9 The MOS model, level 902

9.1 Introduction

General Remarks

MOS Model 9 is a compact MOS-transistor model, intended for the simulation of circuit behaviour with emphasis on analogue applications. The model gives a complete description of all transistor-action related quantities: nodal currents and charges, noise-power spectral densities and weak-avalanche currents. The equations describing these quantities are based on the gradual-channel approximation with a number of first-order corrections for small-size effects. The consistency is maintained by using the same carrier-density and electrical-field expressions in the calculation of all model quantities. Model 9 only provides a model for the intrinsic transistor. Junction charges and leakage currents are not included. They are covered by the separate **Juncap** model. Similarly, interconnect capacitances are deferred to the **Intcap** or **ConnectDPEM** model.

Structural Elements of Model 9

Model 9 is separable into a number of relatively independent parts, namely

- **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, usually called the "miniset". Each of these actual parameters can be determined by purely electrical measurements. Since most of these parameters scale with geometry and temperature the process as a whole is characterized by an enlarged set of parameters, which is denoted as the set of reference and scaling parameters, usually called the "maxiset". This set of parameters contains most of the actual parameters for a reference device, a large set of sensitivity coefficients and the reference conditions. From this, the actual parameters for an arbitrary transistor under non-reference conditions are obtained by applying a set of transformation rules to the reference parameters. The transformation rules describe the dependencies of the actual parameters on the length, width, and temperature. This procedure is called preprocessing, as it is normally done only once, prior to the actual electrical simulation.

- **Clipping:** For very uncommon geometries or temperatures, the preprocessing rules may generate parameters that are outside a physically realistic range or that may create difficulties in the numerical evaluation of the model, for example division by zero. In order to prevent this, all parameters are limited to a pre-specified range directly after the preprocessing. This procedure is called clipping.

- **Current equations:** These are all expressions needed to obtain the nodal currents as a function of the bias conditions. They are segmentable in equations for the channel current and for the bulk current. For the channel current many auxiliary equations are needed, e.g. equations for the threshold voltage including back-bias dependency and small-size corrections, for the channel-conductance including mobility reduction and velocity saturation effects, and for the subthreshold region. These finally lead to an expression for the channel current I_{DS}. Due to the small device dimensions, high electrical fields occur, in particular in the vicinity of the drain. The carriers that are responsible for the channel current, can gain sufficient energy from this electrical field to induce electron-hole-pair creation. In turn, for an n-channel device, these extra electrons contribute to the channel current as do the holes to the bulk current. Vice versa, the same holds for p-channel devices.

- **Charge equations:** These are all the equations that are used to calculate the charge quantities Q_D, Q_G, Q_S, and Q_B, which are assigned to the nodes. To a large degree the same auxiliary expressions are used as for the current equations. In a few instances deviations were necessary for numerical reasons.

- **Noise equations:** The total noise output of a transistor consists of a thermal- and a flicker-noise part. They create fluctuations in the channel current. Because of the capacitive coupling between gate and channel region, also current fluctuations in the gate current are induced. These two aspects are covered in Model 9 by assigning two correlated noise-current sources, one connected between drain and source, the other one between gate and source, and an uncorrelated noise-current source between drain and source. The correlated current sources are directional!

- **Embedding model 9:** The electrical model only describes the behaviour of an n-channel device. Therefore, any p-channel device and its bias conditions have to be mapped onto those of an equivalent n-channel transistor. This mapping comprises a number of sign-changes. Also, the model describes a symmetrical device, i.e. the source and drain nodes can be interchanged without changing the electrical properties. The assignment of source and drain to the channel nodes is based on the voltages of these nodes: for an n-channel transistor the node at the highest potential is called the drain. In a circuit simulator the nodes are denoted by their network numbers, based on the circuit configuration. Again, a transformation is necessary involving a number of sign changes, including the directional noise-current sources.

Structure of the Documentation

After this introductory section, first the nomenclature as it is used in this model is defined. Next, there is a separate section on the physical background of the model.

Then, each of the structural elements of model 9 is discussed in detail. Finally, a chapter on the general validity range is added. More precise information on the accuracy for a certain type of transistor can be found in the appropriate process document, because such a discussion only makes sense in combination with a specific parameter set. One is therefore referred to the various “Blue Books’’ (design rules, parameter sets etc.).

9.1.1 Changes from MOS level 901

For the modelled capacitance expressions of MOS Model 901 the following deficiencies have been observed :

- in the capacitance C_{GD} an overshoot becomes manifest for values of V_{DS} near V_{DSS}.
- in the passive mode (with for instance all bias voltages set to zero), the capacitances are not reciprocal (mostly Q_{BD}).

These problems appear to be due to the bulk charge expression, and in particular the part Q_{BD}, which does not saturate for $V_{DS}>V_{DSS}$.

The above-mentioned problems have been cured in MOS Model 902 by making the following changes :

- the value of the smoothing factor ε_6 is changed from 0.5 to 0.03;
- V_{DB} in the Q_{BD} expression is changed to $V_{DS2} + V_{SB}$.
- The influence of V_{DS} on Q_{BS} by using V_{T1} instead of V_{T2}

The preprocessing of V_{TO} with length has also been changed. When measuring the threshold voltage of p-channel transistors a so called roll-up of this parameter is found as the length decreases. In the preprocessing of MOS Model 901 this effect is not included in the preprocessing rule.

- A new scaling rule for the mobility reduction parameter ϑ_1 has been implemented in MOS MODEL 9, leading to a considerably improved modelling accuracy in both the linear and saturation regime. See equations (9.71), (9.72), and (9.73).

The model change is based on calculations of the series resistance for devices that exhibit the phenomenon of dogboning, i.e. the contacted source / drain area of narrow channels is broader than the actual channel under the gate, as imposed by the layout design rules.

The new scaling rule uses two new parameters, W_{DOG} and f_{θ_1}. The default values of these parameters have been chosen in such a way that the adapted model is backwards compatible. (If W_{DOG} and f_{θ_1} are not specified, you won't notice the change.)

Finally we note that the choice of the reference transistor is now restricted to

$$W_{ER} \geq W_{EDOG}.$$

9.2 Nomenclature

The symbolic representation and the programming names of the quantities listed in the following sections, have been chosen in such a way to express their purpose and relations to other quantities and to preclude ambiguity and inconsistency.

9.2.1 Glossary of used symbols

All parameters which refer to the reference transistor and / or the reference temperature have a symbol with the subscript R and a programming name ending with R. All characters 0 (zero) in subscripts of parameters are represented by the capital letter O in the programming name. Scaling parameters are indicated by S with a subscript where the variables on which the parameter depends, preceed a semicolon whereas the parameter succeeds it, e.g. $S_{\mathrm{T},L;\theta 1}$. Generally, voltages related to energy levels are indicated by ϕ, exponents by η, the small smoothing parameters by ε and the model constants by λ. In the programming names, the greek characters are abbreviated by the first three letters of their names, e.g. β by BET.

The drain, gate, source and bulk terminals are indicated by D, G, S and B respectively.

The electrical variables are split into the external electrical variables which represent the electrical quantities, observed at the nodes of the physical device, and the internal electrical variables.

External Electrical Variables

The definitions of the external electrical variables are illustrated in Fig. 39.

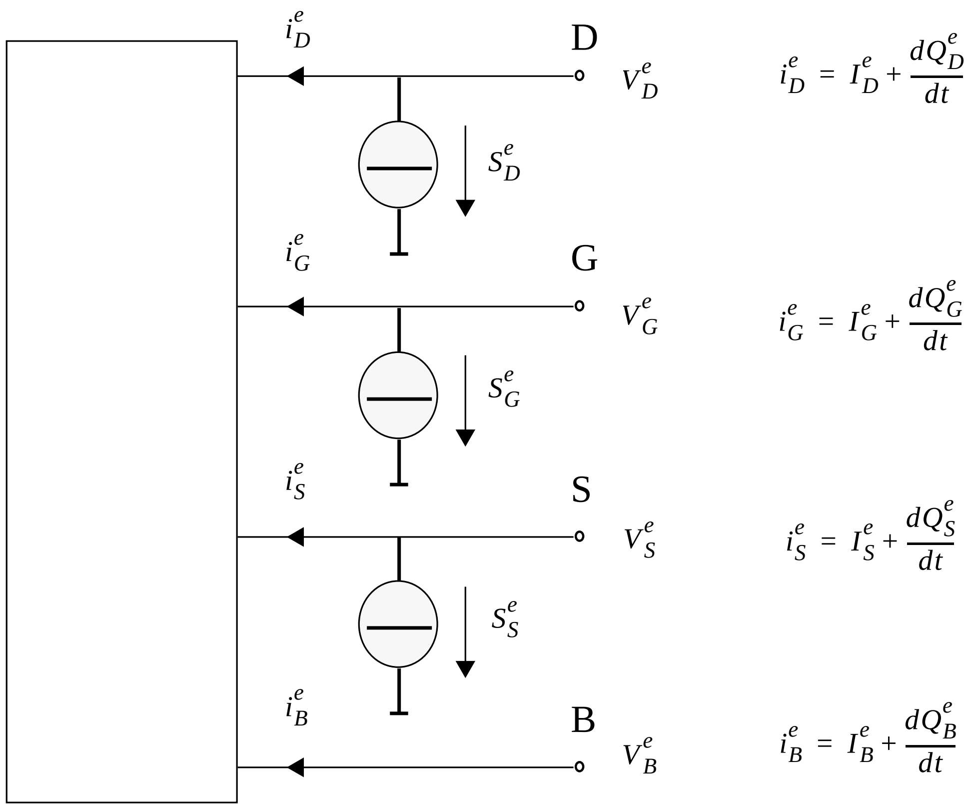


Figure 39: Definition of the external electrical variables

No.	Variable	Prog. Name	Units	Description
1	V_D^e	VDE	V	Potential applied to the drain node
2	V_G^e	VGE	V	Potential applied to the gate node
3	V_S^e	VSE	V	Potential applied to the source node
4	V_B^e	VBE	V	Potential applied to the bulk node
5	I_D^e	IDE	A	DC current into the drain
6	I_G^e	IGE	A	DC current into the gate
7	I_S^e	ISE	A	DC current into the source
8	I_B^e	IBE	A	DC current into the bulk
9	Q_D^e	QDE	C	Charge in the device attributed to the drain node
10	Q_G^e	QGE	C	Charge in the device attributed to the gate node
11	Q_S^e	QSE	C	Charge in the device attributed to the source node
12	Q_B^e	QBE	C	Charge in the device attributed to the bulk node
13	S_D^e	SDE	A^2s	Spectral density of the noise current into the drain
14	S_G^e	SGE	A^2s	Spectral density of the noise current into the gate
15	S_S^e	SSE	A^2s	Spectral density of the noise current into the source

No.	Variable	Prog. Name	Units	Description
16	S^e_{DG}	SDGE	A^2s	Cross spectral density of the noise current into the drain and the noise current into the gate
17	S^e_{GS}	SGSE	A^2s	Cross spectral density of the noise current into the gate and the noise current into the source
18	S^e_{SD}	SSDE	A^2s	Cross spectral density of the noise current into the source and the noise current into the drain

Internal Electrical Variables

No.	Variable	Progr. Name	Units	Description
1	V_{DS}	VDS	V	Drain-to-source voltage applied to the equivalent n-MOS
2	V_{GS}	VGS	V	Gate-to-source voltage applied to the equivalent n-MOS
3	V_{SB}	VSB	V	Source-to-bulk voltage applied to the equivalent n-MOS
4	I_{DS}	IDS	A	DC current through the channel flowing from drain to source
5	I_{AVL}	IAVL	A	DC current flowing from drain to the bulk due to the weak-avalanche effect
6	Q_D	QD	C	Charge in the equivalent n-MOS attributed to the drain node
7	Q_G	QG	C	Charge in the equivalent n-MOS attributed to the gate node
8	Q_S	QS	C	Charge in the equivalent n-MOS attributed to the source node
9	Q_B	QB	C	Charge in the equivalent n-MOS attributed to the bulk node
10	S_{th}	STH	A^2s	Spectral density of the thermal-noise current of the channel
11	S_{fl}	SFL	A^2s	Spectral density of the flicker-noise current of the channel
12	S_{ig}	SIG	A^2s	Spectral density of the noise current induced in the gate
13	S_{igth}	SIGTH	A^2s	Cross spectral density of the noise current induced in the gate and the thermal-noise current of the channel

9.2.2 Parameters

Parameters of the geometrical model

These parameters correspond to the geometrical model (MN, MP) in **Pstar.**

No.	Symbol	Progr. Name	Units	Description
1		LEVEL	-	Must be 902
2	L_{ER}	LER	m	Effective channel length of the reference transistor
3	W_{ER}	WER	m	Effective channel width of the reference transistor
4	ΔL_{PS}	LVAR	m	Difference between the actual and the programmed poly-silicon gate length
5	$\Delta L_{\mathrm{overlap}}$	LAP	m	Effective channel length reduction per side due to the lateral diffusion of the source/drain dopant ions
6	ΔW_{OD}	WVAR	m	Difference between the actual and the programmed field-oxide opening
7	$\Delta W_{\mathrm{narrow}}$	WOT	m	Effective reduction of the channel width per side due to the lateral diffusion of the channel-stop dopant ions
8	T_R	TR	°C	Temperature at which the parameters for the reference transistor have been determined
9	V_{T0R}	VTOR	V	Threshold voltage at zero black-bias for the reference transistor at the reference temperature
10	$S_{T;V_{T0}}$	STVTO	VK^{-1}	Coefficient of the temperature dependence V_{T0}
11	$S_{L;V_{T0}}$	SLVTO	Vm	Coefficient of the length dependence of V_{T0}
12	$S_{L2;V_{T0}}$	SL2VTO	Vm^2	Second coefficient of the length dependence of V_{T0}
13	$S_{W;V_{T0}}$	SWVTO	Vm	Coefficient of the width dependence of V_{T0}

No.	Symbol	Progr. Name	Units	Description
14	K_{0R}	KOR	$V^{1/2}$	Low-backbias body factor for the reference transistor
15	$S_{L;K_0}$	SLKO	$V^{1/2}m$	Coefficient of the length dependence of K_0
16	$S_{W;K_0}$	SWKO	$V^{1/2}m$	Coefficient of the width dependence of K_0
17	K_R	KR	$V^{1/2}$	High-backbias body factor for the reference transistor
18	$S_{L;K}$	SLK	$V^{1/2}m$	Coefficient of the length dependence of K
19	$S_{W;K}$	SWK	$V^{1/2}m$	Coefficient of the width dependence of K
20	ϕ_{BR}	PHIBR	V	Surface potential at strong inversion for the reference transistor at the reference temperature
21	V_{SBXR}	VSBXR	V	Transition voltage for the dual-k-factor model for the reference transistor
22	$S_{L;V_{SBX}}$	SLVSBX	Vm	Coefficient of the length dependence of V_{SBX}
23	$S_{W;V_{SBX}}$	SWVSBX	Vm	Coefficient of the width dependence V_{SBX}
24	β_{sq}	BETSQ	AV^{-2}	Gain factor for an infinite square transistor at the reference temperature
25	η_β	ETABET	-	Exponent of the temperature dependence of the gain factor
26	θ_{1R}	THE1R	V^{-1}	Coefficient of the mobility reduction due to the gate-induced field for the reference transistor at the reference temperature
27	$S_{T;\theta_1,R}$	STTHE1R	$V^{-1}K^{-1}$	Coefficient of the temperature dependence of θ_1 for the reference transistor
28	$S_{L;\theta_1,R}$	SLTHE1R	$V^{-1}m$	Coefficient of the length dependence of θ_1 at the reference temperature
29	$S_{T,L;\theta_1}$	STLTHE1	$V^{-1}mK^{-1}$	Coefficient of the temperature dependence of the length dependence of θ_1
30	$S_{W;\theta_1}$	SWTHE1	$V^{-1}m$	Coefficient of the width dependence of θ_1

