Q_D + Q_S) \tag{9.233}$$

9.5.4 Noise Equations

Noise transfer function:

$$g_{m_{ch}} = \max\left[\beta_T \cdot \frac{\Delta\psi_s}{G_{mob}} \cdot \left(1 - \theta_1 \cdot \frac{\overline{V_{inv}}}{F_{mob}}\right), 1 \times 10^{-10}\right] \tag{9.234}$$

$$g_{ds_{ch}} = \max\left[\beta_T \cdot \frac{V_{inv0} + \xi \cdot V_{\text{limit}} - \xi \cdot \Delta\psi_s - \frac{1}{2} \cdot \theta_{3_T} \cdot \xi \cdot (\Delta\psi_s)^2}{G_{mob} \cdot F_{mobsat}}, 0\right] \tag{9.235}$$

$$V_{DiB_t} = \text{hyp}[V_{SB} + V_{DiS} + 0.9 \cdot \phi_{BD_T};\ \varepsilon_2] + 0.1 \cdot \phi_{BD_T} \tag{9.236}$$

$$V_{GDi_{teff}} = \begin{cases} V_{GDi_t}, & V_{GDi_t} \geq 0 \\ \text{hypm}[V_{GDi_t},\ V_{DiB_t} + k_{0D} \cdot \sqrt{V_{DiB_t}};\ 8], & V_{GDi_t} < 0 \end{cases} \tag{9.237}$$

$$V_{q_{eff}}^{dr} = \text{hyp}[V_q^{dr}[V_{GDi_{t\ eff}}];\ \varepsilon_2] \tag{9.238}$$

$$V_{DDisat} = \frac{2 \cdot V_{q_{eff}}^{dr}}{1 + \sqrt{1 + 2 \cdot \theta_{3DT} \cdot V_{q_{eff}}^{dr}}} \tag{9.239}$$

$$V_{DDi_{eff}} = \text{hypm}[V_{DDi},\ V_{DDisat};\ m_D] \tag{9.240}$$

$$F_{mobsat}^{dr} = 1 + \theta_{3DT} \cdot V_{DDi_{eff}} \tag{9.241}$$

$$g_{m_{dr}} = \max\left[\beta_{accT} \cdot \frac{\partial V_{q_{eff}}^{dr}}{\partial V_{GDi_{t\ eff}}} \cdot \frac{\partial V_{GDi_{t\ eff}}}{\partial V_{GDi_t}} \cdot \frac{V_{DDi_{eff}}}{F_{mobacc} \cdot F_{mobsat}^{dr}},\ 1 \times 10^{-10}\right] \tag{9.242}$$

$$g_{ds_{dr}} = \max\left[\beta_{accT} \cdot \frac{V_{q_{eff}}^{dr} - V_{DDi_{eff}} - \frac{1}{2} \cdot \theta_{3DT} \cdot (V_{DDi_{eff}})^2}{F_{mobacc} \cdot (F_{mobsat}^{dr})^2},\ 1 \times 10^{-10}\right] \tag{9.243}$$

$$g_{transfer} = \frac{g_{ds_{dr}} + g_{m_{dr}}}{g_{ds_{ch}} + g_{ds_{dr}} + g_{m_{dr}}} \tag{9.244}$$

Flicker noise:

$$N_0 = \frac{\varepsilon_{ox}}{q \cdot t_{ox}} \cdot V_{inv_{ex0}} \tag{9.245}$$

$$N_L = \frac{\varepsilon_{ox}}{q \cdot t_{ox}} \cdot V_{inv_{exL}} \tag{9.246}$$

$$N^* = \frac{\varepsilon_{ox}}{q \cdot t_{ox}} \cdot \xi \cdot \phi_T \tag{9.247}$$

$$S_{D_{fl0}} = \frac{q \cdot \phi_T^2 \cdot t_{ox} \cdot \beta_T \cdot I_{DS}}{\varepsilon_{ox} \cdot N* \cdot G_{mob}} \left\{ (N_{fA} - N^* \cdot N_{fB} + N^{*2} \cdot N_{fC}) \cdot 1n\left[\frac{N_0 + N^*}{N_L + N^*}\right] \right.$$
$$\left. + (N_{fB} - N^* \cdot N_{fC}) \cdot (N_0 - N_L) + \frac{N_{fC}}{2} \cdot (N_0{}^2 - N_L{}^2) \right\}$$
$$+ \phi_T \cdot I_{DS}^2 \cdot (1 - G_{\Delta L}) \cdot \frac{N_{fA} + N_{fB} \cdot N_L + N_{fC} \cdot N_L{}^2}{(N_L + N^*)^2} \tag{9.248}$$

$$S_{D_{fl}} = g_{transfer}^2 \cdot \frac{\max[S_{D_{fl0}},\ \ 0]}{f} \tag{9.249}$$

Thermal noise:

$$S_{D_{th0}} = \beta_T \cdot \left\{ \frac{F_{mobsat} \cdot G_{\Delta L}}{F_{mob}} \cdot \left(\overline{V_{inv}} + \frac{\xi^2}{12} \cdot \frac{\Delta\psi_s{}^2}{\overline{V_{inv}} + \xi \cdot \phi_T} \right) \right.$$
$$\left. - \frac{\phi_{3_T} \cdot \overline{V_{inv}} \cdot \Delta\psi_s}{F_{mob}} \cdot \left(2 - \frac{\phi_{3_T} \cdot \Delta\psi_s}{F_{mobsat} \cdot G_{\Delta L}} \right) \right\} \tag{9.250}$$

$$S_{D_{th}} = g_{transfer}^2 \cdot N_{T_T} \cdot max[S_{D_{th0}},\ \ 0] \tag{9.251}$$

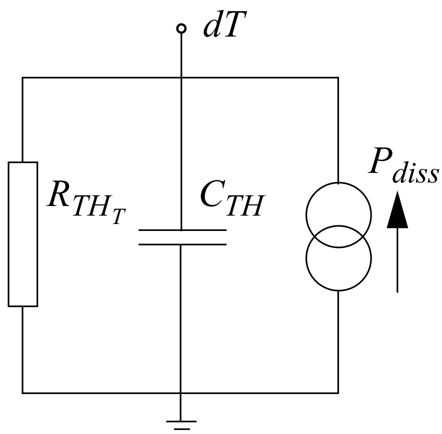
$$S_{G_{th}} = \frac{N_{T_T} \cdot \frac{(2 \cdot \pi \cdot C_{ox})^2}{3 \cdot g_{m_{ch}}} \cdot f^2}{1 + 0.075 \cdot (2 \cdot \pi \cdot f \cdot C_{ox} / g_{m_{ch}})^2} \tag{9.252}$$

$$S_{GD_{th}} = 0.4 \cdot j \cdot \sqrt{S_{G_{th}} \cdot S_{D_{th}}} \tag{9.253}$$

9.6 Self-heating

9.6.1 Equivalent circuit

Self-heating is part of the model. It is defined in the usual way by adding a self-heating network (see Figure 4) containing a current source describing the dissipated power and both a thermal resistance R_{TH} and a thermal capacitance C_{TH}.



Material	A_{TH}
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 4: 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 *dT*. 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, see equations (9.2) and (9.34).

For the value of A_{TH} we recommend using values from literature that describes the temperature scaling of the thermal conductivity. For the most important materials, the values are given in Figure 4, which is largely based on Ref. [8], see also [1].

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

9.6.2 Model equations

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

$$P_{diss} = I_D^e \cdot V_D^e + I_S^e \cdot V_S^e + I_B^e \cdot V_B^e$$

$$= I''_{DS} \cdot V''_{DS} + I''_{DB} \cdot (V''_{DS} - V''_{SB}) + I''_{SB} \cdot V''_{SB}$$

where all variables are given in Figure 6 on page 74. Note that only the steady-state currents contribute to the dissipated power.

The total dissipation applies for the electrical model (mnet[1], mpet[1], mos2002et[2]) and geometrical model (mnt[1], mpt[1], mos2002t[2]).

9.6.3 Usage

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

Example

Title: example self-heating 2002;

```
circuit;


e_ddl (1, 0) 20;
e_gl (2, 0) 2;
e_ssl (3, 0) 0;
e_bbl (4, 0) 0;
mnet_1(1, 2, 3, 4, dt) level=2002, rth=300,cth=3e-9;
r_2 (dT, 0) 1e6;


end;
```

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

```
dc;
print: vn(dT), pdiss.mnet_1;
end; run;
```

```
result:
DC   Analysis.
VN(dT)         =1.066E+00
Pdiss.MNT_1    =3.556e-03
```

The voltage on node *dT* is `1.066E+00` V, which means that the local temperature is increased by `1.066E+00` ^{o}C.

9.7 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. f_T). The objective of the DC operating point 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.

