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MOS Model 20

Level 2001

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Abstract: A new transistor model for high-voltage MOS devices has been developed, called MOS Model 20. This transistor model can be used in circuit simulation of high-voltage integrated circuits. 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. It thus combines the MOSFET-operation of the channel region with that of the drift region under the thin gate oxide. As such, MOS Model 20 is aimed as a successor of the combination of MOS Model 9 in series with MOS Model 31 in macro models of various high-voltage MOS devices.

Since MOS Model 20 is a so-called surface-potential-based model, it gives an accurate description in all operation regimes. MOS Model 20 includes strong inversion, depletion and accumulation, in both the channel region and the drift region. Furthermore, by the calculation of the so-called internal drain voltage *inside* the model itself, MOS Model 20 aims at a better convergence behaviour during circuit simulation than a macro model consisting of MOS Model 9 in series with MOS Model 31.

The objective of this report is to present the full definition of MOS Model 20, including the model parameter set, the temperature and geometrical scaling rules, and all the implemented model equations for the currents, charges and noise sources. The physical background of the model is briefly explained, as well as the parameter extraction strategy is given.

Preface and History of Model and Documentation

Preface

A first version of the compact LDMOS model, MOS MODEL 20 (level 2001), has become available in October 2002. Future changes and additions to the model have been documented by extending or changing the documentation in this report.

History of Model

October 2003 : Release of MOS MODEL 20, level 2001, test version
January 2004 : Update of MOS MODEL 20, level 2001, test version.
This update, for instance, omits the source-drain interchange for the dc-current description
October 2004 : Introduction of MOS MODEL 20, level 2001.
This update includes some practical changes, like the pinch-off voltage V_{oxp0}, the clip-low value of m and of λ_{D},
and the implementation of the noise transfer function.

History of Documentation

August 2003 : First documentation of MOS MODEL 20, level 2001, test version
January 2004 : Update of documentation of MOS MODEL 20, level 2001, test version,
according to model formulation of January 2004.
October 2004 : Introduction of MOS MODEL 20, level 2001.
This update includes some practical changes, like the pinch-off voltage V_{oxp0}, the clip-low value of m and of λ_{D}.

Contents

1 Introduction

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.

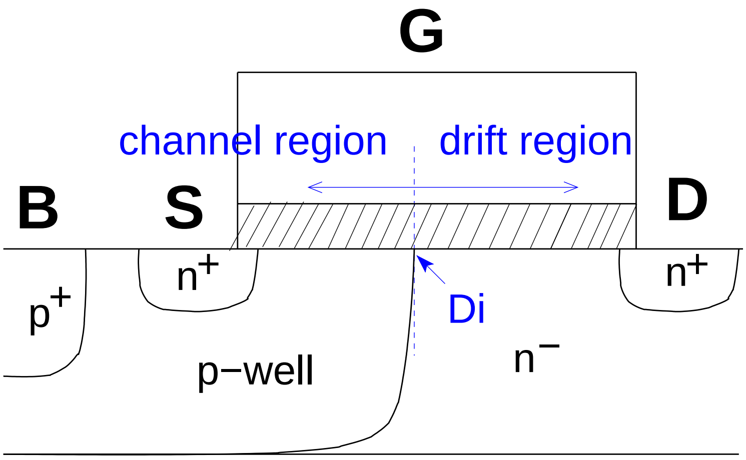


Figure 1: *the region under the thin gate oxide of an n-channel LDMOS device, described by MOS Model 20*

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 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.

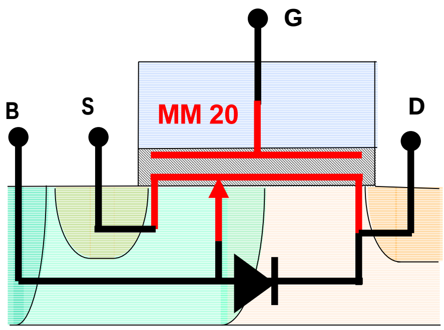


Figure 2: *macro model for an LDMOS transistor*

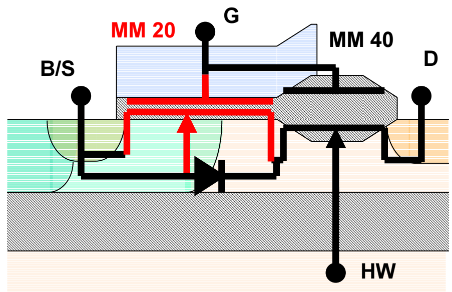


Figure 3: *macro model for an SOI-LDMOS transistor with a thick field oxide*

1.1 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 to generate 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 3.3.1.