No.	Symbol	Progr. Name	Units	Description
31	θ_{2R}	THE2R	$V^{-1/2}$	Coefficient of the mobility reduction due to the back-bias for the reference transistor at the reference temperature
32	$S_{T;\theta_2,R}$	STTHE2R	$V^{-1/2}K^{-1}$	Coefficient of the temperature dependence of θ_2 for the reference transistor
33	$S_{L;\theta_2,R}$	SLTHE2R	$V^{-1/2}m$	Coefficient of the length dependence of θ_2 at the reference temperature
34	$S_{T,L;\theta_2}$	STLTHE2	$V^{-1/2}mK^{-1}$	Coefficent of the temperature dependence of the length dependence of θ_2
35	$S_{W;\theta_2}$	SWTHE2	$V^{-1/2}m$	Coefficient of the width dependence of θ_2
36	θ_{3R}	THE3R	V^{-1}	Coefficient of the mobility reduction due to the lateral field for the reference transistor at the reference temperature
37	$S_{T;\theta_3,R}$	STTHE3R	$V^{-1}K^{-1}$	Coefficient of the temperature dependence of θ_3 for the reference temperature
38	$S_{L;\theta_3,R}$	SLTHE3R	$V^{-1}m$	Coefficient of the length dependence of θ_3 at the reference temperature
39	$S_{T,L;\theta_3}$	STLTHE3	$V^{-1}mK^{-1}$	Coefficient of the temperature dependence of the length dependence of θ_3
40	$S_{W;\theta_3}$	SWTHE3	$V^{-1}m$	Coefficient of the width dependence of θ_3
41	γ_{1R}	GAM1R	$V^{(1-\eta_{DS})}$	Coefficient for the drain induced threshold shift for large gate drive for the reference transistor
42	$S_{L;\gamma_1}$	SLGAM1	$V^{(1-\eta_{DS})}m$	Coefficient of the length dependence of γ_1
43	$S_{W;\gamma_1}$	SWGAM1	$V^{(1-\eta_{DS})}m$	Coefficient of the width dependence of γ_1
44	η_{DSR}	ETADSR	-	Exponent of the V_{DS} dependence of γ_1 for the reference transistor
45	α_R	ALPR	-	Factor of the channel-length modulation for the reference transistor
46	η_α	ETAALP	-	Exponent of the length dependence of α

No.	Symbol	Progr. Name	Units	Description
47	$S_{L;\alpha}$	SLALP	m^{η_α}	Coefficient of the length dependence of α
48	$S_{W;\alpha}$	SWALP	m	Coefficient of the width dependence of α
49	V_{PR}	VPR	V	Characteristic voltage of the channel-length modulation for the reference transistor
50	γ_{00R}	GAMOOR	-	Coefficient of the drain induced threshold shift at zero gate drive for the reference transistor
51	$S_{L;\gamma_{00}}$	SLGAMOO	m^2	Coefficient of the length dependence of γ_{00}
52	$\eta_{\gamma R}$	ETAGAMR	-	Exponent of the back-bias dependence of γ_0 for the reference transistor
53	m_{0R}	MOR	-	Factor of the subthreshold slope for the reference transistor at the reference temperature
54	$S_{T;m_0}$	STMO	K^{-1}	Coefficient of the temperature dependence of m_0
55	$S_{L;m_0}$	SLMO	$m^{1/2}$	Coefficient of the length dependence of m_0
56	η_{mR}	ETAMR	-	Exponent of the back-bias dependence of m for the reference transistor
57	ζ_{1R}	ZET1R	-	Weak-inversion correction factor for the reference transistor
58	η_ζ	ETAZET	-	Exponent of the length dependence of ζ_1
59	$S_{L;\zeta_1}$	SLZET1	m^{η_ζ}	Coefficient of the length dependence of ζ_1
60	V_{SBTR}	VSBTR	V	Limiting voltage of the V_{SB} dependence of m and γ_0 for the reference transistor
61	$S_{L;V_{SBT}}$	SLVSBT	Vm	Coefficient of the length dependence of V_{SBT}

No.	Symbol	Progr. Name	Units	Description
62	a_{1R}	A1R	-	Factor of the weak-avalanche current for the reference transistor at the reference temperature
63	$S_{T;a_1}$	STA1	K^{-1}	Coefficient of the temperature dependence of a_1
64	$S_{L;a_1}$	SLA1	m	Coefficient of the length dependence of a_1
65	$S_{W;a_1}$	SWA1	m	Coefficient of the width dependence of a_1
66	a_{2R}	A2R	V	Exponent of the weak-avalanche current for the reference transistor
67	$S_{L;a_2}$	SLA2	Vm	Coefficient of the length dependence of a_2
68	$S_{W;a_2}$	SWA2	Vm	Coefficient of the width dependence of a_2
69	a_{3R}	A3R	-	Factor of the drain-source voltage above which weak-avalanche occurs, for the reference transistor
70	$S_{L;a_3}$	SLA3	m	Coefficient of the length dependence of a_3
71	$S_{W;a_3}$	SWA3	m	Coefficient of the width dependence of a_3
72	t_{ox}	TOX	m	Thickness of the oxide layer
73	C_{ol}	COL	Fm^{-1}	Gate overlap capacitance per unit channel width
74	N_{TR}	NTR	J	Coefficient of the thermal noise for the reference transistor
75	N_{FR}	NFR	V^2	Coefficient of the flicker noise for the reference transistor
76	L	L	m	Drawn channel length in the lay-out of the actual transistor
77	W	W	m	Drawn channel width in the lay-out of the actual transistor
78	ΔT_A	DTA	°C	Temperature offset of the device with respect to T_A

No.	Symbol	Progr. Name	Units	Description
79	N_{MULT}	MULT	-	Number of devices in parallel
80	W_{DOG}	WDOG	m	Characteristic drawn gate width, below which dogboning appears
81	f_{θ_1}	FTHE1	-	Coefficient describing the width dependence of θ_1 for $W < W_{\mathrm{DOG}}$

Remark: The parameters *L, W,* and *DTA* are used to calculate the electrical parameters of the actual transistor, as specified in the section on parameter preprocessing.

Parameters of the electrical model

These parameter correspond to the electrical model in **Pstar** (MNE, MPE).

No.	Symbol	Progr. Name	Units	Description
1		LEVEL	-	Must be 902
2	V_{T0}	VTO	V	Threshold voltage at zero back-bias for the actual transistor at the actual temperature
3	K_0	K0	$V^{1/2}$	Low-backbias body factor for the actual transistor
4	K	K	$V^{1/2}$	High-backbias body factor for the actual transistor
5	ϕ_B	PHIB	V	Surface potential at strong inversion for the actual transistor at the actual temperature
6	V_{SBX}	VSBX	V	Transition voltage for the dual-k-factor model for the actual transistor
7	β	BET	AV^{-2}	Gain factor for the actual transistor at the actual temperature
8	θ_1	THE1	V^{-1}	Coefficient of the mobility reduction due to the gate-induced field for the actual transistor at the actual temperature
9	θ_2	THE2	$V^{-1/2}$	Coefficient of the mobility reduction due to the back-bias for the actual transistor at the actual temperature
10	θ_3	THE3	V^{-1}	Coefficient of the mobility reduction due to the lateral field for the actual transistor at the actual temperature
11	γ_1	GAM1	$V^{(1-\eta_{DS})}$	Coefficient for the drain induced threshold shift for large gate drive for the actual transistor
12	η_{DS}	ETADS	-	Exponent of the V_{DS} dependence of γ_1 for the actual transistor
13	α	ALP	-	Factor of the channel-length modulation for the actual transistor
14	V_P	VP	V	Characteristic voltage of the channel-length modulation for the actual transistor

No.	Symbol	Progr. Name	Units	Description
15	γ_{00}	GAM00	-	Coefficient of the drain induced threshold shift at zero gate drive for the actual transistor
16	η_{γ}	ETAGAM	-	Exponent of the back-bias dependence of γ_0 for the actual transistor
17	m_0	MO	-	Factor of the subthreshold slope for the actual transistor at the actual temperature
18	η_m	ETAM	-	Exponent of the back-bias dependence m for the actual transistor
19	ϕ_T	PHIT	V	Thermal voltage at the actual temperature
20	ζ_1	ZET1	-	Weak-inversion correction factor for the actual transistor
21	V_{SBT}	VSBT	V	Limiting voltage of V_{SB} dependence of m and γ_0 for the actual transistor
22	a_1	A1	-	Factor of the weak-avalanche current for the actual transistor
23	a_2	A2	V	Exponent of the weak-avalanche current for the actual transistor
24	a_3	A3	-	Factor of the drain-source voltage above which weak-avalanche occurs for the actual transistor
25	C_{ox}	COX	F	Gate-to-channel capacitance for the actual transistor
26	C_{GDO}	CGDO	F	Gate-drain overlap capacitance for the actual transistor
27	C_{GSO}	CGSO	F	Gate-source overlap capacitance for the actual transistor
28	N_T	NT	J	Coefficient of the thermal noise for the actual transistor
29	N_F	NF	V^2	Coefficient of the flicker noise for the actual transistor
30	$MULT$	MULT	-	Number of devices operating in parallel

9.2.3 Model constants

The following is a list of constants hardcoded in **Pstar**.

No.	Constant	Units	Description
1	T_0	K	Offset for conversion from Celsius to Kelvin temperature scale (273.15)
2	k	JK^{-1}	Boltzmann constant $(1.3806226 \cdot 10^{-23})$
3	q	C	Elementary unit charge $(1.6021918 \cdot 10^{-19})$
4	ε_{ox}	Fm^{-1}	Absolute permittivity of the oxide layer $(3.453143800 \cdot 10^{-11})$

9.3 Pstar specific items

9.3.1 Syntax

n-channel geometrical model	:	MN_n (D, G, S, B)	<parameters>
p-channel geometrical model	:	MP_n (D, G, S, B)	<parameters>
n-channel electrical model	:	MNE_n (D, G, S, B)	<parameters>
p-channel electrical model	:	MPE_n (D, G, S, B)	<parameters>

n	:	occurrence indicator
<parameters>	:	list of model parameters

D, G, S and B are drain, gate, source and bulk terminals respectively.

9.3.2 Pstar specific values

The default values and clipping values as used by **Pstar** for the parameters of the geometrical MOS model, level 902 (n-channel) are listed below.

No.	Parameter	Units	Default	Clip low	Clip high
1	*LEVEL*	-	902	-	-
2	*LER*	m	1.10×10^{-6}	1.0×10^{-10}	-
3	*WER*	m	20.00×10^{-6}	1.0×10^{-10}	-
4	*LVAR*	m	-0.220×10^{-6}	-	-
5	*LAP*	m	0.100×10^{-6}	-	-
6	*WVAR*	m	-0.025×10^{-6}	-	-
7	*WOT*	m	0.000×10^{-6}	-	-
8	*TR*	°C	21.00	-273.15	-
9	*VTOR*	V	0.730	-	-
10	*STVTO*	VK^{-1}	-1.20×10^{-3}	-	-
11	*SLVTO*	Vm	-0.135×10^{-6}	-	-
12	*SL2VTO*	Vm^2	0.0	-	-
13	*SWVTO*	Vm	0.130×10^{-6}	-	-
14	*KOR*	$V^{1/2}$	0.650	-	-
15	*SLKO*	$V^{1/2}m$	-0.130×10^{-6}	-	-
16	*SWKO*	$V^{1/2}m$	0.002×10^{-6}	-	-
17	*KR*	$V^{1/2}$	0.110	-	-
18	*SLK*	$V^{1/2}m$	-0.280×10^{-6}	-	-
19	*SWK*	$V^{1/2}m$	0.275×10^{-6}	-	-
20	*PHIBR*	V	0.650	-	-
21	*VSBXR*	V	0.660	-	-

No.	Parameter	Units	Default	Clip low	Clip high
22	*SLVSBX*	Vm	0.000×10^{-6}	-	-
23	*SWVSBX*	Vm	-0.675×10^{-6}	-	-
24	*BETSQ*	AV^{-2}	83.00×10^{-6}	-	-
25	*ETABET*	-	1.600	-	-
26	*THE1R*	V^{-1}	0.190	-	-
27	*STTHE1R*	$V^{-1}K^{-1}$	0.000×10^{-3}	-	-
28	*SLTHE1R*	$V^{-1}m$	0.140×10^{-6}	-	-
29	*STLTHE1*	$V^{-1}mK^{-1}$	0.000×10^{-3}	-	-
30	*SWTHE1*	$V^{-1}m$	-0.058×10^{-6}	-	-
31	*THE2R*	$V^{-1/2}$	0.012	-	-
32	*STTHE2R*	$V^{-1/2}K^{-1}$	0.000×10^{-9}	-	-
33	*SLTHE2R*	$V^{-1/2}m$	-0.033×10^{-6}	-	-
34	*STLTHE2*	$V^{-1/2}mK^{-1/2}$	0.000×10^{-3}	-	-
35	*SWTHE2*	$V^{-1/2}m$	0.030×10^{-6}	-	-
36	*THE3R*	V^{-1}	0.145	-	-
37	*STTHE3R*	$V^{-1}K^{-1}$	-0.660×10^{-3}	-	-
38	*SLTHE3R*	$V^{-1}m$	0.185×10^{-6}	-	-
39	*STLTHE3*	$V^{-1}mK^{-1}$	-0.620×10^{-9}	-	-
40	*SWTHE3*	$V^{-1}m$	0.020×10^{-6}	-	-
41	*GAM1R*	$V^{(1-\eta_{DS})}$	0.145	-	-
42	*SLGAM1*	$V^{(1-\eta_{DS})}$ m	0.160×10^{-6}	-	-
43	*SWGAM1*	$V^{(1-\eta_{DS})}$ m	-0.010×10^{-6}	-	-
44	*ETADSR*	-	0.600	-	-

No.	Parameter	Units	Default	Clip low	Clip high
45	*ALPR*	-	0.003	-	-
46	*ETAALP*	-	0.150	-	-
47	*SLALP*	m^{η_α}	-5.65×10^{-3}	-	-
48	*SWALP*	m	1.67×10^{-9}	-	-
49	*VPR*	V	0.340	-	-
50	*GAMOOR*	-	0.018	-	-
51	*SLGAMOO*	m^2	20.00×10^{-15}	-	-
52	*ETAGAMR*	-	2.0	-	-
53	*MOR*	-	0.500	-	-
54	*STMO*	K^{-1}	$0.000 \times 10^{+0}$	-	-
55	*SLMO*	$m^{1/2}$	0.280×10^{-3}	-	-
56	*ETAMR*	-	2.0	-	-
57	*ZET1R*	-	0.420	-	-
58	*ETAZET*	-	0.170	-	-
59	*SLZET1*	m^{η_ζ}	-0.390	-	-
60	*VSBTR*	V	2.10	-	-
61	*SLVSBT*	Vm	-4.40×10^{-6}	-	-
62	*A1R*	-	6.00	-	-
63	*STA1*	K^{-1}	$0.000 \times 10^{+0}$	-	-
64	*SLA1*	m	1.30×10^{-6}	-	-
65	*SWA1*	m	3.00×10^{-6}	-	-
66	*A2R*	V	38.0	-	-
67	*SLA2*	Vm	1.00×10^{-6}	-	-
68	*SWA2*	Vm	2.00×10^{-6}	-	-

No.	**Parameter**	**Units**	**Default**	**Clip low**	**Clip high**
69	*A3R*	-	0.650	-	-
70	*SLA3*	m	-0.550×10^{-6}	-	-
71	*SWA3*	m	0.000×10^{-6}	-	-
72	*TOX*	m	25.0×10^{-9}	-	-
73	*COL*	Fm^{-1}	0.320×10^{-9}	-	-
74	*NTR*	J	0.244×10^{-19}	-	-
75	*NFR*	V^2	0.700×10^{-10}	-	-
76	*L*	m	1.50×10^{-6}	-	-
77	*W*	m	20.0×10^{-6}	-	-
78	*DTA*	°C	0.0	-	-
79	*MULT*	-	1.0	0.0	-
80	WDOG	m	0.0	0.0	-
81	FTHE1	-	0.0	-	-

The default values and clipping values as used by **Pstar** for the parameters of the geometrical MOS model, level 902 (p-channel) are listed below.