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

Symbol	Program Name	Units	Description
I_{DS}	IDS	A	Drain current, excluding avalanche current
I_{AVL}	IAVL	A	Substrate current due to weak-avalanche
V_{DS}	VDS	V	Drain-source voltage
V_{GS}	VGS	V	Gate-source voltage
V_{SB}	VSB	V	Source-bulk voltage
V_{TO}	VTO	V	Zero-bias threshold voltage of the channel region (after geometric and temperature scaling): $V_{T0} = V_{FB_T} + \phi_{B_T} + k_0 \cdot \sqrt{\phi_{B_T}}$
V_{TS}	VTS	V	Threshold voltage including back-bias effects: $V_{TS} = V_{FB_T} + \phi_{B_T} + k_0 \cdot \sqrt{V_{SB_t}}$
V_{TH}	VTH	A	Threshold voltage including back-bias and drain-bias effects: $V_{TH} = V_{FB_T} + \phi_{B_T} + k_0 \cdot \sqrt{V_{SB_t}} - \Delta V_G$
V_{GT}	VGT	A	Effective gate drive voltage including back-bias and drain voltage effects: $V_{GT} = V_{inv_{ex0}}$

Symbol	Program Name	Units	Description
V_{TOD}	VTOD	V	Treshold voltage of the drift region: $V_{TOD} = V_{FBD_T} - \phi_{BD_T} + k_{0D} \cdot \sqrt{\phi_{BD_T}}$
$V_{DiS_{eff}}$	VDISEFF	V	Effective internal drain to source voltage at actual bias
$V_{DiSsat_{eff}}$	VDISSAT	V	Saturation voltage of channel region at actual bias
V_{DDisat}	VDDISAT	V	Saturation voltage of drift region at actual bias
g_m	GM	A/V	Transconductance (assumed $V_{DS} > 0$): $g_m = \partial I_{DS}/\partial V_{GS}$
g_{mb}	GMB	A/V	Substrate-transconductance (assumed $V_{DS} > 0$): $g_{mb} = \partial I_{DS}/\partial V_{BS}$
g_{ds}	GDS	A/V	Output conductance: $g_{ds} = \partial I_{DS}/\partial V_{DS}$
C_{DD}	CDD	F	$C_{DD} = \partial Q_D/\partial V_{DS}$
C_{DG}	CDG	F	$C_{DG} = -\partial Q_D/\partial V_{GS}$
C_{DS}	CDS	F	$C_{DS} = C_{DD} - C_{DG} - C_{DB}$
C_{DB}	CDB	F	$C_{DB} = \partial Q_D/\partial V_{SB}$
C_{GD}	CGD	F	$C_{GD} = -\partial Q_G/\partial V_{DS}$
C_{GG}	CGG	F	$C_{GG} = \partial Q_G/\partial V_{GS}$
C_{GS}	CGS	F	$C_{GS} = C_{GG} - C_{GD} - C_{GB}$
C_{GB}	CGB	F	$C_{GB} = \partial Q_G/\partial V_{SB}$
C_{SD}	CSD	F	$C_{SD} = -\partial Q_S/\partial V_{DS}$
C_{SG}	CSG	F	$C_{SG} = -\partial Q_S/\partial V_{GS}$
C_{SS}	CSS	F	$C_{SS} = C_{SG} + C_{SD} + C_{SB}$
C_{SB}	CSB	F	$C_{SB} = \partial Q_S/\partial V_{SB}$

Symbol	Program Name	Units	Description
C_{BD}	CBD	F	$C_{BD} = -\partial Q_B / \partial V_{DS}$
C_{BG}	CBG	F	$C_{BG} = -\partial Q_B / \partial V_{GS}$
C_{BS}	CBS	F	$C_{BS} = C_{BB} - C_{BD} - C_{BG}$
C_{BB}	CBB	F	$C_{BB} = -\partial Q_B / \partial V_{SB}$
W_E	WEFF	m	Effective channel region width for geometrical model
W_{ED}	WDEFF	m	Effective drift region width for geometrical model
u	U	-	Transistor gain: $u = g_m / g_{ds}$
R_{OUT}	ROUT	Ω	Small-signal output resistance: $R_{out} = 1/g_{ds}$
V_{Early}	VEARLY	V	Equivalent Early voltage: $V_{Early} = \lvert I_{DS} \rvert / g_{ds}$
β_{eff}	BEFF	A/V^2	Gain factor: $\beta_{eff} = 2 \cdot \lvert I_{DS} \rvert / V_{inv_{ex0}}^2$
f_T	FUG	Hz	Unity gain frequency at actual bias: $f_T = \dfrac{g_m}{2 \cdot \pi \cdot (C_{GG} + C_{GSO} + C_{GDO})}$
$g_{m_{ch}}$	GMMOS	A/V	Transconductance of channel region
$\sqrt{S_{V_{Gth}}}$	SQRTSFW	$V/(\sqrt{Hz})$	Input-referred RMS thermal noise voltage density: $\sqrt{S_{V_{Gth}}} = \sqrt{S_{D_{th}}} / g_{m_{ch}}$
$\sqrt{S_{V_{Gfl}}}$	SQRTSFF	$V/(\sqrt{Hz})$	Input-referred RMS flicker noise voltage density at 1 kHz: $\sqrt{S_{V_{Gfl}}} = \sqrt{S_{D_{fl}}[1kHz]} / g_{m_{ch}}$
f_{knee}	FKNEE	Hz	Cross-over frequency above which thermal noise is dominant: $f_{knee} = 1Hz \cdot S_{D_{fl}}[1Hz] / S_{D_{ti}}$

9.8 Embedding

In high-voltage technologies both *n*- and *p*-channel LDMOS transistors are supported. It is convenient to use one single model for both type of transistors instead of two separate models. This is accomplished by mapping a *p*-channel device with its bias conditions and parameter set onto an equivalent *n*-channel device with appropriately changed bias conditions (i.e. currents, voltages and charges) and parameters. In this way, both type of transistors can be treated as an *n*-channel transistor. In MOS Model 20, we let the electrons and holes have the same electrical behaviour. As a result, the same equations are used in case of *n*- or *p*-type transistors.

Since a DMOS transistor in an asymmetric device, no source drain interchange is applied in case the external voltage mapped onto an *n*-channel transistor is negative. Thus, in MOS Model 20, the dc-currents and charges are calculated by use of the externally applied voltages mapped onto an equivalent *n*-channel transistor.

The total transformation procedure is in detail explained in Section 9.8.3.

9.8.1 External Electrical Quantities and Variables

Variable	Prog. Name	Units	Description
V_D^e	VDE	V	Potential applied to the drain node
V_G^e	VGE	V	Potential applied to the gate node
V_S^e	VSE	V	Potential applied to the source node
V_B^e	VBE	V	Potential applied to the bulk node
I_D^e	IDE	A	DC current into the drain
I_G^e	IGE	A	DC current into the gate
I_S^e	ISE	A	DC current into the source
I_B^e	IBE	A	DC current into the bulk
Q_D^e	QDE	C	Charge in the device attributed to the drain node
Q_G^e	QGE	C	Charge in the device attributed to the gate node
Q_S^e	QSE	C	Charge in the device attributed to the source node
Q_B^e	QBE	C	Charge in the device attributed to the bulk node
S_D^e	SDE	A^2s	Spectral density of the noise current into the drain
S_G^e	SGE	A^2s	Spectral density of the noise current into the gate
S_S^e	SSE	A^2s	Spectral density of the noise current into the source
S_{DG}^e	SDGE	A^2s	Cross spectral density between the drain and the gate noise currents
S_{GS}^e	SGSE	A^2s	Cross spectral density between the gate and the source noise currents

Variable	Prog. Name	Units	Description
S^e_{SD}	SSDE	$A^2 s$	Cross spectral density between the source and the drain noise currents

The definitions of the external electrical variables are illustrated in Figure 5.