  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 3.2.1.

- **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.

1.2 Structure of this report

After this introductory section, the procedure of embedding MOS Model 20 in a circuit simulator is outlined. Next, the nomenclature is explained, while in Section 5 the implemented equations are listed. Finally the operating point output (OPO) parameters are described.

2 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.

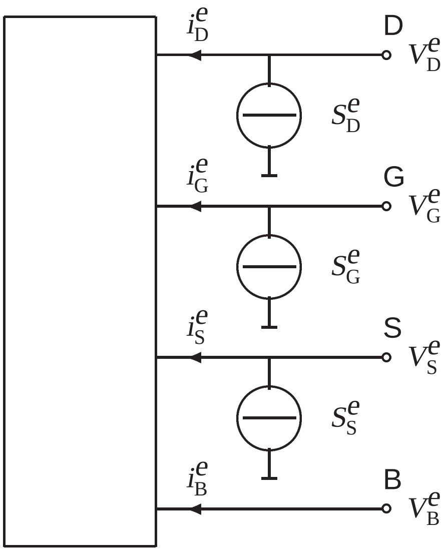
The total transformation procedure is in detail explained in Section 2.3.

2.1 External Electrical Quantities and Variables

No.	Variable	Program 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
16	S_{DG}^e	SDGE	A^2s	Cross spectral density between the drain and the gate noise currents
17	S_{GS}^e	SGSE	A^2s	Cross spectral density between the gate and the source noise currents
18	S_{SD}^e	SSDE	A^2s	Cross spectral density between the source and the drain noise currents

The definitions of the external electrical variables are illustrated in Figure 4.



$$i_D^e = I_D^e + \frac{dQ_D^e}{dt}$$

$$i_G^e = I_G^e + \frac{dQ_G^e}{dt}$$

$$i_S^e = I_S^e + \frac{dQ_S^e}{dt}$$

$$i_B^e = I_B^e + \frac{dQ_B^e}{dt}$$

Figure 4: Definition of the external electrical quantities and variables

2.2 Internal Electrical Quantities and Variables

No.	Variable	Program Name	Units	Description
1	V_{DS}	VDS	V	Drain–to–source voltage applied to the equivalent n–MOST

2	V_{GS}	VGS	V	Gate–to–source voltage applied to the equivalent n–MOST
3	V_{SB}	VSB	V	Source–to–bulk voltage applied to the equivalent n–MOST
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 bulk due to the weak–avalanche effect
6	Q_{D}	QD	C	Intrinsic charge in the equivalent n–MOST attributed to the drain node
7	Q_{G}	QG	C	Intrinsic charge in the equivalent n–MOST attributed to the gate node
8	Q_{S}	QS	C	Intrinsic charge in the equivalent n–MOST attributed to the source node
9	Q_{B}	QB	C	Intrinsic charge in the equivalent n–MOST attributed to the bulk node
10	$S_{\mathrm{D_{th}}}$	SDTH	A^2s	Spectral density of the thermal–noise current of the channel region
11	$S_{\mathrm{D_{fl}}}$	SDFL	A^2s	Spectral density of the flicker–noise current of the channel region
12	$S_{\mathrm{G_{th}}}$	SGTH	A^2s	Spectral density of the thermal noise current induced in the gate
13	$S_{\mathrm{GD_{th}}}$	SGDTH	A^2s	Cross spectral density of the thermal–noise current induced in the gate and the thermal–noise current of the channel

2.3 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 2.3 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.