No.	Parameter	Units	Default	Clip low	Clip high
1	*LEVEL*	-	902	-	-
2	*LER*	m	1.25×10^{-6}	1.0×10^{-10}	-
3	*WER*	m	20.00×10^{-6}	1.0×10^{-10}	-
4	*LVAR*	m	-0.460×10^{-6}	-	-
5	*LAP*	m	0.025×10^{-6}	-	-
6	*WVAR*	m	-0.130×10^{-6}	-	-
7	*WOT*	m	0.000×10^{-6}	-	-
8	*TR*	°C	21.0	-273.15	-
9	*VTOR*	V	1.100	-	-
10	*STVTO*	VK^{-1}	-1.7×10^{-3}	-	-
11	*SLVTO*	Vm	0.035×10^{-6}	-	-
12	*SL2VTO*	Vm	0.0	-	-
13	*SWVTO*	Vm	0.050×10^{-6}	-	-
14	*KOR*	$V^{1/2}$	0.470	-	-
15	*SLKO*	$V^{1/2}m$	-0.200×10^{-6}	-	-
16	*SWKO*	$V^{1/2}m$	0.115×10^{-6}	-	-
17	*KR*	$V^{1/2}$	0.470	-	-
18	*SLK*	$V^{1/2}m$	-0.200×10^{-6}	-	-
19	*SWK*	$V^{1/2}m$	0.115×10^{-6}	-	-
20	*PHIBR*	V	0.650	-	-
21	*VSBXR*	V	0.0	-	-
22	*SLVSBX*	Vm	0.0	-	-
23	*SWVSBX*	Vm	0.0	-	-

No.	Parameter	Units	Default	Clip low	Clip high
24	*BETSQ*	AV^{-2}	26.1×10^{-6}	-	-
25	*ETABET*	-	1.6	-	-
26	*THE1R*	V^{-1}	0.190	-	-
27	*STTHE1R*	$V^{-1}K^{-1}$	0.000×10^{-3}	-	-
28	*SLTHE1R*	$V^{-1}m$	0.70×10^{-6}	-	-
29	*STLTHE1*	$V^{-1}mK^{-1}$	0.000×10^{-3}	-	-
30	*SWTHE1*	$V^{-1}m$	-0.080×10^{-6}	-	-
31	*THE2R*	$V^{-1/2}$	0.165	-	-
32	*STTHE2R*	$V^{-1/2}K^{-1}$	0.000×10^{-9}	-	-
33	*SLTHE2R*	$V^{-1/2}m$	-0.075×10^{-6}	-	-
34	*STLTHE2*	$V^{-1/2}mK^{-1/2}$	0.000×10^{-3}	-	-
35	*SWTHE2*	$V^{-1/2}m$	0.020×10^{-6}	-	-
36	*THE3R*	V^{-1}	0.027	-	-
37	*STTHE3R*	$V^{-1}K^{-1}$	0.000×10^{-9}	-	-
38	*SLTHE3R*	$V^{-1}m$	0.027×10^{-6}	-	-
39	*STLTHE3*	$V^{-1}mK^{-1}$	0.000×10^{-3}	-	-
40	*SWTHE3*	$V^{-1}m$	0.011×10^{-6}	-	-
41	*GAM1R*	$V^{(1-\eta_{DS})}$	0.077	-	-
42	*SLGAM1*	$V^{(1-\eta_{DS})}\,m$	0.105×10^{-6}	-	-
43	*SWGAM1*	$V^{(1-\eta_{DS})}\,m$	-0.011×10^{-6}	-	-
44	*ETADSR*	-	$0.600 \times 10^{+0}$	-	-
45	*ALPR*	-	0.044	-	-
46	*ETAALP*	-	0.170	-	-

No.	Parameter	Units	Default	Clip low	Clip high
47	*SLALP*	m^{η_α}	9.00×10^{-3}	-	-
48	*SWALP*	m	0.180×10^{-9}	-	-
49	*VPR*	V	0.235	-	-
50	*GAMOOR*	-	0.007	-	-
51	*SLGAMOO*	m^2	11.0×10^{-15}	-	-
52	*ETAGAMR*	-	1.0	-	-
53	*MOR*	-	0.375	-	-
54	*STMO*	K^{-1}	$0.000 \times 10^{+0}$	-	-
55	*SLMO*	$m^{1/2}$	0.047×10^{-3}	-	-
56	*ETAMR*	-	1.0	-	-
57	*ZET1R*	-	1.30	-	-
58	*ETAZET*	-	0.03	-	-
59	*SLZET1*	m^{η_α}	-2.80	-	-
60	*VSBTR*	V	100.0	-	-
61	*SLVSBT*	Vm	0.00×10^{-6}	-	-
62	*A1R*	-	10.0	-	-
63	*STA1*	K^{-1}	$0.000 \times 10^{+0}$	-	-
64	*SLA1*	m	-15.0×10^{-6}	-	-
65	*SWA1*	m	30.0×10^{-6}	-	-
66	*A2R*	V	59.0	-	-
67	*SLA2*	Vm	-8.00×10^{-6}	-	-
68	*SWA2*	Vm	15.0×10^{-6}	-	-
69	*A3R*	-	0.520	-	-
70	*SLA3*	m	-0.450×10^{-6}	-	-

No.	Parameter	Units	Default	Clip low	Clip high
71	*SWA3*	m	-0.140×10^{-6}	-	-
72	*TOX*	m	25.0×10^{-9}	-	-
73	*COL*	Fm^{-1}	0.320×10^{-9}	-	-
74	*NTR*	J	0.211×10^{-19}	-	-
75	*NFR*	V^2	0.214×10^{-10}	-	-
76	*L*	m	1.50×10^{-6}	-	-
77	*W*	m	20.0×10^{-6}	-	-
78	*DTA*	°C	0.0	-	-
79	*MULT*	-	1.0	0.0	-
80	*WDOG*	m	0.0	0.0	-
81	*FTHE1*	-	0.0	-	-

The default values and clipping values as used by **Pstar** for the parameters of the electrical MOS model, level 902 (n-channel) are listed below.

No.	Parameter	Units	Default	Clip low	Clip high
1	*LEVEL*	-	902	-	-
2	*VTO*	V	7.099154×10^{-01}	-	-
3	*KO*	$V^{-1/2}$	6.478116×10^{-01}	1.0×10^{-12}	-
4	*K*	$V^{-1/2}$	4.280174×10^{-01}	See note [a]	-
5	*PHIB*	V	6.225999×10^{-01}	1.0×10^{-12}	-
6	*VSBX*	V	6.599578×10^{-01}	1.0×10^{-12}	-
7	*BET*	AV^{-2}	1.418789×10^{-03}	0.0	-
8	*THE1*	V^{-1}	1.923533×10^{-01}	0.0	-
9	*THE2*	$V^{-1/2}$	1.144632×10^{-02}	0.0	1.0
10	*THE3*	V^{-1}	1.381597×10^{-01}	0.0	-
11	*GAM1*	$V^{(1-\eta_{DS})}$	1.476930×10^{-01}	0.0	-
12	*ETADS*	-	6.000000×10^{-01}	-	-
13	*ALP*	-	2.878165×10^{-03}	0.0	-
14	*VP*	V	3.338182×10^{-01}	1.0×10^{-12}	-
15	*GAM00*	-	1.861785×10^{-02}	0.0	-
16	*ETAGAM*	-	$2.000000 \times 10^{+00}$	-	-
17	*MO*	-	5.024606×10^{-01}	1.0×10^{-12}	-
18	*ETAM*	-	$2.000000 \times 10^{+00}$	-	-
19	*PHIT*	V	2.662680×10^{-02}	0.0	-
20	*ZET1*	-	4.074464×10^{-01}	1.0×10^{-12}	-
21	*VSBT*	V	$2.025926 \times 10^{+00}$	0.0	-

No.	Parameter	Units	Default	Clip low	Clip high
22	*A1*	-	$6.022073 \times 10^{+00}$	0.0	-
23	*A2*	V	$3.801696 \times 10^{+01}$	1.0×10^{-12}	-
24	*A3*	-	6.407407×10^{-01}	0.0	-
25	*COX*	F	2.979787×10^{-14}	0.0	-
26	*CGDO*	F	6.392000×10^{-15}	0.0	-
27	*CGSO*	F	6.392000×10^{-15}	0.0	-
28	*NT*	J	2.563182×10^{-20}	0.0	-
29	*NF*	V^2	7.138553×10^{-11}	0.0	-
30	*MULT*	-	1.0	0.0	-

a. The lower bound for $K = K_0 \cdot \dfrac{\sqrt{\mathrm{hyp}_1(-V_{SBX}, \varepsilon_2)}}{\sqrt{V_{SBX} + \phi_B}}$

The default values and clipping values as used by **Pstar** for the parameters of the electrical MOS model, level 902 (p-channel) are listed below.

No.	Parameter	Units	Default	Clip low	Clip high
1	*LEVEL*	-	902	-	-
2	*VTO*	V	$1.082125\times10^{+00}$	-	-
3	*KO*	$V^{-1/2}$	4.280174×10^{-01}	1.0×10^{-12}	-
4	*K*	$V^{-1/2}$	4.280174×10^{-01}	See note [a]	-
5	*PHIB*	V	6.225999×10^{-01}	1.0×10^{-12}	-
6	*VSBX*	V	1.000000×10^{-12}	1.0×10^{-12}	-
7	*BET*	AV^{-2}	4.841498×10^{-04}	0.0	-
8	*THE1*	V^{-1}	2.046809×10^{-01}	0.0	-
9	*THE2*	$V^{-1/2}$	1.492490×10^{-01}	0.0	1.0
10	*THE3*	V^{-1}	3.267633×10^{-02}	0.0	-
11	*GAM1*	$V^{(1-\eta_{DS})}$	9.905701×10^{-01}	0.0	-
12	*ETADS*	-	6.000000×10^{-01}	-	-
13	*ALP*	-	4.766925×10^{-02}	0.0	-
14	*VP*	V	1.861200×10^{-01}	1.0×10^{-12}	-
15	*GAM00*	-	1.118334×10^{-02}	0.0	-
16	*ETAGAM*	-	$1.000000\times10^{+00}$	-	-
17	*MO*	-	3.801987×10^{-01}	1.0×10^{-12}	-
18	*ETAM*	-	$1.000000\times10^{+00}$	-	-
19	*PHIT*	V	2.662680×10^{-02}	0.0	-
20	*ZET1*	-	$1.270446\times10^{+00}$	1.0×10^{-12}	-
21	*VSBT*	V	$1.000000\times10^{+02}$	0.0	-

No.	Parameter	Units	Default	Clip low	Clip high
22	*A1*	-	$6.858299 \times 10^{+00}$	0.0	-
23	*A2*	V	$5.732410 \times 10^{+01}$	1.0×10^{-12}	-
24	*A3*	-	4.254087×10^{-01}	0.0	-
25	*COX*	F	2.717113×10^{-14}	0.0	-
26	*CGDO*	F	6.358400×10^{-15}	0.0	-
27	*CGSO*	F	6.358400×10^{-15}	0.0	-
28	*NT*	J	2.216522×10^{-20}	0.0	-
29	*NF*	V^2	2.719698×10^{-11}	0.0	-
30	*MULT*	-	1.0	0.0	-

a. The lower bound for $K = K_0 \cdot \frac{\sqrt{\mathrm{hyp}_1(-V_{SBX}, \varepsilon_2)}}{\sqrt{V_{SBX} + \phi_B}}$

9.3.3 The ON/OFF condition

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 non-linear 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}	2.5	2.5	5.0
V_{GS}	2.5	2.5	0.0
V_{SB}	0.0	0.0	0.0

p-channel			
	Default	ON	OFF
V_{DS}	-2.5	-2.5	-5.0
V_{GS}	-2.5	-2.5	0.0
V_{SB}	0.0	0.0	0.0

9.3.4 Numerical adaptation

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

9.3.5 DC operating point

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_{ug}). The objective of the DCOP-facility is twofold:

- Calculate small-signal equivalent circuit element values.
- Open a window on the internal bias conditions of the device and its basic capabilities (e.g. F_{ug}).