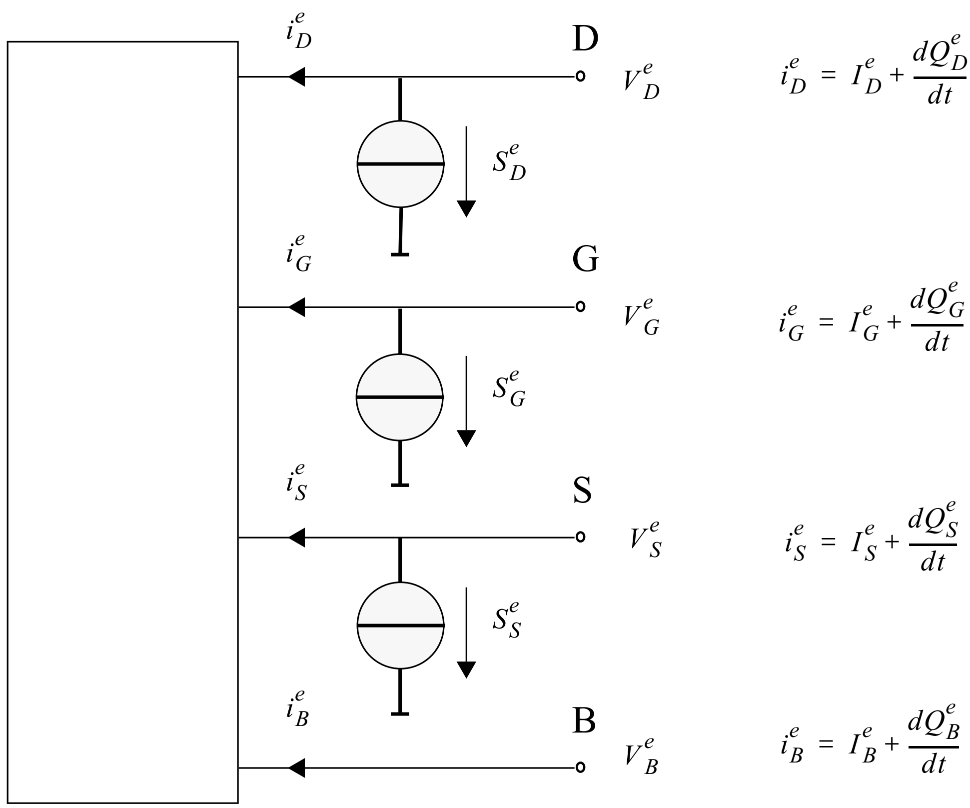


Figure 5: Definition of the external electrical quantities and variables.

9.8.2 Internal Electrical Quantities and Variables

Variable	Progr. Name	Units	Description
V_{DS}	VDS	V	Drain-to-source voltage applied to the equivalent n-MOST
V_{GS}	VGS	V	Gate-to-source voltage applied to the equivalent n-MOST
V_{SB}	VSB	V	Source-to-bulk voltage applied to the equivalent n-MOST
I_{DS}	IDS	A	DC current through the channel flowing from drain to source
I_{AVL}	IAVL	A	DC current flowing from drain to bulk due to the weak-avalanche effect
Q_D	QD	C	Intrinsic charge in the equivalent n-MOST attributed to the drain node
Q_G	QG	C	Intrinsic charge in the equivalent n-MOST attributed to the gate node
Q_S	QS	C	Intrinsic charge in the equivalent n-MOST attributed to the source node
Q_B	QB	C	Intrinsic charge in the equivalent n-MOST attributed to the bulk node
$S_{D_{th}}$	SDTH	A^2s	Spectral density of the thermal-noise current of the channel region
$S_{D_{fl}}$	SDFL	A^2s	Spectral density of the flicker-noise current of the channel region
$S_{G_{th}}$	SGTH	A^2s	Spectral density of the thermal-noise current induced in the gate
$S_{GD_{th}}$	SGDTH	A^2s	Cross spectral density of the thermal-noise current induced in the gate and the thermal-noise current of the channel

9.8.3 Embedding Procedure of MOS Model 20 in a Circuit Simulator

In order to embed MOS Model 20 correctly into a circuit simulator, the following procedure, illustrated in detail in Figure 6 should be followed. We have assumed that indeed the simulator provides the nodal potentials V_D^e, V_G^e, V_S^e and V_B^e based on an a priori assignment of drain, gate, source and bulk. As a DMOS is an asymmetric device, no source-drain interchange is applied as is done in a conventional (symmetric) MOSFET.

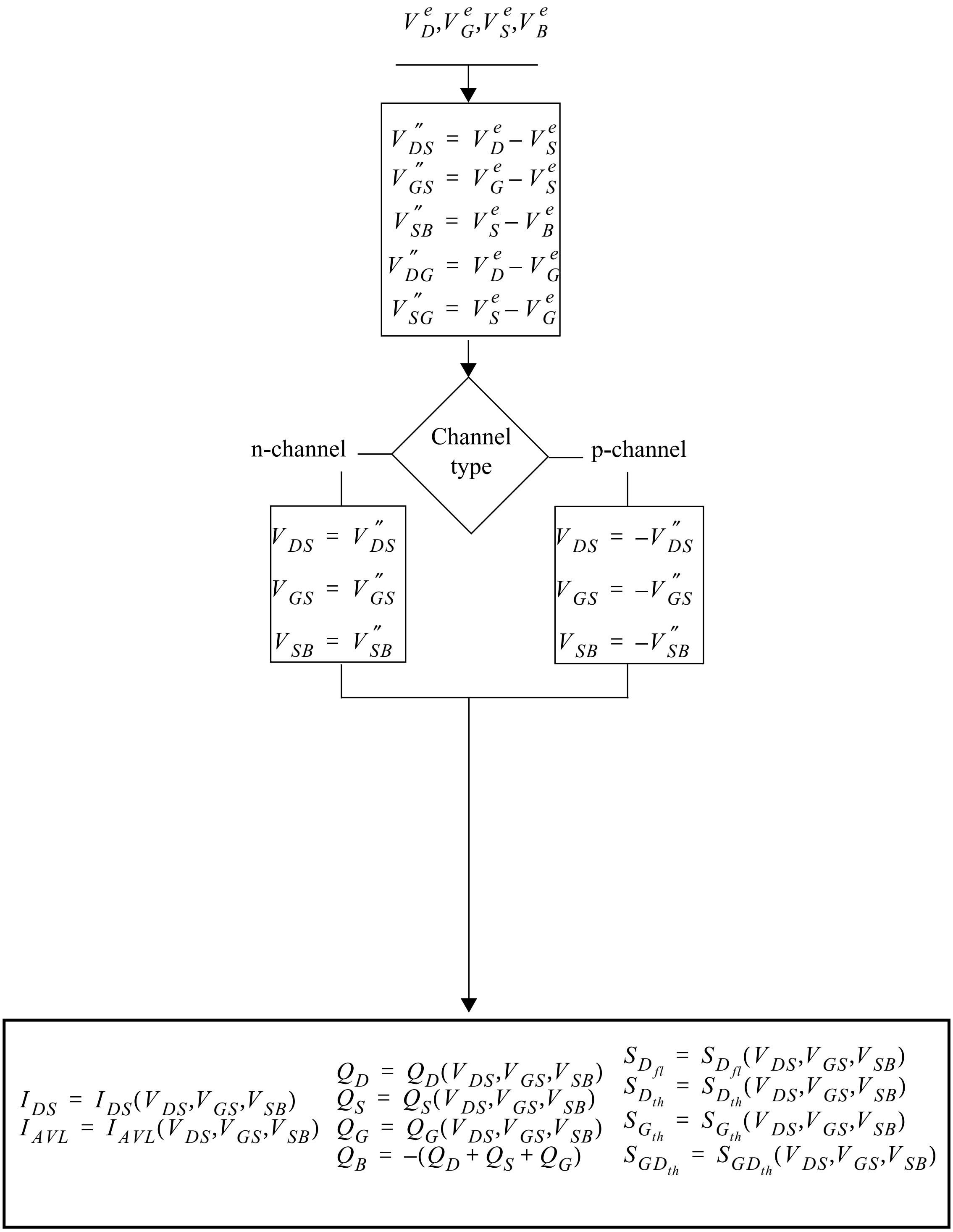
Step 1 Calculate the voltages V_{DS}'', V_{GS}'' and V_{SB}'', and the additional voltages V_{DG}'' and V_{SG}''. The latter are used for calculating the charges associated with overlap capacitances.