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

Quantity	**Equation**	**Description**
Level	902	Model level
I_{ds}		Drain current, excluding substrate current
I_{avl}		Substrate current

Quantity	**Equation**	**Description**
V_{ds}		Drain-Source voltage
V_{gs}		Gate-Source voltage
V_{sb}		Source-Bulk voltage
V_{TO}		Threshold voltage after geometric and T-scaling
V_{TS}	V_{T1}	V_{T0} including backbias effects
V_{GT}	V_{GT2}	Effective gate drive including backbias and drain effects
V_{dss}	$\vert V_{DSS1} \vert$	Saturation voltage at actual bias
V_{sat}	$\vert V_{ds} \vert$ - V_{dss}	Saturation limit
g_m	dI_{ds}/dV_{gs}	transconductance (assumed V_{ds}>0)
g_{mb}	dI_{ds}/dV_{bs}	bulk transconductance (assumed V_{ds}>0)
g_{ds}	dI_{ds}/dV_{ds}	output conductance
$C_{d(d)}$	$+CDDS$	$+dQ_d/dV_d$
$C_{d(g)}$	$-CDGS$	$-dQ_d/dV_g$
$C_{d(s)}$	$+CDDS+CDGS-CDSB$	$-dQ_d/dV_s$
$C_{d(b)}$	$+CDSB$	$-dQ_d/dV_b$
$C_{g(d)}$	$-CGDS$	$-dQ_g/dV_d$
$C_{g(g)}$	$+CGGS$	$+dQ_g/dV_g$
$C_{g(s)}$	$+CGDS+CGGS-CGSB$	$-dQ_g/dV_s$
$C_{g(b)}$	$+CGSB$	$-dQ_g/dV_b$
$C_{s(d)}$	$-CSDS$	$-dQ_s/dV_d$
$C_{s(g)}$	$-CSGS$	$-dQ_s/dV_g$
$C_{s(s)}$	$-CSDS-CSGS+CSSB$	$+dQ_s/dV_s$
$C_{s(b)}$	$+CSSB$	$-dQ_s/dV_b$
$C_{b(d)}$	$-CBDS$	$-dQ_b/dV_d$

Quantity	**Equation**	**Description**
$C_{b(g)}$	$-CBGS$	$-dQ_b/dV_g$
$C_{b(s)}$	$+CBDS+CBGS-CBSB$	$-dQ_b/dV_s$
$C_{b(b)}$	$-CBSB$	$+dQ_b/dV_b$
C_{GDOL}	$C_{OL}*W_E$	Drain overlap capacitance of the actual transistor
C_{GSOL}	$C_{OL}*W_E$	Gate overlap capacitance of the actual transistor
W_{eff}		Effective channel width for geometrical models
L_{eff}		Effective channel length for geometrical models
u	g_m/g_{ds}	Transistor gain
R_{out}	$1/g_{ds}$	Small signal output resistance
$V_{\text{m early}}$	$\lvert I_d \rvert /g_{ds}$	Equivalent Early voltage
K_{eff}	$\frac{(V_{T1}-V_{T0})}{\sqrt{V_{SB}+2\Theta_B}-\sqrt{2\Theta_B}}$	Describes body effect at actual bias
B_{eff}	$\frac{2\lvert I_{ds}\rvert}{V_{GT3}^2}$	Effective β at actual bias in the simple MOS model
F_{ug}	$g_m/(2\delta\, C_{in})$	Unity gain frequency at actual bias
$SQRT(S_{fw})$	$\sqrt{S_{th}}/g_m$	input-referred RMS white noise voltage
$SQRT(S_{ff})$	$\sqrt{N'_F/1000}$	input-referred RMS 1/f noise voltage at 1 kHz
F_{knee}	$N_F*g^2{}_m/S_{th}$ $S_{ff}/S_{fw}\cdot 1000$	Cross-over frequency above which white noise is dominant

Remarks:

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

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

- The *simple model* mentioned above states that

$$I_d = \begin{cases} \beta_{\mathrm{eff}} \cdot [V_{GT} V_{ds} - V_{ds}^2/2] & \textit{when } V_{ds} \le V_{dss} \\ \beta_{\mathrm{eff}} \cdot V_{GT}^2/2 & \textit{when } V_{ds} > V_{dss} \end{cases}$$

- The calculation of F_{ug} assumes that the total load capacitance on the drain is identical to C_{ox} so that the actual load in the circuit is not taken into account! Intrinsically F_{ug} is related to the transit time

$$T_{tr} = \frac{3}{4} \frac{L^2{}_{\mathrm{eff}}}{\mu_{\mathrm{eff}} V_{GT}}$$

where $\mu_{eff} = B_{eff}/C_{ox}$. However as this transit time has no practical meaning, the rough estimation of the unity gain frequency is preferred.

- The input referred noise power densities S_{fw} and S_{ff} are only defined when g_m>0.

- *W* and *L* are not available for the electrical MOS models.

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

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

- $C_{in} = C_{g(g)} + C_{gsol} + C_{gdol}$

9.4 Physics

9.4.1 Comments and Physical Background

For more information on the comments and the physical background we refer to the section Comments and Physical Background on page 418. The significant difference between level 902 and level 903 of MOS model 9 is the implementation of the $1/f$ noise model. See also page 431.

9.4.2 Basic Equations

The equations listed in the following sections, are the basic equations of MOST model 9 without any adaptation necessary for numerical reasons. As such they form the base for parameter extraction. The definitions of the hyp functions, which provide for a smooth clipping, are found in appendix A.

Current Equations

$$u_s = \sqrt{V_{SB} + \phi_B} \tag{9.1}$$

$$u_{s0} = \sqrt{\phi_B} \tag{9.2}$$

$$u_{st} = \sqrt{V_{SBT} + \phi_B} \tag{9.3}$$

$$u_{sx} = \sqrt{V_{SBX} + \phi_B} \tag{9.4}$$

$$\Delta V_{T0} = \begin{cases} K_0 \cdot (u_s - u_{s0}) \,, & u_s < u_{sx} \\ \left[1 - \left(\dfrac{K}{K_0}\right)^2\right] \cdot K_0 \cdot u_{sx} - K_0 \cdot u_{s0} & \\ + K \cdot \sqrt{u_s^2 - \left[1 - \left(\dfrac{K}{K_0}\right)^2\right] \cdot u_{sx}^2} \,, & u_s \geq u_{sx} \end{cases} \tag{9.5}$$

$$V_{T1} = V_{T0} + \Delta V_{T0} \tag{9.6}$$

$$u_{s1} = \begin{cases} u_s , & u_s \le u_{st} \\ u_{st} , & u_s > u_{st} \end{cases} \tag{9.7}$$

$$\gamma_0 = \gamma_{00} \cdot \left(\frac{u_{s1}}{u_{s0}}\right)^{\eta_\Upsilon} \tag{9.8}$$

$$V_{GT1} = \begin{cases} V_{GS} - V_{T1} , & V_{GS} \ge V_{T1} \\ 0 , & V_{GS} < V_{T1} \end{cases} \tag{9.9}$$

$$V_{GTX} = \frac{1}{2} \cdot \sqrt{2} \tag{9.10}$$

$$\Delta V_{T1} = -\gamma_0 \cdot \frac{V_{GTX}^2}{V_{GTX}^2 + V_{GT1}^2} \cdot V_{DS} - \gamma_1 \cdot \frac{V_{GT1}^2}{V_{GTX}^2 + V_{GT1}^2} \cdot V_{DS}^{\eta_{DS}} \tag{9.11}$$

$$V_{T2} = V_{T1} + \Delta V_{T1} \tag{9.12}$$

$$V_{GT2} = V_{GS} - V_{T2} \tag{9.13}$$

$$m = 1 + m_0 \cdot \left(\frac{u_{s0}}{u_{s1}}\right)^{\eta_m} \tag{9.14}$$

$$G_1 = \exp\left(\frac{V_{GT2}}{2 \cdot m \cdot \phi_T}\right) \tag{9.15}$$

$$V_{GT3} = 2 \cdot m \cdot \phi_T \cdot \ln(1 + G_1) \tag{9.16}$$

$$\lambda_1 = 0.3 \tag{9.17}$$

$$\lambda_2 = 0.1 \tag{9.18}$$

$$\delta_1 = \frac{\lambda_1}{u_s} \cdot \left\{ K + \frac{(K_0 - K) \cdot V_{SBX}^2}{V_{SBX}^2 + (\lambda_2 \cdot V_{GT1} + V_{SB})^2} \right\} \tag{9.19}$$

$$V_{DSS1} = \frac{V_{GT3}}{1 + \delta_1} \cdot \frac{2}{1 + \sqrt{1 + \dfrac{2 \cdot \theta_3 \cdot V_{GT3}}{1 + \delta_1}}} \tag{9.20}$$

$$\lambda_3 = 0.3 \tag{9.21}$$

$$V_{DSSX} = 1 \tag{9.22}$$

$$\varepsilon_3 = \lambda_3 \cdot \frac{V_{DSS1}}{V_{DSSX} + V_{DSS1}} \tag{9.23}$$

$$V_{DS1} = \mathrm{hyp}_5(V_{DS};V_{DSS1},\varepsilon_3) \tag{9.24}$$

$$G_2 = 1 + \alpha \cdot \ln\left(1 + \frac{V_{DS} - V_{DS1}}{V_P}\right) \tag{9.25}$$

$$G_3 = \frac{\varsigma_1 \cdot \left\{1 - \exp\left(\frac{-V_{DS}}{\phi_T}\right)\right\} + G_1 \cdot G_2}{\frac{1}{\varsigma_1} + G_1} \tag{9.26}$$

$$I_{DS} = \beta \cdot G_3 \cdot \frac{V_{GT3} \cdot V_{DS1} - \left(\frac{1 + \delta_1}{2}\right) \cdot V_{DS1}^2}{\{1 + \theta_1 \cdot V_{GT1} + \theta_2 \cdot (u_s - u_{s0})\} \cdot (1 + \theta_3 \cdot V_{DS1})} \tag{9.27}$$

$$V_{DSA} = a_3 \cdot V_{DSS1} \tag{9.28}$$

$$I_{AVL} = \begin{cases} 0, & V_{DS} \le V_{DSA} \\ I_{DS} \cdot a_1 \cdot \exp\left(\frac{-a_2}{V_{DS} - V_{DSA}}\right), & V_{DS} > V_{DSA} \end{cases} \tag{9.29}$$

Charge Equations

$$V_{DB} = V_{DS} + V_{SB} \tag{9.30}$$

$$u_d = \sqrt{V_{DB} + \phi_B} \tag{9.31}$$

$$\Delta V_{T0d} = \begin{cases} K_0 \cdot (u_d - u_{s0}) , & u_d < u_{sx} \\ \left[1 - \left(\frac{K}{K_0}\right)^2\right] \cdot K_0 \cdot u_{sx} - K_0 \cdot u_{s0} & \\ + K \cdot \sqrt{u_d^2 - \left[1 - \left(\frac{K}{K_0}\right)^2\right] \cdot u_{sx}^2} , & u_d \ge u_{sx} \end{cases} \tag{9.32}$$

$$V_{T1d} = V_{T0} + \Delta V_{T0d} \tag{9.33}$$

$$\delta_2 = \frac{\partial V_{T2}}{\partial V_{SB}} - \frac{\partial V_{T2}}{\partial V_{GS}} - \frac{\partial V_{T2}}{\partial V_{DS}} \tag{9.34}$$

$$V_{DSS2} = \frac{V_{GT3}}{1 + \delta_2} \cdot \frac{2}{1 + \sqrt{1 + \dfrac{2 \cdot \theta_3 \cdot V_{GT3}}{1 + \delta_2}}} \tag{9.35}$$

$$V_{DS2} = \begin{cases} V_{DS}, & V_{DS} \le V_{DSS2} \\ V_{DSS2}, & V_{DS} > V_{DSS2} \end{cases} \tag{9.36}$$

$$F_J = \frac{(1 + \delta_2) \cdot (1 + \theta_3 \cdot V_{DS2}) \cdot V_{DS2}}{2 \cdot V_{GT3} - (1 + \delta_2) \cdot V_{DS2}} \tag{9.37}$$

$$Q_D = -C_{OX} \cdot \left[\frac{1}{2} \cdot V_{GT3} + (1 + \delta_2) \cdot V_{DS2} \cdot \left(\frac{1}{12} \cdot F_J - \frac{1}{60} \cdot F_J^2 - \frac{1}{3}\right)\right] \tag{9.38}$$

$$Q_S = -C_{OX} \cdot \left[\frac{1}{2} \cdot V_{GT3} + (1 + \delta_2) \cdot V_{DS2} \cdot \left(\frac{1}{12} \cdot F_J - \frac{1}{60} \cdot F_J^2 - \frac{1}{6}\right)\right] \tag{9.39}$$

$$V_{GB} = V_{GS} + V_{SB} \tag{9.40}$$

$$V_{FB} = V_{T0} - \phi_B - K_0 \sqrt{\phi_B} \tag{9.41}$$

$$Q_{BS} = \begin{cases} -C_{OX} \cdot (V_{GB} - V_{FB})\,, & V_{GB} < V_{FB} \\ -C_{OX} \cdot K_0 \left\{ -\dfrac{K_0}{2} + \sqrt{\dfrac{K_0^2}{4} + (V_{GB} - V_{FB})} \right\}, & V_{FB} \le V_{GB} \le V_{SB} + V_{T1} \\ -C_{OX} \cdot K_0 \left\{ -\dfrac{K_0}{2} + \sqrt{\dfrac{K_0^2}{4} + (V_{SB} + V_{T1} - V_{FB})} \right\}, & V_{GB} > V_{SB} + V_{T1} \end{cases} \tag{9.42}$$

$$Q_{BD} = \begin{cases} -C_{OX} \cdot (V_{GB} - V_{FB})\,, & V_{GB} < V_{FB} \\ -C_{OX} \cdot K_0 \left\{ -\dfrac{K_0}{2} + \sqrt{\dfrac{K_0^2}{4} + (V_{GB} - V_{FB})} \right\}, & V_{FB} \le V_{GB} \le V_{DS2} + V_{SB} + V_{T1d} \\ -C_{OX} \cdot K_0 \left\{ -\dfrac{K_0}{2} + \sqrt{\dfrac{K_0^2}{4} + (V_{DS2} + V_{SB} + V_{T1d} - V_{FB})} \right\}, & V_{GB} > V_{DS2} + V_{SB} + V_{T1d} \end{cases} \tag{9.43}$$

$$Q_B = \frac{1}{2} \cdot (Q_{BS} + Q_{BD}) \tag{9.44}$$

$$Q_G = -(Q_S + Q_D + Q_B) \tag{9.45}$$

Noise Equations

In these equations *f* represents the operation frequency of the transistor.

$$g_m = \frac{\partial I_{DS}}{\partial V_{GS}} \tag{9.46}$$

$$F_I = \frac{(1 + \delta_1) \cdot (1 + \theta_3 \cdot V_{DS1}) \cdot V_{DS1}}{2 \cdot V_{GT3} - (1 + \delta_1) \cdot V_{DS1}} \tag{9.47}$$

$$h_3 = \beta \cdot G_3 \cdot \left[\frac{V_{GT3} - \frac{1}{2} \cdot (1 + \delta_1) \cdot V_{DS1}}{\{1 + \theta_1 \cdot V_{GT1} + \theta_2 \cdot (u_s - u_{s0})\} \cdot (1 + \theta_3 \cdot V_{DS1})} \right] \tag{9.48}$$

$$h_4 = 1 + \theta_3 \cdot V_{DS1} + \frac{1}{3} \cdot F_I^2 \tag{9.49}$$

$$h_5 = \frac{V_{DSS1}}{2 \cdot \phi_T} \tag{9.50}$$

$$S_{th} = \begin{cases} N_T \cdot h_3 \cdot h_4 & h_4 < h_5 \\ N_T \cdot h_3 \cdot h_5 & h_4 \geq h_5 \end{cases} \tag{9.51}$$

$$S_{fl} = N_F \cdot \frac{g_m^2}{f} \tag{9.52}$$

$$S_{ig} = N_T \cdot \frac{(2 \cdot \pi \cdot f \cdot C_{OX})^2}{3 \cdot g_m} \cdot \left\{ 1 + 0.075 \cdot \left(\frac{2 \cdot \pi \cdot f \cdot C_{OX}}{g_m} \right)^2 \right\}^{-1} \tag{9.53}$$

$$\rho_{igth} = 0.4j \tag{9.54}$$

$$S_{igth} = \rho_{igth} \cdot \sqrt{S_{ig} \cdot S_{th}} \tag{9.55}$$

9.5 Accuracy and Validity Range

For more information we refer to the section 10.5 on page 444.