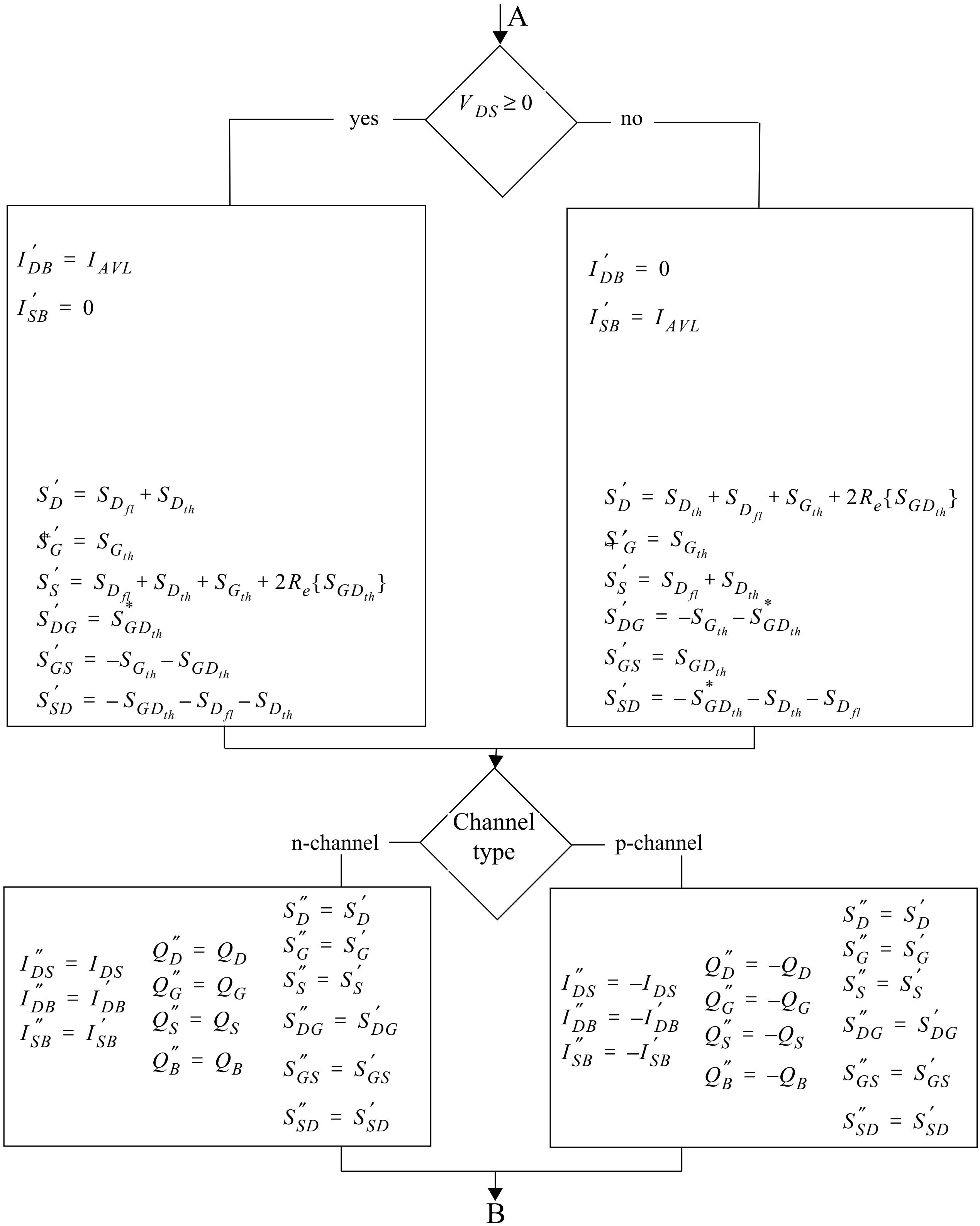
Step 2 Based on *n*- or *p*-channel devices, calculate the modified voltages V_{DS}, V_{GS}, and V_{SB}. From here onwards only *n*-channel behaviour needs to be considered.

Step 3 Evaluate all the internal output quantities - channel current, weak-avalanche current, nodal charges, and noise-power spectral densities - using the MOS Model 20 equations and the corresponding voltages.

Step 4 Correct for a possible *p*-channel transformation.

Step 5 Change from branch current to nodal currents, establishing the external current output quantities. Add the overlap charges to the nodal charges, thus forming the external charge output quantities.


$V_D^e, V_G^e, V_S^e, V_B^e$
$V_{DS}'' = V_D^e - V_S^e$
$V_{GS}'' = V_G^e - V_S^e$
$V_{SB}'' = V_S^e - V_B^e$
$V_{DG}'' = V_D^e - V_G^e$
$V_{SG}'' = V_S^e - V_G^e$
n-channel
Channel type
p-channel
$V_{DS} = V_{DS}''$
$V_{GS} = V_{GS}''$
$V_{SB} = V_{SB}''$
$V_{DS} = -V_{DS}''$
$V_{GS} = -V_{GS}''$
$V_{SB} = -V_{SB}''$
$I_{DS} = I_{DS}(V_{DS}, V_{GS}, V_{SB})$
$I_{AVL} = I_{AVL}(V_{DS}, V_{GS}, V_{SB})$
$Q_D = Q_D(V_{DS}, V_{GS}, V_{SB})$
$Q_S = Q_S(V_{DS}, V_{GS}, V_{SB})$
$Q_G = Q_G(V_{DS}, V_{GS}, V_{SB})$
$Q_B = -(Q_D + Q_S + Q_G)$
$S_{D_{fl}} = S_{D_{fl}}(V_{DS}, V_{GS}, V_{SB})$
$S_{D_{th}} = S_{D_{th}}(V_{DS}, V_{GS}, V_{SB})$
$S_{G_{th}} = S_{G_{th}}(V_{DS}, V_{GS}, V_{SB})$
$S_{GD_{th}} = S_{GD_{th}}(V_{DS}, V_{GS}, V_{SB})$


A
$V_{DS} \geq 0$
yes
no
$I'_{DB} = I_{AVL}$
$I'_{SB} = 0$
$S'_D = S_{D_{fl}} + S_{D_{th}}$
$S'_G = S_{G_{th}}$
$S'_S = S_{D_{fl}} + S_{D_{th}} + S_{G_{th}} + 2R_e\{S_{GD_{th}}\}$
$S'_{DG} = S^*_{GD_{th}}$
$S'_{GS} = -S_{G_{th}} - S_{GD_{th}}$
$S'_{SD} = -S_{GD_{th}} - S_{D_{fl}} - S_{D_{th}}$
$I'_{DB} = 0$
$I'_{SB} = I_{AVL}$
$S'_D = S_{D_{th}} + S_{D_{fl}} + S_{G_{th}} + 2R_e\{S_{GD_{th}}\}$
$S'_G = S_{G_{th}}$
$S'_S = S_{D_{fl}} + S_{D_{th}}$
$S'_{DG} = -S_{G_{th}} - S^*_{GD_{th}}$
$S'_{GS} = S_{GD_{th}}$
$S'_{SD} = -S^*_{GD_{th}} - S_{D_{th}} - S_{D_{fl}}$
Channel type
n-channel
p-channel
$I''_{DS} = I_{DS}$
$I''_{DB} = I'_{DB}$
$I''_{SB} = I'_{SB}$
$Q''_D = Q_D$
$Q''_G = Q_G$
$Q''_S = Q_S$
$Q''_B = Q_B$
$S''_D = S'_D$
$S''_G = S'_G$
$S''_S = S'_S$
$S''_{DG} = S'_{DG}$
$S''_{GS} = S'_{GS}$
$S''_{SD} = S'_{SD}$
$I''_{DS} = -I_{DS}$
$I''_{DB} = -I'_{DB}$
$I''_{SB} = -I'_{SB}$
$Q''_D = -Q_D$
$Q''_G = -Q_G$
$Q''_S = -Q_S$
$Q''_B = -Q_B$
$S''_D = S'_D$
$S''_G = S'_G$
$S''_S = S'_S$
$S''_{DG} = S'_{DG}$
$S''_{GS} = S'_{GS}$
$S''_{SD} = S'_{SD}$
B

B

$$I_D^e = I_{DS}'' + I_{DB}''$$
$$I_G^e = 0$$
$$I_S^e = -I_{DS}'' + I_{SB}''$$
$$I_B^e = -I_{DB}'' - I_{SB}''$$

$$Q_D^e = Q_D'' + C_{GDO} \cdot V_{DG}''$$
$$Q_G^e = Q_G'' - C_{GDO} \cdot V_{DG}'' - C_{GSO} \cdot V_{SG}''$$
$$Q_S^e = Q_S'' + C_{GSO} \cdot V_{SG}''$$
$$Q_B^e = Q_B''$$

$$S_D^e = S_D''$$
$$S_G^e = S_G''$$
$$S_S^e = S_S''$$
$$S_{DG}^e = S_{DG}''$$
$$S_{GS}^e = S_{GS}''$$
$$S_{SD}^e = S_{SD}''$$

I_D^e I_G^e I_S^e I_B^e Q_D^e Q_G^e Q_S^e Q_B^e S_D^e S_G^e S_S^e S_{DG}^e S_{GS}^e S_{SD}^e

Figure 6: Transformation scheme

It is customary to have separate user models in the circuit simulators for *n*- and *p*-channel transistors. In that manner it is easy to use a different set of reference and scaling parameters for the two channel types. As a consequence, the changes in the parameter values necessary for a *p*-channel type transistor are normally already included in the parameter sets on file. The changes should not be included simulator.

9.9 Simulator Specific Items

9.9.1 Pstar Syntax

n channel electrical model:	mne_n (d,g,s,b) level=2002, <parameters>
p channel electrical model:	mpe_n (d,g,s,b) level=2002, <parameters>
n channel geometrical model:	
	mn_n (d,g,s,b) level=2002 <parameters>
p channel geometrical model:	
	mp_n (d,g,s,b) level=2002 <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.

9.9.2 Spectre syntax

n channel electrical model:	model modelname mos2002e type=n <modpar>
	componentname d g s b modelname <inpar>
p channel electrical model:	model modelname mos2002e type=p <modpar>
	componentname d g s b modelname <inpar>
n channel geometrical model:	
	model modelname mos2002 type=n <modpar>
	componentname d g s b modelname <inpar>
p channel geometrical model:	
	model modelname mos2002 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,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.

9.9.3 ADS syntax

n channel electrical model: model modelname mos2002e gender=1 <modpar>
modelname:componentname d g s b <instpar>
p channel electrical model: model modelname mos2002e gender=0 <modpar>
modelname:componentname d g s b <instpar>
n channel geometrical model:
model modelname mos2002 gender=1 <modpar>
modelname:componentname d g s b <instpar>
p channel geometrical model:
model modelname mos2002 gender=0 <modpar>
modelname:componentname d g s b <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.

9.9.4 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 [9]. By default the devices start in the default state.

n-channel			
	Default	ON	OFF
V_{DS}	6.0	6.0	12.0
V_{GS}	6.0	6.0	0.0
V_{SB}	0.0	0.0	0.0

p-channel			
	Default	ON	OFF
V_{DS}	-6.0	-6.0	-12.0
V_{GS}	-6.0	-6.0	0.0
V_{SB}	0.0	0.0	0.0

9.9.5 The ON/OFF condition for Spectre

n-channel							
	OFF	Triode	Saturation	Subthreshold	Reverse	Forward	Breakdown
V_{DS}	0.0	0.5	1.25	0.0	0	0	0
V_{GS}	0.0	0.5	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	-0.5	-1.25	0.0	0	0	0
V_{GS}	0.0	-0.5	-1.25	0.0	0	0	0
V_{SB}	0.0	0.0	0.0	0.0	0	0	0

9.9.6 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

9.10 Parameter Extraction

The parameter extraction strategy for MOS Model 20 excluding the effect of self-heating is analoguous to the four different steps described in [4]. However, in case of a non-negligable temperature rise due to self-heating, one can not divide the parameter extraction procedure into a separate parameter extraction of miniset parameters at room temperature and a separate parameter extraction of the temperature scaling parameters. The reason is that once self-heating has been incorporated, the miniset parameters are internally corrected for this temperature rise due to self-heating, and can therefore not be determined from measurements performed at one single temperature only. Hence, to extract parameters for a device including self-heating, the following three steps are performed:
– measurements
– extraction of miniset parameters (including temperature scaling parameters)
– extraction of width scaling parameters

Notice that, in contrast to a conventional MOS transistor, mostly the LDMOS transistor has only one gate length L available in a process. Therefore, the division of this length into a length L_{ch} of the channel region and a length L_{dr} of the drift region is difficult. Further insight into this division can be obtained if one has various LDMOS transistors of different drift region lengths L_{dr} available.

The above three steps of the parameter extraction strategy will be briefly described in the following sections.

9.10.1 Measurements

The parameter extraction routine consists of four different dc-measurements and one (optional) capacitance measurement[1]:

- **Measurement I (idvg):** I_D and g_m versus V_{GS} characteristics in linear region:

n-channel : $V_{GS} = 0, ..., V_{GS,\ max}$
$V_{DS} = 100$ mV
$V_{SB} = 0, 1, 2, 3$ and 4 V

p-channel : $V_{GS} = 0, ..., -V_{GS,\ max}$
$V_{DS} = -100$ mV
$V_{SB} = 0, -1, -2, -3$ and -4 V

1.The bias conditions to be used for the measurements are dependent on the maximum voltages $V_{DS,\ max}$ and $V_{GS,\ max}$. Of course it is advisable to restrict the range of voltages to these maximum voltages. Otherwise physical effects a-typical for normal transistor operation and therefore less well described by MOS Model 20 may dominate the characteristics.

- **Measurement II (subvt):** Sub-treshold I_D versus V_{GS} characteristics:

n-channel : $V_{GS} = V_T$ - 0.6 V, ..., V_T + 0.3 V
V_{DS} = 3 values starting from 100 mV to $V_{DS,\ max}$
V_{SB} = 0, 1, 2, 3 and 4 V

p-channel : $V_{GS} = V_T$ + 0.6 V, ..., V_T - 0.3 V
V_{DS} = 3 values starting from -100 mV to -$V_{DS,\ max}$
V_{SB} = 0, -1, -2, -3 and -4 V

- **Measurement III (idvd):** I_D and g_{DS} versus V_{DS} characteristics:

n-channel : V_{DS} = 0, ..., $V_{DS,\ max}$
$V_{GS} = V_T$ + 0.1 V, V_T + 1.1 V, V_T + 2.1 V, V_T + 3.1 V
V_{SB} = 0, 2 and 4 V

p-channel : V_{DS} = 0, ..., -$V_{DS,\ max}$
$V_{GS} = V_T$ -0.1 V, V_T -1.1 V, V_T -2.1 V, V_T -3.1 V
V_{SB} = 0, -2 and -4 V

- **Measurement IV (idvdh):** I_D and g_{DS} versus V_{DS} characteristics:

n-channel : V_{DS} = 0, ..., $V_{DS,\ max}$
V_{GS} = 4 values starting from ($V_{GS,\ max}$/4) to $V_{GS,\ max}$
V_{SB} = 0 V

p-channel : V_{DS} = 0, ..., -$V_{DS,\ max}$
V_{GS} = 4 values starting from -($V_{GS,\ max}$/4) to -$V_{GS,\ max}$
V_{SB} = 0 V

- **Measurement V (ibvg):** I_D and I_B versus V_{GS} characteristics in high-field operation regions:

n-channel : V_{GS} = 0, ..., $V_{GS,\ max}$
$V_{DS} = V_{DS,\ max}$ -4 V, $V_{DS,\ max}$ -2 V and $V_{DS,\ max}$
V_{SB} = 0 V

p-channel : $V_{GS} = 0, ..., -V_{GS,\ max}$
$V_{DS} = -V_{DS,\ max} + 4$ V, $-V_{DS,\ max} + 2$ V and $-V_{DS,\ max}$
$V_{SB} = 0$ V

- **Measurement VI(Cvg):** C_{gg} , C_{sg} , C_{dg} and C_{bg} versus V_{GS} - characteristics:

n/p-channel : $V_{GS} = -V_{GS,\ max}, ..., V_{GS,\ max}$
$V_{DS} = 0$ V
$V_{SB} = 0$ V

The values of transconductance g_{m} and output conductance g_{DS} are extracted from the I - V-curves by calculating in a numerical way the derivative of I_{D} to V_{GS} and V_{DS}, respectively. In the measurements II and III use is made of threshold voltage V_{T}, which has to be determined for all the used source-bulk bias values V_{SB} from measurement I (idvg). The way V_{T} is determined is rather arbitrary: it can be either obtained by the use of a linear extrapolation method or by a constant current criterion.

For the miniset extraction, measurements I through V have to be performed for a certain device width at various temperatures, ranging from about $T_{min} = -40^{\mathrm{o}}$C to $T_{max} = 125^{\mathrm{o}}$C. Finally, to determine the width scaling parameters, the measurements at room temperature need to be performed for a narrow and broad transistor.

9.10.2 Extraction of Miniset Parameters (including Temperature Scaling)

In case of a non-negligable temperature rise due to self-heating, the extraction of miniset parameters is performed by the use of an external thermal network. This thermal network provides the temperature rise $\Delta T_{self-heating}$ due to self-heating. The reference temperature T_{ref} is chosen equal to the chuck temperature T_{chuck}, while the temperature rise ΔT is set equal to the temperature rise $\Delta T_{self-heating}$ due to self-heating, according to:

$$\Delta T_{self-heating} = R_{th} \cdot I_{DS} \cdot V_{DS} \tag{9.254}$$

Here, R_{th} denotes the thermal resistance (in Kelvin per Watt), and has to be determined before one starts the extraction of miniset parameters. In case of a one-dimensional heat-flow, the thermal resistance is given by:

$$R_{th_{SOI}} = \left(\frac{t_{BOX}}{k_{ox}} + \frac{t_{Si}}{k_{Si}}\right) \cdot \frac{1}{A} \qquad or \qquad R_{th_{bulk}} = \frac{t_{Si}}{k_{Si}} \cdot \frac{1}{A} \tag{9.255}$$

for an SOI-process and a bulk process, respectively. Here, t_{Si} represents the thickness of the silicon wafer, t_{BOX} the thickness of the buried oxide (BOX) layer, and A denotes the area over which dissipation takes place, see Figure 7. The physical constants k_{Si} and k_{ox} are the thermal conductivity of silicon and oxide, respectively. At $T = 27^{o}\mathrm{C}$ these conductivities are given by $k_{ox} = 1.4 W/(K \cdot m)$ and $k_{Si} = 1.41 \cdot 10^{2} W/(K \cdot m)$. Thus, in general R_{th} depends on the device temperature as well as device geometry. More details on how to incorporate the effect of self-heating into the parameter extraction strategy can be found in e.g. [7].