9.6 Parameter scaling

9.6.1 Geometrical scaling and temperature scaling

Calculation of Transistor Geometry

$$L_E = L + \Delta L_{PS} - 2 \cdot \Delta L_{\text{overlap}} \tag{9.56}$$

$$W_E = W + \Delta W_{OD} - 2 \cdot \Delta W_{\text{narrow}} \tag{9.57}$$

WARNING : L_E and W_E after calculation can not be less than 0 !

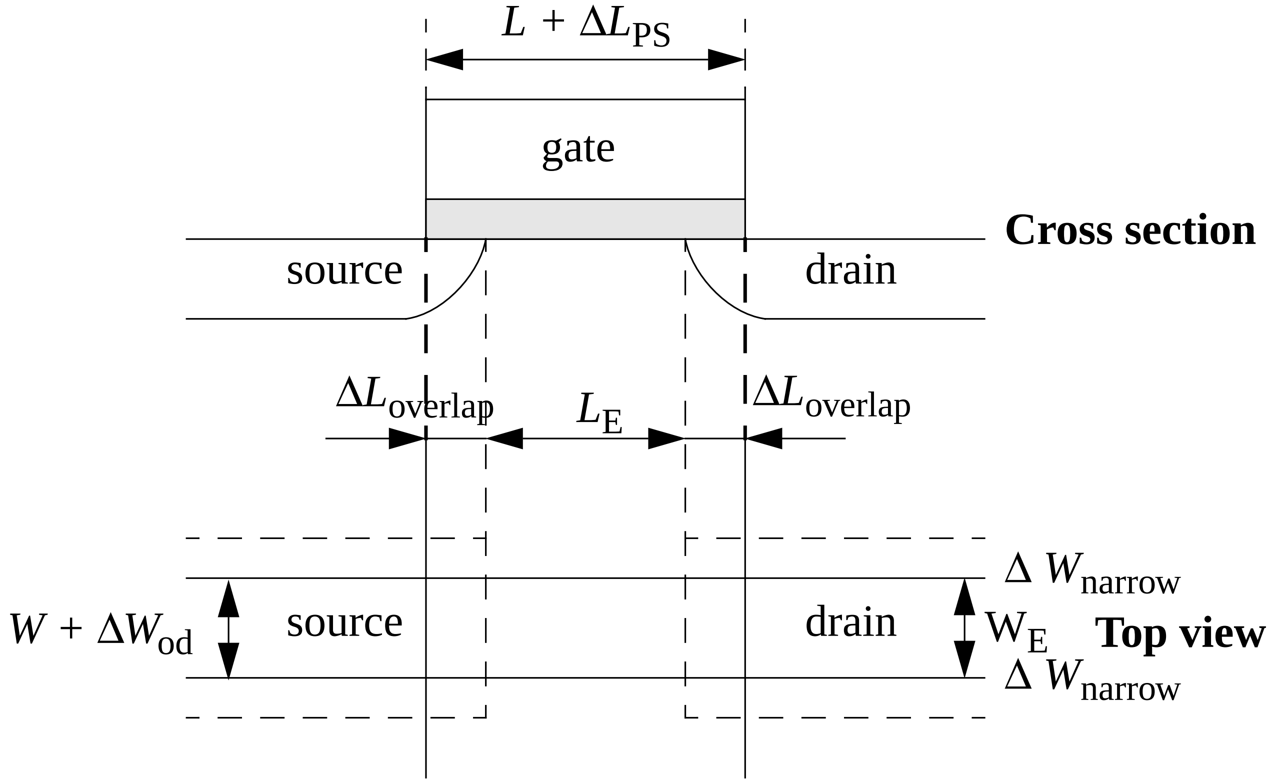


Figure 40: Specification of the dimensions of an MOS transistor

Calculation of Transistor Temperature

T_{A} is the ambient or the circuit temperature.

$$T_{KR} = T_0 + T_R \tag{9.58}$$

$$T_{KD} = T_0 + T_A + \Delta T_A \tag{9.59}$$

Calculation of Threshold-Voltage Parameters

$$\tilde{V}_{T0} = V_{T0R} + (T_{KD} - T_{KR}) \cdot S_{T;V_{T0}} \tag{9.60}$$

$$V_{T0} = \tilde{V}_{T0} + \left(\frac{1}{L_E} - \frac{1}{L_{ER}}\right) \cdot S_{L;V_{T0}} + \left(\frac{1}{L_E^2} - \frac{1}{L_{ER}^2}\right) \cdot S_{L2;V_{T0}} + \left(\frac{1}{W_E} - \frac{1}{W_{ER}}\right) \cdot S_{W;V_{T0}} \tag{9.61}$$

$$K_0 = K_{0R} + \left(\frac{1}{L_E} - \frac{1}{L_{ER}}\right) \cdot S_{L;K_0} + \left(\frac{1}{W_E} - \frac{1}{W_{ER}}\right) \cdot S_{W;K_0} \tag{9.62}$$

$$K = k_R + \left(\frac{1}{L_E} - \frac{1}{L_{ER}}\right) \cdot S_{L;K} + \left(\frac{1}{W_E} - \frac{1}{W_{ER}}\right) \cdot S_{W;K} \tag{9.63}$$

$$S_{T;\phi_B} = \frac{\phi_{BR} - 1.13 - 2.5 \cdot 10^{-4} \cdot T_{KR}}{300} \tag{9.64}$$

$$\phi_B = \phi_{BR} + (T_{KD} - T_{KR}) \cdot S_{T;\phi_B} \tag{9.65}$$

$$V_{SBX} = V_{SBXR} + \left(\frac{1}{L_E} - \frac{1}{L_{ER}}\right) \cdot S_{L;V_{SBX}} + \left(\frac{1}{W_E} - \frac{1}{W_{ER}}\right) \cdot S_{W;V_{SBX}} \tag{9.66}$$

Calculation of Channel-Current Parameters

$$\tilde{\beta} = \beta_{sq} \cdot \left(\frac{T_{KR}}{T_{KD}}\right)^{\eta_\beta} \tag{9.67}$$

$$\beta = \tilde{\beta} \cdot \frac{W_E}{L_E} \tag{9.68}$$

$$\tilde{\theta}_1 = \theta_{1R} + (T_{KD} - T_{KR}) \cdot S_{T;\theta_1,R} \tag{9.69}$$

$$S_{L;\theta_1} = S_{L;\theta_1,R} + (T_{KD} - T_{KR}) \cdot S_{T,L;\theta_1} \tag{9.70}$$

$$W_{EDOG} = W_{DOG} + \Delta W_{OD} - 2 \cdot \Delta W_{\mathrm{narrow}} \tag{9.71}$$

$W_{EDOG} \leq W_{ER}$

$W \geq W_{DOG}$:

$$\theta_1 = \tilde{\theta}_1 + \left(\frac{1}{L_E} - \frac{1}{L_{ER}}\right) \cdot S_{L;\theta_1} + \left(\frac{1}{W_E} - \frac{1}{W_{ER}}\right) \cdot S_{W;\theta_1} \tag{9.72}$$

$W < W_{DOG}$:

$$\theta_1 = \tilde{\theta}_1 + \left(\frac{1}{L_E} - \frac{1}{L_{ER}}\right) \cdot S_{L;\theta_1} + \left(\frac{1}{W_E} - \frac{1}{W_{ER}}\right) \cdot S_{W;\theta_1} + \tag{9.73}$$

$$\left(\frac{W_E}{W_{EDOG}} - 1\right) \cdot \frac{f_{\theta_1}}{L_E} \cdot S_{L;\theta_1}$$

$$\tilde{\theta}_2 = \theta_{2R} + (T_{KD} - T_{KR}) \cdot S_{T;\theta_2,R} \tag{9.74}$$

$$S_{L;\theta_2} = S_{L;\theta_2,R} + (T_{KD} - T_{KR}) \cdot S_{T,L;\theta_2} \tag{9.75}$$

$$\theta_2 = \tilde{\theta}_2 + \left(\frac{1}{L_E} - \frac{1}{L_{ER}}\right) \cdot S_{L;\theta_2} + \left(\frac{1}{W_E} - \frac{1}{W_{ER}}\right) \cdot S_{W;\theta_2} \tag{9.76}$$

$$\tilde{\theta}_3 = \theta_{3R} + (T_{KD} - T_{KR}) \cdot S_{T;\theta_3,R} \tag{9.77}$$

$$S_{L;\theta_3} = S_{L;\theta_3,R} + (T_{KD} - T_{KR}) \cdot S_{T,L;\theta_3} \tag{9.78}$$

$$\theta_3 = \tilde{\theta}_3 + \left(\frac{1}{L_E} - \frac{1}{L_{ER}}\right) \cdot S_{L;\theta_3} + \left(\frac{1}{W_E} - \frac{1}{W_{ER}}\right) \cdot S_{W;\theta_3} \tag{9.79}$$

Calculation of Drain-Feedback Parameters

$$\gamma_1 = \gamma_{1R} + \left(\frac{1}{L_E} - \frac{1}{L_{ER}}\right) \cdot S_{L;\gamma_1} + \left(\frac{1}{W_E} - \frac{1}{W_{ER}}\right) \cdot S_{W;\gamma_1} \tag{9.80}$$

$$\eta_{DS} = \eta_{DSR} \tag{9.81}$$

$$\alpha = \alpha_R + \left(\frac{1}{L_E^{\eta_\alpha}} - \frac{1}{L_{ER}^{\eta_\alpha}}\right) \cdot S_{L;\alpha} + \left(\frac{1}{W_E} - \frac{1}{W_{ER}}\right) \cdot S_{W;\alpha} \tag{9.82}$$

$$V_P = V_{PR} \cdot \left(\frac{L_E}{L_{ER}}\right) \tag{9.83}$$

Calculation of Sub-Threshold Parameters

$$\gamma_{00} = \gamma_{00R} + \left(\frac{1}{L_E^2} - \frac{1}{L_{ER}^2}\right) \cdot S_{L;\gamma_{00}} \tag{9.84}$$

$$\eta_\gamma = \eta_{\gamma R} \tag{9.85}$$

$$\tilde{m}_0 = m_{0R} + (T_{KD} - T_{KR}) \cdot S_{T;m_0} \tag{9.86}$$

$$m_0 = \tilde{m}_0 + \left(\frac{1}{\sqrt{L_e}} - \frac{1}{\sqrt{L_{ER}}}\right) \cdot S_{L;m_0} \tag{9.87}$$

$$\eta_m = \eta_{mR} \tag{9.88}$$

$$\phi_T = \frac{k \cdot T_{KD}}{q} \tag{9.89}$$

$$\varsigma_1 = \varsigma_{1R} + \left(\frac{1}{L_E^{\eta_\varsigma}} - \frac{1}{L_{ER}^{\eta_\varsigma}}\right) \cdot S_{L;\varsigma_1} \tag{9.90}$$

$$V_{SBT} = V_{SBTR} + \left(\frac{1}{L_E} - \frac{1}{L_{ER}}\right) \cdot S_{L;V_{SBT}} \tag{9.91}$$

Calculation of Weak-Avalanche Parameters

$$\tilde{a}_1 = a_{1R} + (T_{KD} - T_{KR}) \cdot S_{T;a_1} \tag{9.92}$$

$$a_1 = \tilde{a}_1 + \left(\frac{1}{L_E} - \frac{1}{L_{ER}}\right) \cdot S_{L;a_1} + \left(\frac{1}{W_E} - \frac{1}{W_{ER}}\right) \cdot S_{W;a_1} \tag{9.93}$$

$$a_2 = a_{2R} + \left(\frac{1}{L_E} - \frac{1}{L_{ER}}\right) \cdot S_{L;a_2} + \left(\frac{1}{W_E} - \frac{1}{W_{ER}}\right) \cdot S_{W;a_2} \tag{9.94}$$

$$a_3 = a_{3R} + \left(\frac{1}{L_E} - \frac{1}{L_{ER}}\right) \cdot S_{L;a_3} + \left(\frac{1}{W_E} - \frac{1}{W_{ER}}\right) \cdot S_{W;a_3} \tag{9.95}$$

Calculation of Charge Parameters

$$C_{ox} = \varepsilon_{ox} \cdot \frac{W_E \cdot L_E}{t_{ox}} \tag{9.96}$$

$$C_{GDO} = W_E \cdot C_{ol} \tag{9.97}$$

$$C_{GSO} = W_E \cdot C_{ol} \tag{9.98}$$

Calculation of Noise Parameters

$$N_T = \frac{T_{KD}}{T_{KR}} \cdot N_{TR} \tag{9.99}$$

$$N_F = \frac{W_{ER} \cdot L_{ER}}{W_E \cdot L_E} \cdot N_{FR} \tag{9.100}$$

9.6.2 MULT scaling

The *MULT* factor determines the number of equivalent parallel devices of a specified model. The *MULT* factor has to be applied on the electrical parameters. Hence after the temperature scaling and other parameter processing. Some electrical parameters cannot be specified by the user as parameters but must always be computed from geometrical parameters. They are called electrical quantities here.

The parameters: β, C_{OX}, C_{GDO}, C_{GSO} and *NF* are affected by the *MULT* factor:

$$\begin{aligned} \beta &= \beta \times MULT \\ C_{OX} &= C_{OX} \times MULT \\ C_{GDO} &= C_{GDO} \times MULT \\ C_{GSO} &= C_{GSO} \times MULT \\ N_F &= N_F / MULT \end{aligned}$$

Convention:
No distinction is made between the symbol before and after the *MULT* scaling, e.g: the symbol β represents the actual parameter after the *MULT* processing and temperature scaling. This parameter may be used to put several MOSTs in parallel.

9.7 Model Equations

Although the basic equations, given in section Basic Equations, form a complete set of model equations, they are not yet suited for a circuit simulator. Several equations have to be adapted in order to obtain smooth transitions of the characteristics between adjacent regions of operation conditions and to prevent numerical problems during the iteration process for solving the network equations. In the following section a list of numerical adaptations and elucidations is given, followed by the extended set of model equations.

The definitions of the hyp functions are found in the appendix A.