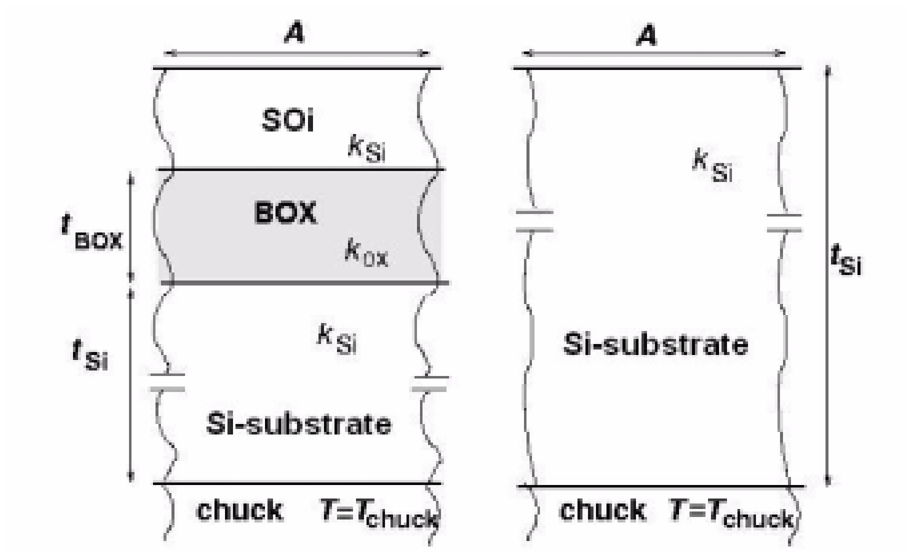


Figure 7: Geometry for the one-dimensional heat-flow in a transisor in an SOI process (left) and a bulk process (right).

Next, a first estimate of the miniset parameters is given for a certain device width W, based on an estimate for the oxide thickness t_{ox}, the channel length L_{ch} and drift region length L_{dr}, according to the following table:

Table 1: Starting miniset parameter values for parameter extraction of a typical DMOS transistor with channel length L_{ch} (m), drift region length L_{dr} (m), device width W (m) and oxide thickness t_{ox} (m).

Parameter	**Program Name**	**Parameter Value**	
		NMOS	**PMOS**
V_{FB}	VFB	-1.0	-1.0
$S_{T;V_{FB}}$	STVFB	$-1.0 \cdot 10^{-3}$	$-1.0 \cdot 10^{-3}$
V_{FBD}	VFBD	0.0	0.0
$S_{T;V_{FB}}$	STVFB	0.0	0.0
k_O	KO	1.6	1.6
k_{OD}	KOD	1.0	1.0

Table 1: Starting miniset parameter values for parameter extraction of a typical DMOS transistor with channel length L_{ch} (m), drift region length L_{dr} (m), device width W (m) and oxide thickness t_{ox} (m).

Parameter	Program Name	Parameter Value	
		NMOS	**PMOS**
ϕ_B	PHIB	0.9	0.9
$S_{T;\phi_B}$	STPHIB	$-1.0 \cdot 10^{-3}$	$-1.0 \cdot 10^{-3}$
ϕ_{BD}	PHIBD	0.8	0.8
$S_{T;\phi_{BD}}$	STPHIBD	$-1.0 \cdot 10^{-3}$	$-1.0 \cdot 10^{-3}$
β	BET	$(2.2 \cdot 10^{-12}/t_{ox}) \cdot (W/L_{ch})$	$(0.8 \cdot 10^{-12}/t_{ox}) \cdot (W/L_{ch})$
η_β	ETABET	1.6	1.6
β_{acc}	BETACC	$(2.2 \cdot 10^{-12}/t_{ox}) \cdot (W/L_{dr})$	$(0.8 \cdot 10^{-12}/t_{ox}) \cdot (W/L_{dr})$
$\eta_{\beta_{acc}}$	ETABETACC	1.6	1.6
R_D	RD	$5.0 \cdot 10^{3} \cdot (L_{dr}/W)$	$1.5 \cdot 10^{4} \cdot (L_{dr}/W)$
η_{R_D}	ETARD	1.5	1.5
λ_D	LAMD	0.2	0.2
θ_1	THE1	0.05	0.05
θ_{1acc}	THE1ACC	0.05	0.05
θ_2	THE2	0.03	0.03
θ_3	THE3	0.4	0.4
η_{θ_3}	ETATHE3	1.0	1.0
m	MEXP	2.0	2.0
θ_{3D}	THE3D	0.0	0.0
$\eta_{\theta_{3D}}$	ETATHE3D	1.0	1.0
m_D	MEXPD	2.0	2.0
α	ALP	$2.0 \cdot 10^{-3}$	$2.0 \cdot 10^{-3}$

Table 1: Starting miniset parameter values for parameter extraction of a typical DMOS transistor with channel length L_{ch} (m), drift region length L_{dr} (m), device width W (m) and oxide thickness t_{ox} (m).

Parameter	**Program Name**	**Parameter Value**	
		NMOS	**PMOS**
V_p	VP	$5.0 \cdot 10^{-2}$	$5.0 \cdot 10^{-2}$
σ_{dibl}	SDIBL	$1.0 \cdot 10^{-3}$	$1.0 \cdot 10^{-3}$
$m_{\sigma_{dibl}}$	MSDIBL	1.0	1.0
m_0	MO	$1.0 \cdot 10^{-3}$	$1.0 \cdot 10^{-3}$
σ_{sf}	SSF	$1.0 \cdot 10^{-6}$	$1.0 \cdot 10^{-6}$
a_{1ch}	A1CH	18	18
$S_{T;a_{1ch}}$	STA1CH	0.0	0.0
a_{2ch}	A2CH	73	73
a_{3ch}	A3CH	1.0	1.0
a_{1dr}	A1DR	18	18
$S_{T;a_{1dr}}$	STA1DR	0.0	0.0
a_{2dr}	A2DR	73	73
a_{3dr}	A3DR	1.0	1.0
C_{ox}	COX	$(3.453 \cdot 10^{-11} / t_{ox}) \cdot W \cdot L_{ch}$	$(3.453 \cdot 10^{-11} / t_{ox}) \cdot W \cdot L_{ch}$
C_{oxD}	COXD	$(3.453 \cdot 10^{-11} / t_{ox}) \cdot W \cdot L_{dr}$	$(3.453 \cdot 10^{-11} / t_{ox}) \cdot W \cdot L_{dr}$
C_{GDO}	CGDO	$3.0 \cdot 10^{-10} \cdot W$	$3.0 \cdot 10^{-10} \cdot W$
C_{GSO}	CGSO	$3.0 \cdot 10^{-10} \cdot W$	$3.0 \cdot 10^{-10} \cdot W$

Parameters COX, COXD, CGSO and CGDO are only important for the charge model, and do not affect the dc-model; they have to be extracted from *C-V*-characteristics. Furthermore, in practice the parameters PHIBD, STPHIBD, KOD, VFBD and STVFBD can not be determined accurately from DC-measurements, and as a consequence they are determined from *C-V*-measurements.

In general the simultaneous determination of all miniset parameters is not advisable, because the value of some parameters can be wrong due to correlation and suboptimization. Therefore it is more practical to split the parameters into several groups, where each parameter group can be determined using specific measurements.

Next, the parameter extraction strately is described, from both DC- and AC measurements.

DC-parameters

The extraction strategy for the DC-parameters for an *n*-channel DMOS transistor is outlined in Table 2. For *p*-channel DMOS transistors all voltages and currents have to be multiplied by -1. The optimisation is either performed on the absolute (abs) or relative (rel) deviation between model and measurements.

Table 2: DC-parameter extraction strategy for an n-channel DMOS transistor, including self-heating.

Step	Optimised Parameters	Measurement	Fitted on	abs/ rel	Specific Conditions
1	ϕ_B , k_0	I (idvg), $T = T_{ref}$	I_D	abs	$I_D < 0.1 \cdot I_{D,max_{idvg}}$
2	ϕ_B , m_0, σ_{dibl} , $m_{\sigma_{dibl}}$	II(subvt), $T = T_{ref}$	I_D	rel	$I_D < 0.1 \cdot I_{D,max_{idvg}}$
3	$S_{T;\phi_B}$	I(idvg), $T = T_{min}$, ..., T_{max}	I_D	abs	$I_D < 0.1 \cdot I_{D,max_{idvg}}$
4	θ_1 , θ_3 , η_{θ_3}	IV(idvdh), $T = T_{min}$, ..., T_{max}	I_D	abs	in saturation
5	θ_{3D} , $\eta_{\theta_{3D}}$	IV(idvdh), $T = T_{min}$, ..., T_{max}	I_D	abs	in saturation
6	β , η_β	IV(idvdh), $T = T_{min}$, ..., T_{max}	I_D	abs	in saturation
7	α , V_p, σ_{sf}	III(idvd), T = Tref	g_{DS}	rel	in saturation, $V_{GS} < V_T + 3.1V$
8	β , η_β	III(idvd), T = Tref	g_{DS}	rel	in saturation, $V_{GS} = V_T + 3.1V$
9	β_{acc} , $\eta_{\beta_{acc}}$, R_D	IV(idvdh), $T = T_{min}$, ..., T_{max}	I_D	abs	in linear region, $\eta_{R_D} = \eta_{\beta_{acc}}$

Step	Optimised Parameters	Measurement	Fitted on	abs/ rel	Specific Conditions
10	θ_{1acc}	I (idvg), $T = T_{ref}$	I_D	abs	-
11	θ_2	III(idvd), $T = T_{ref}$	I_D	abs	$V_{SB} > 0$
12	λ_D	I (idvg), $T = T_{ref}$	I_D	abs	$V_{SB} > 0$
13	a_{1ch}, a_{2ch}, a_{3ch}	V(ibvg), $T = T_{ref}$	I_B	abs	-
15	$S_{T;a_{1ch}}$	V(ibvg), $T = T_{min}$, ..., T_{max}	I_B	abs	-
16	a_{1dr}, a_{2dr}, a_{3dr}	V(ibvg), $T = T_{ref}$	I_B	abs	-
17	$S_{T;a_{1dr}}$	V(ibvg), $T = T_{min}$, ..., T_{max}	I_B	abs	-

AC-parameters

The extraction strategy for the AC-parameters for an *n*-channel DMOS transistor is outlined in Table 3. For *p*-channel DMOS transistors all voltages and currents have to be multiplied by -1. The optimisation is either performed on the absolute (abs) or relative (rel) deviation between model and measurements.

Table 3: AC-parameter extraction strategy for an n-channel DMOS transistor, including self-heating.

Step	Optimised Parameters	Measurement	Fitted on	abs/ rel	Specific Conditions
1	C_{ox}, C_{oxD}, ϕ_{BD}, k_{0D}, V_{FBD}	VI (Cvg), $T = T_{ref}$	C_{ig}	abs	-
2	$S_{T;\phi_{BD}}$, $S_{T;V_{FB}}$, $S_{T;V_{FBD}}$	VI(Cvg), $T = T_{min}$, ..., T_{max}	C_{GG}	abs	-

9.10.3 Extraction of Maxiset Parameters

Since in most high-voltage processes the LDMOS transistor has only one gate length L, there is no length scaling scheme present in MOS Model 20. Thus, geometry scaling consists of only width scaling, and can be separated into a width scaling scheme for the channel region and a width scaling scheme for the drift region. The most important part of the geometry scaling scheme is the determination of ΔW and ΔW_D, since it affects the DC-, the AC- as well as the noise model; see Section 9.3.2. Here, ΔW and ΔW_D can be determined from the extrapolated zero-crossing in the gain factor β and β_{acc} (or $1/R_D$), respectively, versus mask width *W*. As an LDMOS transistor may have different mask widths for the source and the drain, also different values of ΔW and ΔW_D can be obtained.

When using the physical scaling relations of Section 9.3.2, it is possible to calculate a parameter set for a process, given the parameter set of typical transistors of this process. To accomplish this, transistors of different widths have to be measured. Using these measurements the sensitivities of the parameters on the width can be found. For the determination of a geometry-scaled parameter set a three-step procedure is recommended:

1. determine minisets (ϕ_B, k_0, β, ...) including temperature scaling for all measured devices, as explained in Section 9.10.2.
2. the width sensitivity coefficients are optimised by fitting the appropriate geometry scaling rules to these miniset parameters.
3. finally, the width and length sensitivity coefficients are optimised by fitting the result of the scaling rules and current equations to the measured currents of all devices simultaneously.

9.11 References

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A Hyp functions

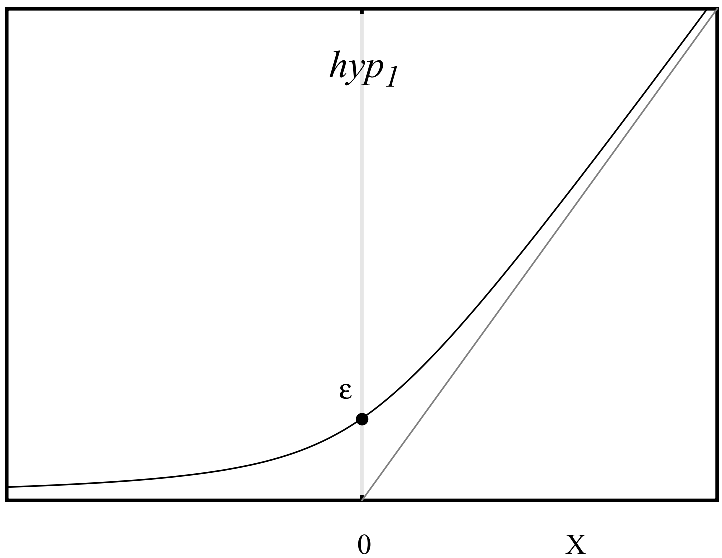


Figure 8: $hyp_1(x;\varepsilon) = \frac{1}{2} \cdot (x + \sqrt{x^2 + 4 \cdot \varepsilon^2})$

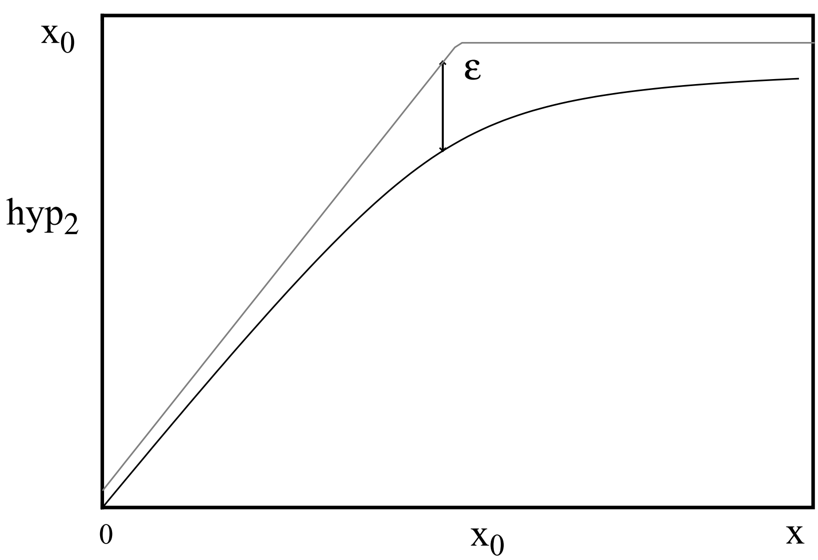


Figure 9: $hyp_2(x;x_0;\varepsilon) = x - hyp_1(x - x_0;\varepsilon)$

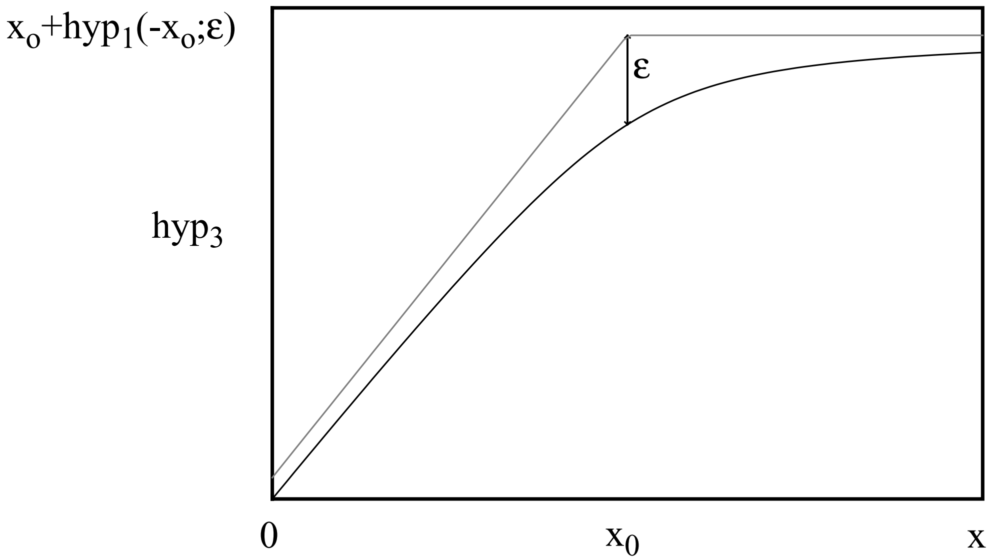


Figure 10: $hyp_3(x;x_0;\varepsilon) = hyp_2(x;x_0;\varepsilon) - hyp_2(0;x_0;\varepsilon)$ *for* $\varepsilon = \varepsilon(x_0)$