DC current model

$$\varepsilon_1 = 10^{-2} \tag{9.101}$$

$$h_1 = \mathrm{hyp}_1\left(V_{SB} + \frac{1}{2} \cdot \phi_B ; \varepsilon_1\right) + \frac{1}{2} \cdot \phi_B \tag{9.102}$$

$$u_s = \sqrt{h_1} \tag{9.103}$$

$$u_{s0} = \sqrt{\phi_B} \tag{9.104}$$

$$u_{st} = \sqrt{V_{SBT} + \phi_B} \tag{9.105}$$

$$u_{sx} = \sqrt{V_{SBX} + \phi_B} \tag{9.106}$$

$$\varepsilon_2 = 0.1 \tag{9.107}$$

$$\Delta V_{T0} = \begin{aligned} & K \cdot \left\{ \sqrt{\mathrm{hyp}_4(V_{SB}; V_{SBX}, \varepsilon_2) + \left(\frac{K}{K_0}\right)^2 \cdot u_{sx}^2} - \left(\frac{K}{K_0}\right) \cdot u_{sx} \right\} \\ & + K_0 \cdot \{ \sqrt{h_1 - \mathrm{hyp}_4(V_{SB}; V_{SBX}, \varepsilon_2)} - u_{s0} \} \end{aligned} \tag{9.108}$$

$$V_{T1} = V_{T0} + \Delta V_{T0} \tag{9.109}$$

$$\varepsilon_3 = 10^{-2} \tag{9.110}$$

$$u_{s1} = \mathrm{hyp}_2(u_s; u_{st}, \varepsilon_3) \tag{9.111}$$

$$\gamma_0 = \gamma_{00} \cdot \left(\frac{u_{s1}}{u_{s0}}\right)^{\eta_\gamma} \tag{9.112}$$

$$\varepsilon_4 = 5 \cdot 10^{-4} \tag{9.113}$$

$$V_{GT1} = \mathrm{hyp}_1(V_{GS} - V_{T1}; \varepsilon_4) \tag{9.114}$$

$$\lambda_1 = 0.1 \tag{9.115}$$

$$\lambda_2 = 10^{-4} \tag{9.116}$$

$$V_{GTX} = \frac{1}{2} \cdot \sqrt{2} \tag{9.117}$$

$$\Delta V_{T1} = \left[-\gamma_0 - \left\{ \gamma_1 \cdot (V_{DS} + \lambda_2)^{\eta_{DS} - 1} - \gamma_0 \right\} \cdot \frac{V_{GT1}^2}{V_{GTX}^2 + V_{GT1}^2} \right] \cdot \frac{V_{DS}^2}{V_{DS} + \lambda_1} \tag{9.118}$$

$$V_{T2} = V_{T1} + \Delta V_{T1} \tag{9.119}$$

$$m = 1 + m_0 \cdot \left(\frac{u_{s0}}{u_{s1}} \right)^{\eta_m} \tag{9.120}$$

$$V_{GT2} = V_{GS} - V_{T2} \tag{9.121}$$

$$\lambda_7 = 37 \tag{9.122}$$

$$V_{GTA} = 2 \cdot m \cdot \phi_T \cdot \lambda_7 \tag{9.123}$$

$$G_1 = \begin{cases} \exp\left(\dfrac{V_{GT2}}{2 \cdot m \cdot \phi_T} \right), & V_{GT2} < V_{GTA} \\ \text{No assignment is necessary,} & V_{GT2} \geq V_{GTA} \end{cases} \tag{9.124}$$

$$\lambda_3 = 10^{-8} \tag{9.125}$$

$$V_{GT3} = \begin{cases} 2 \cdot m \cdot \phi_T \cdot \ln(1 + G_1) + \lambda_3 \, , & V_{GT2} < V_{GTA} \\ V_{GT2} + \lambda_3 \, , & V_{GT2} \geq V_{GTA} \end{cases} \tag{9.126}$$

$$\lambda_4 = 0.3 \tag{9.127}$$

$$\lambda_5 = 0.1 \tag{9.128}$$

$$\delta_1 = \frac{\lambda_4}{u_s} \cdot \left\{ K + \frac{(K_0 - K) \cdot V_{SBX}^2}{V_{SBX}^2 + (\lambda_5 \cdot V_{GT1} + V_{SB})^2} \right\} \tag{9.129}$$

$$V_{DSS1} = \frac{V_{GT3}}{1 + \delta_1} \cdot \frac{2}{1 + \sqrt{1 + \frac{2 \cdot \theta_3 \cdot V_{GT3}}{1 + \delta_1}}} \tag{9.130}$$

$$\lambda_6 = 0.3 \tag{9.131}$$

$$V_{DSSX} = 1 \tag{9.132}$$

$$\varepsilon_5 = \lambda_6 \cdot \frac{V_{DSS1}}{V_{DSSX} + V_{DSS1}} \tag{9.133}$$

$$V_{DS1} = \mathrm{hyp}_5(V_{DS};V_{DSS1},\varepsilon_5) \tag{9.134}$$

$$G_2 = 1 + \alpha \cdot \ln\left(1 + \frac{V_{DS} - V_{DS1}}{V_P}\right) \tag{9.135}$$

$$G_3 = \begin{cases} \dfrac{\varsigma_1 \cdot \left\{1 - \exp\left(\dfrac{-V_{DS}}{\phi_T}\right)\right\} + G_1 \cdot G_2}{\dfrac{1}{\varsigma_1} + G_1}, & V_{GT2} < V_{GTA} \\ G_2\,, & V_{GT2} \geq V_{GTA} \end{cases} \tag{9.136}$$

$$I_{DS} = \beta \cdot G_3 \cdot \frac{V_{GT3} \cdot V_{DS1} - \left(\dfrac{1 + \delta_1}{2}\right) \cdot V_{DS1}^2}{\{1 + \theta_1 \cdot V_{GT1} + \theta_2 \cdot (u_s - u_{s0})\} \cdot (1 + \theta_3 \cdot V_{DS1})} \tag{9.137}$$

$$V_{DSA} = a_3 \cdot V_{DSS1} \tag{9.138}$$

$$I_{AVL} = \begin{cases} 0\,, & V_{DS} \leq V_{DSA} \\ I_{DS} \cdot a_1 \cdot \exp\left(\dfrac{-a_2}{V_{DS} - V_{DSA}}\right), & V_{DS} > V_{DSA} \end{cases} \tag{9.139}$$

Charge model

$$V_{DB} = V_{DS} + V_{SB} \tag{9.140}$$

$$h_2 = \mathrm{hyp}_1\left(V_{DB} + \frac{1}{2} \cdot \phi_B ; \varepsilon_1\right) + \frac{1}{2} \cdot \phi_B \tag{9.141}$$

$$\Delta V_{T0d} = K \cdot \left\{ \sqrt{\mathrm{hyp}_4(V_{DB};V_{SBX},\varepsilon_2) + \left(\frac{K}{K_0}\right)^2 \cdot u_{sx}^2} - \left(\frac{K}{K_0}\right) \cdot u_{sx} \right\} + K_0 \cdot \{ \sqrt{h_2 - \mathrm{hyp}_4(V_{DB};V_{SBX},\varepsilon_2)} - u_{s0} \} \tag{9.142}$$

$$V_{T1d} = V_{T0} + \Delta V_{T0d} \tag{9.143}$$

$$\delta_2 = \frac{\partial V_{T2}}{\partial V_{SB}} - \frac{\partial V_{T2}}{\partial V_{GS}} - \frac{\partial V_{T2}}{\partial V_{DS}} \tag{9.144}$$

$$\Delta_2 = \frac{\partial V_{GT3}}{\partial V_{SB}} + \frac{\partial V_{GT3}}{\partial V_{GS}} + \frac{\partial V_{GT3}}{\partial V_{DS}} \tag{9.145}$$

$$V_{DSS2} = \frac{V_{GT3}}{1 + \delta_2} \cdot \frac{2}{1 + \sqrt{1 + \dfrac{2 \cdot \theta_3 \cdot V_{GT3}}{1 + \delta_2}}} \tag{9.146}$$

$$\lambda_8 = 0.1 \tag{9.147}$$

$$\varepsilon_7 = \lambda_8 \cdot \frac{V_{DSS2}}{V_{DSSX} + V_{DSS2}} \tag{9.148}$$

$$V_{DS2} = \mathrm{hyp}_5(V_{DS};V_{DSS2},\varepsilon_7) \tag{9.149}$$

$$F_J = \frac{(1 + \delta_2) \cdot (1 + \theta_3 \cdot V_{DS2}) \cdot V_{DS2}}{2 \cdot V_{GT3} - (1 + \delta_2) \cdot V_{DS2}} \tag{9.150}$$

$$Q_D = -C_{OX} \cdot \left[\frac{1}{2} \cdot V_{GT3} + \Delta 2 \cdot V_{DS2} \cdot \left(\frac{1}{12} \cdot F_J + \frac{1}{60} \cdot F_J^2 - \frac{1}{3}\right)\right] \tag{9.151}$$

$$Q_S = -C_{OX} \cdot \left[\frac{1}{2} \cdot V_{GT3} + \Delta 2 \cdot V_{DS2} \cdot \left(\frac{1}{12} \cdot F_J - \frac{1}{60} \cdot F_J^2 - \frac{1}{6}\right)\right] \tag{9.152}$$

$$\varepsilon_6 = 0.03 \tag{9.153}$$

$$V_{GB} = V_{GS} + V_{SB} \tag{9.154}$$

$$V_{FB} = V_{T0} - \phi_B - K_0\sqrt{\phi_B} \tag{9.155}$$

$$Q_{BS} = \begin{cases} -C_{OX} \cdot \mathrm{hyp}_3(V_{GB} - V_{FB}; V_{SB} + V_{T1} - V_{FB}, \varepsilon_6), & V_{GB} < V_{FB} \\ -C_{OX} \cdot K_0 \left[-\frac{K_0}{2} + \right. \\ \left. \left[\sqrt{\left(\frac{K_0}{2}\right)^2 + \mathrm{hyp}_3(V_{GB} - V_{FB}; V_{SB} + V_{T1} - V_{FB}, \varepsilon_6)}\right]\right], & V_{GB} \geq V_{FB} \end{cases} \tag{9.156}$$

$$Q_{BD} = \begin{cases} -C_{OX} \cdot \mathrm{hyp}_3(V_{GB} - V_{FB}; V_{DS2} + V_{SB} + V_{T1d} - V_{FB}, \varepsilon_6), & V_{GB} < V_{FB} \\ -C_{OX} \cdot K_0 \left[-\frac{K_0}{2} + \right. \\ \left. \left[\sqrt{\left(\frac{K_0}{2}\right)^2 + \mathrm{hyp}_3(V_{GB} - V_{FB}; V_{DS2} + V_{SB} + V_{T1d} - V_{FB}, \varepsilon_6)}\right]\right], & V_{GB} \geq V_{FB} \end{cases} \tag{9.157}$$

$$Q_B = \frac{1}{2} \cdot (Q_{BS} + Q_{BD}) \tag{9.158}$$

$$Q_G = -(Q_D + Q_S + Q_B) \tag{9.159}$$

Noise model

In these equations *f* represents the operation frequency of the transistor.

$$g_m = \frac{\partial I_{DS}}{\partial V_{GS}} \tag{9.160}$$

$$F_I = \frac{(1+\delta_1)\cdot(1+\theta_3\cdot V_{DS1})\cdot V_{DS1}}{2\cdot V_{GT3}-(1+\delta_1)\cdot V_{DS1}} \tag{9.161}$$

$$h_3 = \beta\cdot G_3\cdot\left[\frac{V_{GT3}-\frac{1}{2}\cdot(1+\delta_1)\cdot V_{DS1}}{\{1+\theta_1\cdot V_{GT1}+\theta_2\cdot(u_s-u_{s0})\}\cdot(1+\theta_3\cdot V_{DS1})}\right] \tag{9.162}$$

$$h_4 = 1+\theta_3\cdot V_{DS1}+\frac{1}{3}\cdot F_I^2 \tag{9.163}$$

$$h_5 = \frac{V_{DSS1}}{2\cdot\phi_T} \tag{9.164}$$

$$h_6 = \begin{cases} h_3\cdot h_4, & h_4 < h_5 \\ h_3\cdot h_5, & h_4 \geq h_5 \end{cases} \tag{9.165}$$

$$S_{th} = N_T\cdot h_6 \tag{9.166}$$

$$S_{fl} = N_F\cdot\frac{g_m^2}{f} \tag{9.167}$$

$$S_{ig} = N_T \cdot \frac{(2 \cdot \pi \cdot f \cdot C_{OX})^2}{3 \cdot g_m} \cdot \left(1 + 0.075 \cdot \left(\frac{2 \cdot \pi \cdot f \cdot C_{OX}}{g_m}\right)^2\right)^{-1} \tag{9.168}$$

$$\rho_{igth} = 0.4j \tag{9.169}$$

$$S_{igth} = \rho_{igth} \cdot N_T \cdot 2 \cdot \pi \cdot f \cdot C_{OX} \cdot \sqrt{\frac{g_m \cdot h_6}{3 \cdot (g_m^2 + 0.075 \cdot (2 \cdot \pi \cdot f \cdot C_{OX})^2)}}$$

$$g_m \geq 0 \tag{9.170}$$

9.7.1 Numerical adaptations

The electrical equations of MOS model 9 to be implemented are essentially based on the physical description in section 9.4. Because in circuit design equal parallel circuited transistors are frequently applied the specification of one transistor together with a multiplication factor N_{MULT} in the circuit description is convenient and saves computation time. The general and safe method to implement this mechanism into the model is to evaluate the currents, charges, noise spectral densities and their derivatives with respect to the external voltages and, at the end, to multiply them by N_{MULT}. In MOS model 9 it is allowed to circumvent these multiplications for each model evaluation during circuit simulation by adjusting some parameters.

- The dependence of the threshold voltage on the back-bias voltage is described by the Eqs. (9.1) through (9.7). Because this description is valid for $V_{SB} \geq 0$ V, and negative values of V_{SB} can occur during the iteration process of the circuit simulator, Eq. (9.1) has been replaced by the Eqs. (9.101), (9.102) and (9.103). The difference between u_s calculated according to Eq. (9.103) and u_s of Eq. (9.1) does not exceed $2 \cdot 10^{-4}$ $V^{1/2}$ for $V_{SB} \geq 0$ V.

- The threshold-voltage shift V_{T0} of Eq. (9.5) yields satisfactory results for the channel current. It is desirable to use the same threshold-voltage shift for the charge equations, which causes a problem. Because all differential capacitances have to be continuous functions of the nodal voltages, it is obvious that via Eq. (9.34) the second derivative of ΔV_{T0} with respect to V_{SB} has to be continuous. Unfortunately this does not hold for $V_{SB} = V_{SBX}$. Therefore Eq. (9.5) has been replaced by Eq. (9.108). For $V_{SB} = 0$ V the results of Eq. (9.5) and of Eq. (9.108) are equal, while the largest deviation (< 4 mV) is obtained at $V_{SB} = V_{SBX}$.

- The threshold-voltage shift ΔV_{T1}, described in Eq. (9.11), contains two parts, the first part dominates for $V_{GT1} < V_{GTX}$ and the second part for $V_{GT2} > V_{GTX}$. To balance these parts for a monotonic behaviour of I_{DS} versus V_{SB} γ_0 should not increase unlimited with V_{SB}. This clipping: Eqs. (9.7) and (9.8), occurs at $V_{SB} = V_{SBT}$, which is far out of the practical region of operation. For mathematical reasons a smooth clipping, Eq. (9.111), has to be implemented instead of Eq. (9.7).

- The equation of the threshold-voltage shift ΔV_{T1}, Eq. (9.11), provides first and second derivative functions with respect to V_{DS}, which are not well-behaved functions for $V_{DS} = 0$ V due to $\eta_{DS} \approx 0.6$. Therefore Eq. (9.11) has to be replaced by

$$\Delta V_{T1} = \left\{ -\gamma_0 \frac{V_{GTX}^2}{V_{GTX}^2 + V_{GT1}^2} - \gamma_1 \frac{V_{GT1}^2}{V_{GTX}^2 + V_{GT1}^2} (V_{DS} + \lambda_2)^{\eta_{DS} - 1} \right\} \cdot \left(\frac{V_{DS}^2}{V_{DS} + \lambda_1} \right)$$

in which λ_1 and λ_2 are model constants. This equation can be simplified. The expression between braces smoothly transists from $-\gamma_0$ to $-\gamma_1 \cdot (V_{DS} + \lambda_2)^{\eta_{DS} - 1}$ which is controlled by the two weighting functions of V_{GT1} which sum equals one. Using one of these functions only, we obtain Eq. (9.118).

- The voltage V_{GS} controls via V_{GT2}, Eq. (9.14), and G_1, Eq. (9.15), the functional behaviour of V_{GT3}, Eq.(9.16) and G_3, Eq. (9.26). For the subthreshold region

$$V_{GT3} \approx 2 \cdot m \cdot \phi_T \cdot \exp\left(\frac{V_{GT2}}{2 \cdot m \cdot \phi_T} \right)$$

and

$$G_3 \approx \varsigma_1^2 \cdot \left\{ 1 - \exp\left(\frac{-V_{DS}}{\phi_T} \right) \right\} ,$$

and for large values of V_{GS} $V_{GT3} \approx V_{GT2}$ and $G_3 \approx G_2$. Although the Eqs. (9.16) and (9.26) are well-behaved analytical functions of G_1, they will cause numerical problems due to the limited value range of the numbers, which can be represented by the computer. If x exceeds the allowed maximum value of the argument range of the exp-function $\ln\{\exp(x)\} \neq x$ and $\exp(x) \cdot y / \exp(x) \neq y$ with $y>1$. To prevent this a maximum value for the argument range λ_7 has been specified, which is the lowest-value of the computer implementations of the circuit simulator, Eq. (9.122). For small values of the arguments i.e. $V_{GT2} < V_{GTA}$, Eq. (9.123), G_1, V_{GT3} and G_3 are calculated according to Eqs. (9.15), (9.16) and (9.26). But for $V_{GT2} \geq V_{GTA}$ no assignment is done to G_1, Eq. (9.124), calculated asymptotic values are assigned to V_{GT3} and G_3 Eqs. (9.126) and (9.136).

- As V_{GT3} decreases to zero the denominator of Eq. (9.37) approaches zero. The addition of a small constant to the denominator is not a good solution for this problem because the first derivatives of Q_D and Q_S will become discontinuous functions. Therefore a small constant λ_3 has been added to V_{GT3}, Eq. (9.126).

- At the outset the charge equations for Q_D and Q_S has been derived for $V_{GS}>V_{T2}$. To extend the validity range of these original equations to the subthreshold region V_{GT3} has been introduced. The remaining problem, the discontinuous transition between the derivatives dQ_D / dV_S and dQ_S / dV_D around $V_{DS} = 0$, can be solved by replacing $1 + \delta$ in Eqs. (9.38) and (9.39) by Δ_2, Eq. (9.145). This yields the Eqs. (9.151) and (9.152).

- The derivation of the equation for the bulk charges Q_{BS} and Q_{BD}, Eqs. (9.42) and (9.43), had to be performed for three successive ranges of V_{GB}. Unfortunately, the first derivatives of Q_{BS} and Q_{BD} with respect to V_{GB} are not continuous at the boundaries $V_{SB} + V_{T2}$ and $V_{DB} + V_{T1\mathrm{d}}$, respectively. A simple remedy is the introduction of the smoothing function hyp_3 into Eqs. (9.42) and (9.43), leading to Eqs. (9.156) and (9.157).

- Calculating the value of the spectral densities for frequency zero leads to a division by zero in Eq. (9.167) and also in Eqs. (9.168), (9.171) when $g_\mathrm{m} = 0$. For these exceptional cases the noise spectral densities should be put to zero.

9.8 Model embedding in a circuit simulator

Although CMOS processes support n- and p-channel MOS's, Model 9 only knows n-channel devices. This can easily be circumvented by mapping a p-channel device with its bias conditions and parameter set onto an equivalent n-channel device with appropriately changed bias conditions and parameters. The criterion is that the equivalent model plus bias conditions plus parameter set should attribute the same charge and the same current value and current direction (DC, AC and noise) to any physical node involved when compared to a hypothetical model that supports both device types.

As said earlier, any circuit simulator internally identifies the terminals of a MOS transistor by a number. However, designers are used to the standard terminology of source, drain, gate and bulk. Therefore, in the context of a circuit simulator it is traditionally possible to address, say, the drain of MOS number 17, even if in reality the corresponding source is at a higher potential (n-channel case). More strongly, most circuit simulators provide for model evaluation a so-called V_{DS}, V_{GS}, and V_{SB} based on an a priori assignment of source, drain and bulk that is independent of the actual bias conditions. The basic Model 902 cannot cope with bias conditions that correspond to $V_{DS} < 0$. Again a transformation of the bias conditions is necessary. In this case, the transformation corresponds to internally reassigning source and drain, applying the standard electrical model, and then reassigning the currents and charges to the original terminals. Especially in combination with weak avalanche and with noise calculations, enormous care should be taken in incorporating these changes.

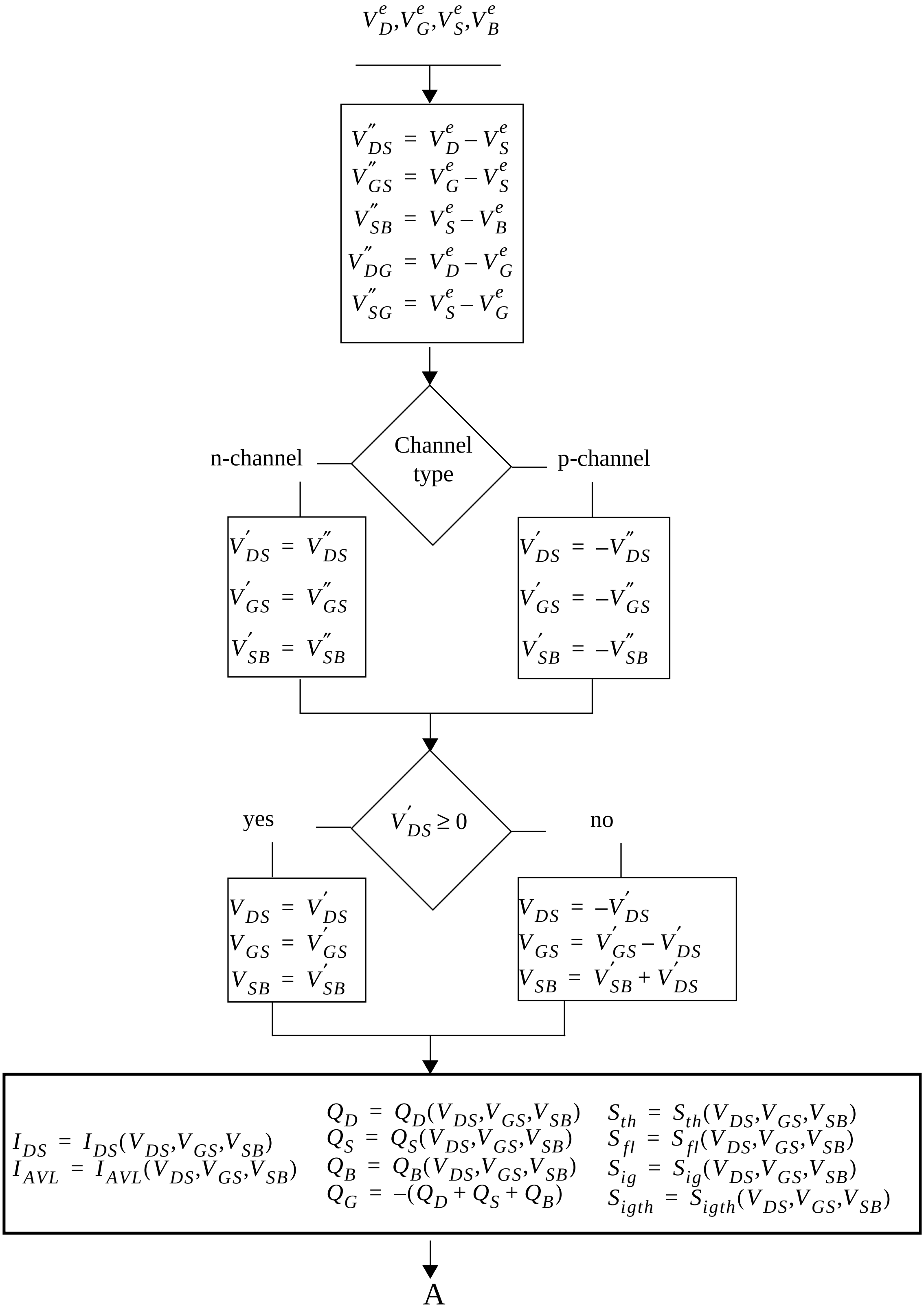
In detail, in order to embed Model 902 correctly into a circuit simulator, the following procedure, illustrated in fig. 41 should be followed.

We have assumed that indeed the simulator provides the nodal potentials $V^e{}_D$, $V^e{}_G$, $V^e{}_S$ and $V^e{}_B$ based on an a priori assignment of drain, gate, source and bulk.

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 Based on a positive or negative V'_{DS}, calculate the internal nodal voltages. At this level, the voltages - and the parameters, see below - comply to all the requirements for input quantities of Model 9.


$V_D^e, V_G^e, V_S^e, V_B^e$
$V''_{DS} = V_D^e - V_S^e$
$V''_{GS} = V_G^e - V_S^e$
$V''_{SB} = V_S^e - V_B^e$
$V''_{DG} = V_D^e - V_G^e$
$V''_{SG} = V_S^e - V_G^e$
Channel type
n-channel
p-channel
$V'_{DS} = V''_{DS}$
$V'_{GS} = V''_{GS}$
$V'_{SB} = V''_{SB}$
$V'_{DS} = -V''_{DS}$
$V'_{GS} = -V''_{GS}$
$V'_{SB} = -V''_{SB}$
$V'_{DS} \geq 0$
yes
no
$V_{DS} = V'_{DS}$
$V_{GS} = V'_{GS}$
$V_{SB} = V'_{SB}$
$V_{DS} = -V'_{DS}$
$V_{GS} = V'_{GS} - V'_{DS}$
$V_{SB} = V'_{SB} + V'_{DS}$
$I_{DS} = I_{DS}(V_{DS}, V_{GS}, V_{SB})$
$I_{AVL} = I_{AVL}(V_{DS}, V_{GS}, V_{SB})$
$Q_D = Q_D(V_{DS}, V_{GS}, V_{SB})$
$Q_S = Q_S(V_{DS}, V_{GS}, V_{SB})$
$Q_B = Q_B(V_{DS}, V_{GS}, V_{SB})$
$Q_G = -(Q_D + Q_S + Q_B)$
$S_{th} = S_{th}(V_{DS}, V_{GS}, V_{SB})$
$S_{fl} = S_{fl}(V_{DS}, V_{GS}, V_{SB})$
$S_{ig} = S_{ig}(V_{DS}, V_{GS}, V_{SB})$
$S_{igth} = S_{igth}(V_{DS}, V_{GS}, V_{SB})$
A

A

$V'_{DS} \geq 0$

yes:

$$I'_{DS} = I_{DS} \qquad Q'_D = Q_D$$
$$I'_{DB} = I_{AVL} \qquad Q'_G = Q_G$$
$$I'_{SB} = 0 \qquad Q'_S = Q_S$$
$$Q'_B = Q_B$$

$$S'_D = S_{th} + S_{fl}$$
$$S'_G = S_{ig}$$
$$S'_S = S_{th} + S_{fl} + S_{ig} + 2R_e\{S_{igth}\}$$
$$S'_{DG} = S^*_{igth}$$
$$S'_{GS} = -S_{ig} - S_{igth}$$
$$S'_{SD} = -S_{igth} - S_{th} - S_{fl}$$

no:

$$I'_{DS} = -I_{DS} \qquad Q'_D = Q_S$$
$$I'_{DB} = 0 \qquad Q'_G = Q_G$$
$$I'_{SB} = I_{AVL} \qquad Q'_S = Q_D$$
$$Q'_B = Q_B$$

$$S'_D = S_{th} + S_{fl} + S_{ig} + 2R_e\{S_{igth}\}$$
$$S'_G = S_{ig}$$
$$S'_S = S_{th} + S_{fl}$$
$$S'_{DG} = -S_{ig} - S^*_{igth}$$
$$S'_{GS} = S_{igth}$$
$$S'_{SD} = -S^*_{igth} - S_{th} - S_{fl}$$

Channel type

n-channel:

$$I''_{DS} = I'_{DS} \qquad Q''_D = Q'_D \qquad S''_D = S'_D$$
$$I''_{DB} = I'_{DB} \qquad Q''_G = Q'_G \qquad S''_G = S'_G$$
$$I''_{SB} = I'_{SB} \qquad Q''_S = Q'_S \qquad S''_S = S'_S$$
$$Q''_B = Q'_B \qquad S''_{DG} = S'_{DG}$$
$$S''_{GS} = S'_{GS}$$
$$S''_{SD} = S'_{SD}$$

p-channel:

$$I''_{DS} = -I'_{DS} \qquad Q''_D = -Q'_D \qquad S''_D = S'_D$$
$$I''_{DB} = -I'_{DB} \qquad Q''_G = -Q'_G \qquad S''_G = S'_G$$
$$I''_{SB} = -I'_{SB} \qquad Q''_S = -Q'_S \qquad S''_S = S'_S$$
$$Q''_B = -Q'_B \qquad S''_{DG} = S'_{DG}$$
$$S''_{GS} = S'_{GS}$$
$$S''_{SD} = S'_{SD}$$

B

B

$$I_D^e = I''_{DS} + I''_{DB} \qquad Q_D^e = Q''_D + C_{GDO} \cdot V''_{DG} \qquad S_D^e = S''_D$$

$$I_G^e = 0 \qquad Q_G^e = Q''_G - C_{GDO} \cdot V''_{DG} - C_{GSO} \cdot V''_{SG} \qquad S_G^e = S''_G$$

$$I_S^e = -I''_{DS} + I''_{SB} \qquad Q_S^e = Q''_S + C_{GSO} \cdot V''_{SG} \qquad S_S^e = S''_S$$

$$I_B^e = -I''_{DB} - I''_{SB} \qquad Q_B^e = Q''_B \qquad S_{DG}^e = S''_{DG}$$

$$S_{GS}^e = S''_{GS}$$

$$S_{SD}^e = S''_{SD}$$

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

Figure 41: Transformation scheme

Step 4 Evaluate all the internal output quantities - channel current, weak-avalanche current, nodal charges, and noise-power spectral densities - using the standard Model 9 equations and the internal voltages.