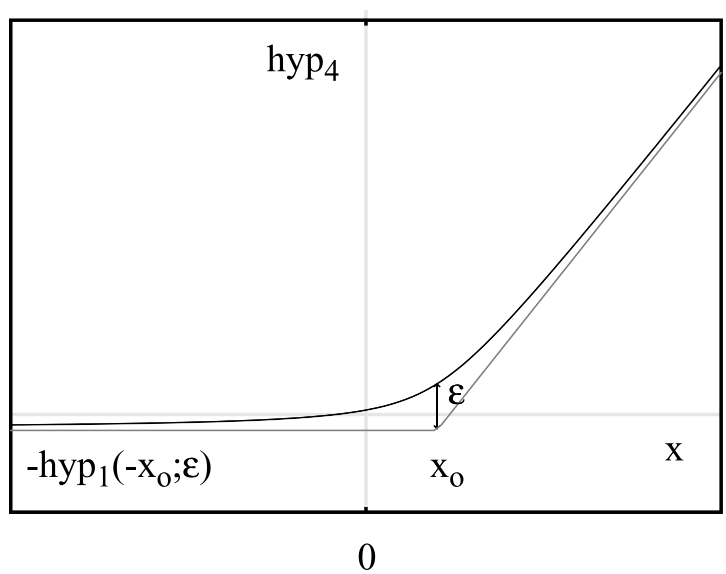


Figure 11: $hyp_4(x;x_0;\varepsilon) = hyp_1(x - x_0;\varepsilon) - hyp_1(-x_0;\varepsilon)$

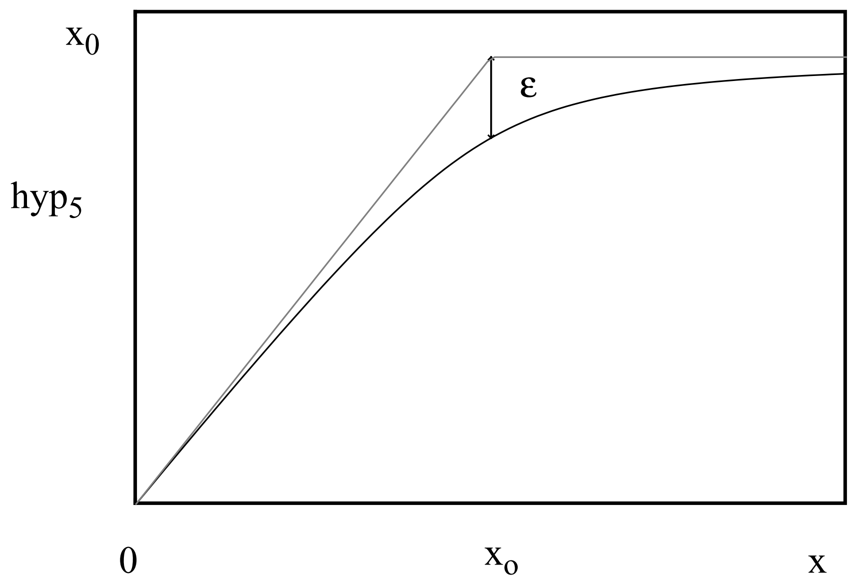


Figure 12: $hyp_5(x;x_0;\varepsilon) = x_0 - hyp_1\left(x_0 - x - \frac{\varepsilon^2}{x_0}, \varepsilon\right) \qquad \mathit{for}\ \varepsilon = \varepsilon(x_0)$

The hypm-function:

$$hypm[x, y; m] = \frac{x \cdot y}{(x^{2 \cdot m} + y^{2 \cdot m})^{1/(2 \cdot m)}} \tag{9.256}$$

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.
The default value of the Imax model parameter is 1000A. Imax should be set to a value which is large enough so it does not affect the extraction procedure.

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

$$I = I_s \exp\left(\frac{V}{N \cdot \phi_{TD}} - 1\right) \tag{9.257}$$

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

$$I_{max} = I_s \exp\left(\frac{V_{\exp l}}{N \cdot \phi_{TD}} - 1\right) \tag{9.258}$$

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

$$V_{\exp l} = N \cdot \phi_{TD} \log\left(\frac{I_{max}}{I_s}\right) + 1 \tag{9.259}$$

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

$$I = I_{max} + (V - V_{expl})\frac{I_s}{N \cdot \phi_{TD}}\exp\left(\frac{V_{expl}}{N \cdot \phi_{TD}}\right) \qquad (9.260)$$

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]

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.

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

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.

C OvervoltageSpecification

Overvoltage warnings in SiMKit

Introduction

Overvoltage flagging is signalling that a (terminal) voltage is outside a specified safe range. A warning will be given when the conditions for giving a warning are fulfilled.

Simple checks for overvoltage have been added to the following models: mos903, mos1100, mos1101, mos1102, mos2002, mos2003, mos3100, mos4000, psp102, psp103.
The checks are done on terminal voltages of the models.

There are many ways to define overvoltage. For a general overvoltage flagging solution Verilog-A should be used.

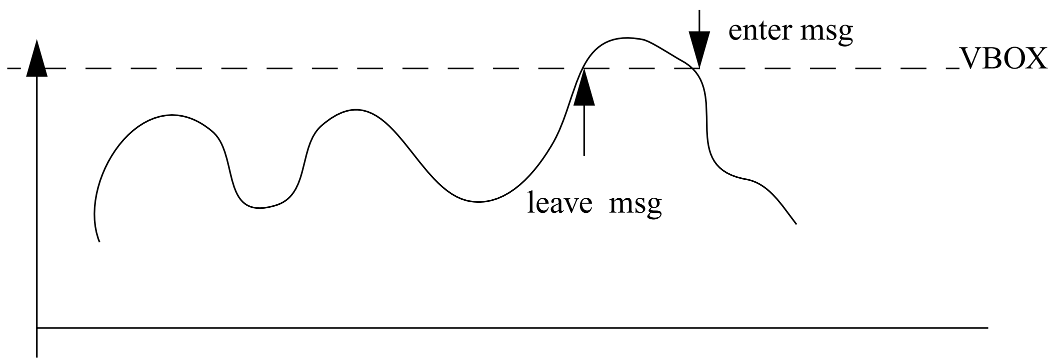
Extra parameters for overvoltage flagging

A set of extra parameters has been added to the mos models mos903, mos1100, mos1101, mos1102, mos2002, mos2003, mos3100, mos4000, psp102, psp103.

Table 4:

Name	Unit	Default	Description
VBOX	V	0.0	Oxide breakdown voltage. Checking will be done if $VBOX > 0$
VBDS	V	0.0	Drain-source breakdown voltage Checking will be done if $VBDS > 0$
TMIN	s	0.0	Ovcheck tmin value

For mos models the safe region is:
$|V_{gs}| < VBOX$ and $|V_{gd}| < VBOX$ and $|V_{ds}| < VBDS$



Ovcheck: two terminal dummy model

A (dummy) two-terminal model ovcheck has been implemented that can be used to check if the voltage between the two terminals is within or without a so called safe region.
The model parameters are:

Name	Unit	Default	Description
VLOW	V	0.0	Lower bound of safe region
VHIGH	V	0.0	Upper bound of safe region Checking will be done when $VHIGH > VLOW$
TMIN	s	0.0	Ovcheck tmin value

For the ovcheck model the safe region is:
$VLOW \le V_{t1} - V_{t2} \le VHIGH$, where t1 is the first and t2 is the second terminal.

Functionality

In Spectre and Pstar

At the end of a DC analysis or in a transient analysis after each time step a check wil be done if the device is inside or outside the safe region.
A warning is given whenever the device enters or leaves the safe region.

In Spectre only

To prevent too many warnings in a Spectre transient analysis the model parameter TMIN has been introduced. If the time between leaving and entering the safe region is less than the TMIN value no warning is given.

Because of the TMIN parameter a warning cannot be issued when leaving the safe region. A warning is given when the device enters the safe region again. This warning includes the time and the voltage when the safe region was exited.At the end of the transient warnings are given for devices that are still out of the safe range.

In Pstar TMIN may be specified as a model parameter, but it will be ignored.

D Parameter PARAMCHK

Parameter PARAMCHK

Introduction

All models have the parameter PARAMCHK. It is not related to the model behavior, but has been introduced control the clip warning messages. Various situations may call for various levels of warnings. This is made possible by setting this parameter.

PARAMCHK model parameter

This model parameter has been added to control the amount of clip warnings.

PARAMCHK	$<$	0	No clip warnings
PARAMCHK	$\geq$	0	Clip warnings for instance parameters (default)
PARAMCHK	$\geq$	1	Clip warnings for model parameters
PARAMCHK	$\geq$	2	Clip warnings for electrical parameters at initialisation
PARAMCHK	$\geq$	3	Clip warnings for electrical parameters during evaluation. This highest level is of interest only for selfheating jobs, where electrical parameters may change dependent on temperature.

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