Step 5 Correct the internal output quantities for a possible source-drain interchange. In fact, this directly establishes the external noise-power spectral densities.

Step 6 Correct for a possible p-channel transformation.

Step 7 Change from branch current to nodal currents, establishing the external current output quantities. Calculate the overlap charges that are related to the physical regions and add them to the nodal charges, thus forming the external charge output quantities.

It is customary to have separate user models in the circuit simulators for p- and n-channel transistors. In that manner it is easy to use different "maxi-set" 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 in the simulator. It is the responsibility of the persons that do the parameter determination to do so!

9.8.1 Cross spectral densities of noise currents in MOS MODEL 9

The cross spectral densities as mentioned in the figure 41 are found in the following way (See also figure 55 on page 433, [25] and [26]):

The noise currents i_s, i_d and i_g, (all in $A/\sqrt{Hz}$) are defined as in the figure below:

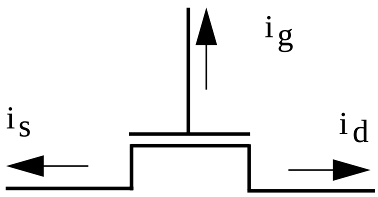


Figure 42: Noise currents in a MOSFET

Here i_d consists of two (uncorrelated) parts $i_{D,\,th}$ and $i_{D,\,fl}$, describing the thermal noise and flicker noise respectively:

$$i_D = i_{D,\,th} + i_{D,\,fl} \tag{9.171}$$

Conservation of current and no noise current flowing to the bulk, leads to:

$$i_S = -i_D - i_G \tag{9.172}$$

Noise spectral densities are defined by:

$$S_{th} \equiv \langle i_{D,\,th} i^*{}_{D,\,th} \rangle \tag{9.173}$$

$$S_{fl} \equiv \langle i_{D,\,fl} i^*{}_{D,\,fl} \rangle \tag{9.174}$$

$$S_{ig} \equiv \langle i_G i^*{}_G \rangle \tag{9.175}$$

where $\langle\ \rangle$ denotes the time average. Gate current amd drain current thermal noise are correlated. The correlation is given by the complex spectral density S_{igth}:

$$S_{igth} \equiv \langle i_G i^*{}_{D,\,th} \rangle \tag{9.176}$$

$$S_S \equiv \langle i_S i^*{}_S \rangle$$

$$= \langle (-i_D - i_G)(-i_D - i_G)^* \rangle$$

$$= \langle i_D i^*{}_D \rangle + \langle i_G i^*{}_G \rangle + \langle i_D i^*{}_G \rangle + \langle i_G i^*{}_D \rangle \tag{9.177}$$

$$= S_{th} + S_{fl} + S_{ig} + 2Re \cdot (S_{igth}) \tag{9.178}$$

The noise spectral densities S_D and S_G are simply:

$$S_D = S_{th} + S_{fl} \tag{9.179}$$

$$S_G = S_{ig} \tag{9.180}$$

Now we turn to the cross-spectral densities and calculate S_{DG}:

$$S_{DG} = \langle i_D i^*{}_G \rangle$$

$$= \langle i_{D,\,th} i^*{}_G \rangle + \langle i_{D,\,fl} i^*{}_G \rangle$$

$$= S^*{}_{igth} \tag{9.181}$$

S_{GD} is the complex conjugate of S_{DG}:

$$S_{GD} = \langle i_G i^*{}_D \rangle = S_{igth}$$

Similarly, S_{GS} is given by:

$$
\begin{aligned}
S_{GS} &= \langle i_G i^*{}_S \rangle \\
&= \langle i_G(-i_D - i_G)^* \rangle \\
&= -\langle i_G i^*{}_D \rangle - \langle i_G i^*{}_G \rangle \\
&= -\langle i_G i^*{}_{D,\,th} \rangle - \langle i_G i^*{}_{D,\,fl} \rangle - \langle i_G i^*{}_G \rangle \\
&= -S_{igth} - S_{ig}
\end{aligned}
\tag{9.182}
$$

S_{SG} is the complex conjugate of S_{GS} :

$$
= -S^*{}_{igth} - S_{ig}
\tag{9.183}
$$

$$
\begin{aligned}
S_{SD} &= \langle i_S i^*{}_D \rangle \\
&= \langle (-i_D - i_G) i^*{}_D \rangle \\
&= S_{th} - S_{fl} - S_{igth}
\end{aligned}
\tag{9.184}
$$

$$
S_{DS} = -S_{th} - S_{fl} - S^*{}_{igth}
\tag{9.185}
$$

It is convenient to summarize the results in matrix form:

$$
\bar{\bar{S}} = \begin{bmatrix} S_D & S_{DG} & S_{DS} \\ S_{GD} & S_G & S_{GS} \\ S_{SD} & S_{SG} & S_S \end{bmatrix}
$$

$$= \begin{bmatrix} S_{th} + S_{fl} & S^*_{igth} & -S_{th} - S_{fl} - S^*_{igth} \\ S_{igth} & S_{ig} & -S_{igth} - S_{ig} \\ -S_{th} - S_{fl} - S_{igth} & -S^*_{igth} - S_{ig} & S_{th} + S_{fl} + S_{ig} + 2Re \cdot (S_{igth}) \end{bmatrix} \tag{9.186}$$

The above applies to the case $V_{DS} \geq 0$. In case $V_{DS} < 0$ we obtain the right equations from equation 9.186 by switching colums 1 and 3 and then switching rows 1 and 3:

$$\bar{\bar{S}} = \begin{bmatrix} S_D & S_{DG} & S_{DS} \\ S_{GD} & S_G & S_{GS} \\ S_{SD} & S_{SG} & S_S \end{bmatrix}$$

$$= \begin{bmatrix} S_{th} + S_{fl} + S_{ig} + 2Re \cdot (S_{igth}) & -S^*_{igth} - S_{ig} & -S_{th} - S_{fl} - S_{igth} \\ -S_{igth} - S_{ig} & S_{ig} & S_{igth} \\ -S_{th} - S_{fl} - S^*_{igth} & S^*_{igth} & S_{th} + S_{fl} \end{bmatrix} \tag{9.187}$$

9.9 Parameter Extraction Method

The parameter extraction for MOST model 9 using an **optimisation method** is described step-by-step in the scheme below. The equations used for the parameter extraction are the basic equations of section 9.4. The simultaneous determination of all parameters is not possible, because the value of some parameters can be wrong due to suboptimisation. Therefore it is more practical to split the parameters into five groups, and, for each group, to measure the characteristics according to the indicated conditions and to determine the particular parameters. It should be noticed that for the p-channel MOST all voltage and current values have to change sign upon entering the optimisation programme as a p-MOST is treated as an equivalent n-MOST.

The bias conditions to be used for the measurements are dependent on the supply voltage of the process. Of course it is advisable to restrict the range of voltages to this supply voltage V_{sup}. Otherwise physical effects, atypical for normal transistor operation and therefore less well described by MOST model 9, may dominate the characteristics. This can lead for certain processes to parameter values dependent on the selected range of voltages.

Before the optimisation starts a parameter set has to be determined which contains a first estimation of the parameters to be extracted and the parameters which remain constant. The values of ϕ_B and ϕ_T are calculated from the device temperature T_{KD} and ϕ_{BR} according eqn. Eq. (9.65) and Eq. (9.89). From our experience with different processes η_{DS} is set to 0.6. The values of η_γ and η_m which characterise the subthreshold behaviour, are 2 for the double *k*-factor model and 1 for the single *k*-factor model.

With this parameter set a first optimisation following the scheme below, is performed. After this the new parameter set serves as an estimation for the second optimisation, which is performed following the same scheme. This method yields a proper set of parameters after the second optimisation. Experiments with transistors of different processes show that the parameter set does not change very much after a third optimisation.

The parameter extraction contains the following steps:

- I_D-V_{GS} :

n-channel	:	V_{GS} = 0 ... V_{sup} (at least 10 steps). V_{DS} = 0.1 V V_{BS} = 0 V
p-channel	:	V_{GS} = 0 ... -V_{sup} (at least 10 steps). V_{DS} = -0.1 V V_{BS} = 0 V

Determination of V_{T0}, β and θ_1.

- I_D-V_{GS}:

n-channel	:	V_{GS} = 0 ... V_{sup} (at least 10 steps). V_{DS} = 0.1 V V_{BS} = 0 ... -V_{sup}
p-channel	:	V_{GS} = 0 ... -V_{sup} (at least 10 steps). V_{DS} = -0.1 V V_{BS} = 0 ... V_{sup}

Determination of θ_2, k, k_0 and V_{SBX} for a n-channel and determination of θ_2 and k for a p-channel.

It is recommended not to incorporate the subthreshold description in the optimisation of the parameters for the I_D-V_{GS} behaviour in the linear region because suboptimisations may result in wrong values and strange characteristics. So during such an optimisation, values of I_D with V_{GS} under V_T have to be neglected.

Normally the value of k_o is larger than the value of k. But for certain processes the value of V_T versus V_{BS} shows a different behaviour and the value of k_o is smaller than the value of k. This behaviour can also be described with the model, but the parameters for this description are very difficult to determine from the above measurements. Therefore these parameters have to be determined from the measurements in the subthreshold region.

- Subthreshold:

n-channel : $V_{GS} = V_{GS1} \dots V_{GS2}$ with I_{DS} (V_{GS1}) ≈ 10 pA and $V_{GS2} > V_{T1}$.
V_{DS} = 3 values starting from 1 V to V_{sup}
V_{BS} = 0V

p-channel : $V_{GS} = -V_{GS1} \dots -V_{GS2}$ with I_{DS} ($-V_{GS1}$) ≈ -10 pA and $V_{GS2} > V_{T1}$.
V_{DS} = 3 values starting from -1 V to $-V_{sup}$
V_{BS} = 0 V

Determination of γ_{00}, m_0 ,ζ_1.
For short-channel transistors V_{SBT} also has to be determined. Therefore three V_{BS} are used starting from 0 V to $-V_{sup}$ (for n-channel transistors) or V_{sup} (for p-channel transistors).

If V_{SBT} is not important, this parameter has to be large! In this case its value is set 100 V. In the subthreshold region it is in principle possible to determine the values of η_γ and η_m. It is also possible to verify in the subthreshold region the correctness of the values of k and k_0. If necessary these parameters can be corrected in order to obtain a better subthreshold behaviour fit.

The output conductance values are extracted from the measurements of I_D-V_{DS} by calculating in a numerical way the derivative of I_D to V_{DS}.

- Output conductance:

n-channel : $V_{DS} = 0.1 \dots V_{\mathrm{sup}}$ (step 0.2 V).
V_{GS} = 3 values starting above threshold, not above V_{sup}
V_{BS} = 3 values starting from 0 V to $-V_{sup}$

p-channel : $V_{DS} = -0.1 \dots -V_{\mathrm{sup}}$ (step -0.2 V).
V_{GS} = 3 values starting below threshold, not below $-V_{sup}$
V_{BS} = 3 values starting from 0 V to V_{sup}

For analogue purposes the behaviour of the output conductance for values at V_T + 100 mV is also important.

Determination of γ_1, α. For long-channel transistors, V_P is also determined.

Because $V_P \sim L_E$, it is difficult to determine this parameter for short-channel transistors. Therefore the proportionality factor for a long-channel transistor is determined and then V_P for a short-channel transistor is calculated. With this calculated value of V_P, the values of α and γ_1 are determined for a short-channel transistor.

If there is no long-channel transistor available one can determine the parameters γ_1, α and V_P from the measurements of the output conductance at V_{BS} = 0 V. Experiments with C300 transistors show that these values are in good agreement with the values, obtained with calculation and optimisation.

Measurements with V_{GS} near threshold, can be used to check the value of γ_{00} after the optimisation of V_P , γ_1 and α.

Especially for short-channel transistors, the weak avalanche parameters also affect the behaviour of the output conductance for large V_{DS} values. The output conductance will increase again when the weak avalanche parameters are taken into account. If these parameters are not available, these output conductance values have to be neglected. Also the values in the corresponding I_D-V_{DS} characteristic have to be neglected to eliminate their influence on the value of θ_3.

- I_D-V_{DS}:

n-channel	:	V_{DS} = 0 ... V_{sup} (step 0.2 V). V_{GS} = 3 values starting above threshold, not above V_{sup} V_{BS} = 3 values starting from 0 V to $-V_{sup}$
p-channel	:	V_{DS} = -0 ... $-V_{sup}$ (step -0.2 V). V_{GS} = 3 values starting below threshold, not below $-V_{sup}$ V_{BS} = 3 values starting from 0 V to V_{sup}

Determination of θ_3.

9.9.1 Scaling of Parameters.

Using the formulae of chapter 9.4 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 lengths, widths and at different temperatures have to be measured. With the results of these measurements the sensitivities of the parameters on length, width and temperature can be found. In the formulae Eq. (9.82) (for α) and Eq. (9.91) the length dependence term contains an exponent. This exponent was introduced to be able to distinguish n- and p-channels. Out of measurements in C3DM a different behaviour of these parameters with the length was found.
For n-channels : $\eta_\alpha = 0$ and $\eta_\zeta = 0.5$
For p-channels : $\eta_\alpha = 1$ and $\eta_\zeta = 1$
During the determination of a parameter set the exponents of the two formulae are best kept constant. Optimising these exponents can lead to strange results and can become very time consuming.

Using the new parameters W_{DOG} and f_{θ_1} generally results in better modelling accuracy. A good strategy is to keep W_{DOG} fixed at the value calculated from the minimum design rules, i.e. the contact dimension plus two times the minimum OD-CO spacing. The parameter f_{θ_1} must be optimized. Care must be taken that the reference transistor is chosen in such a way that $W_{ER} \geq W_{EDOG}$.

For the determination of a geometry-scaled parameter set a three-step procedure is recommended:

1. determine minisets (V_{T0}, β, ...) for all measured devices, as explained above.

2. the width and length sensitivity coefficients are optimized by fitting the appropriate scaling rules to these miniset parameters.

3. finally the width and length sensitivity coefficients are optimized by fitting the result of the scaling rules and current equations to the measured currents of all devices simultaneously.

Note that this extraction procedure is implemented in IC-CAP, which is the standard parameter extraction tool within Philips.

Since the development of MOST model 9, parameter sets have been determined for several processes (e.g. C200, C150, C100 and C075). These can be found in the Blue Books. For all processes good results have been obtained.