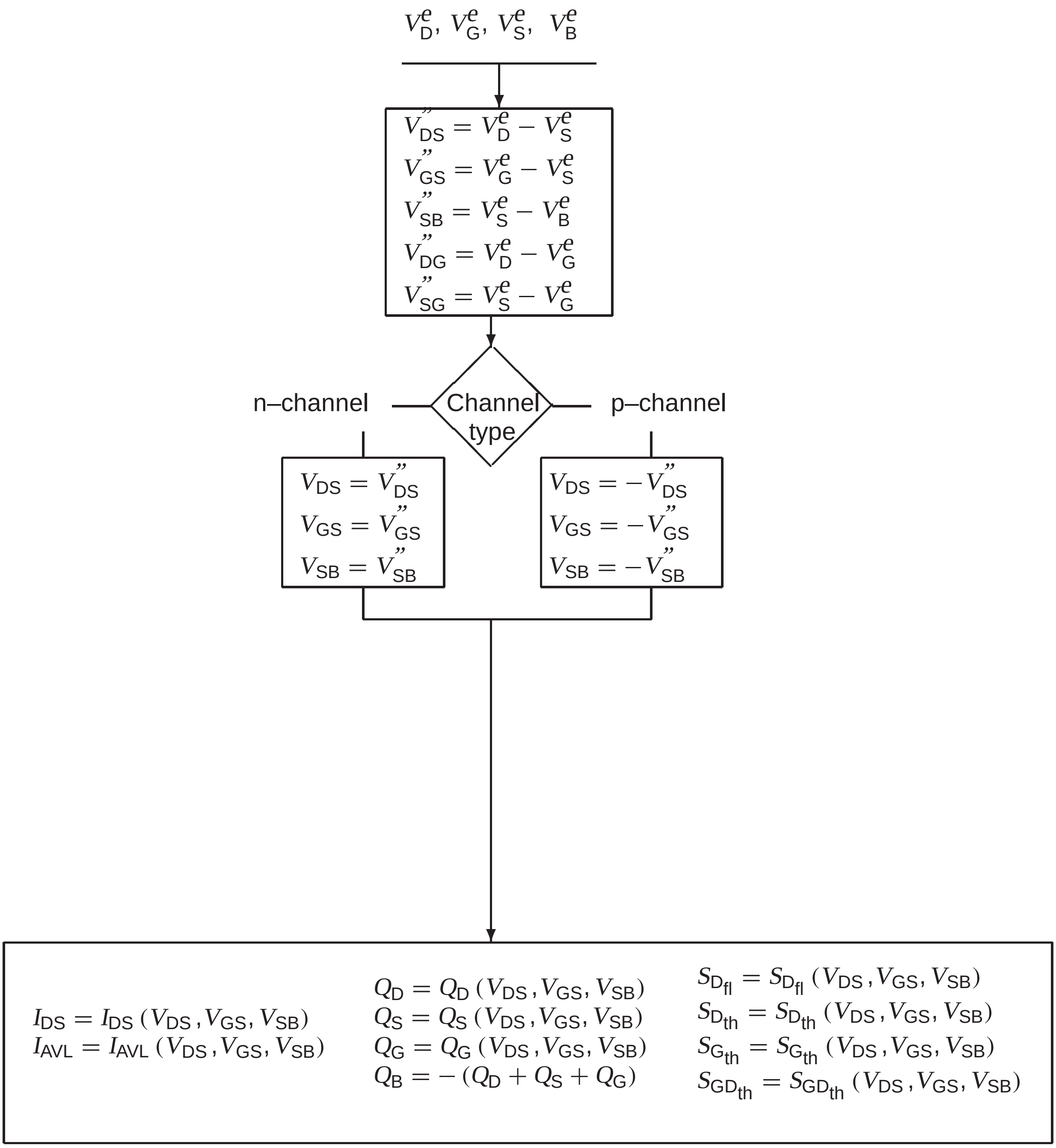
Step 1 Calculate the voltages V''_{DS}, V''_{GS} and V''_{SB}, and the additional voltages V''_{DG} and V''_{SG}. The latter are used for calculating the charges associated with overlap capacitances.

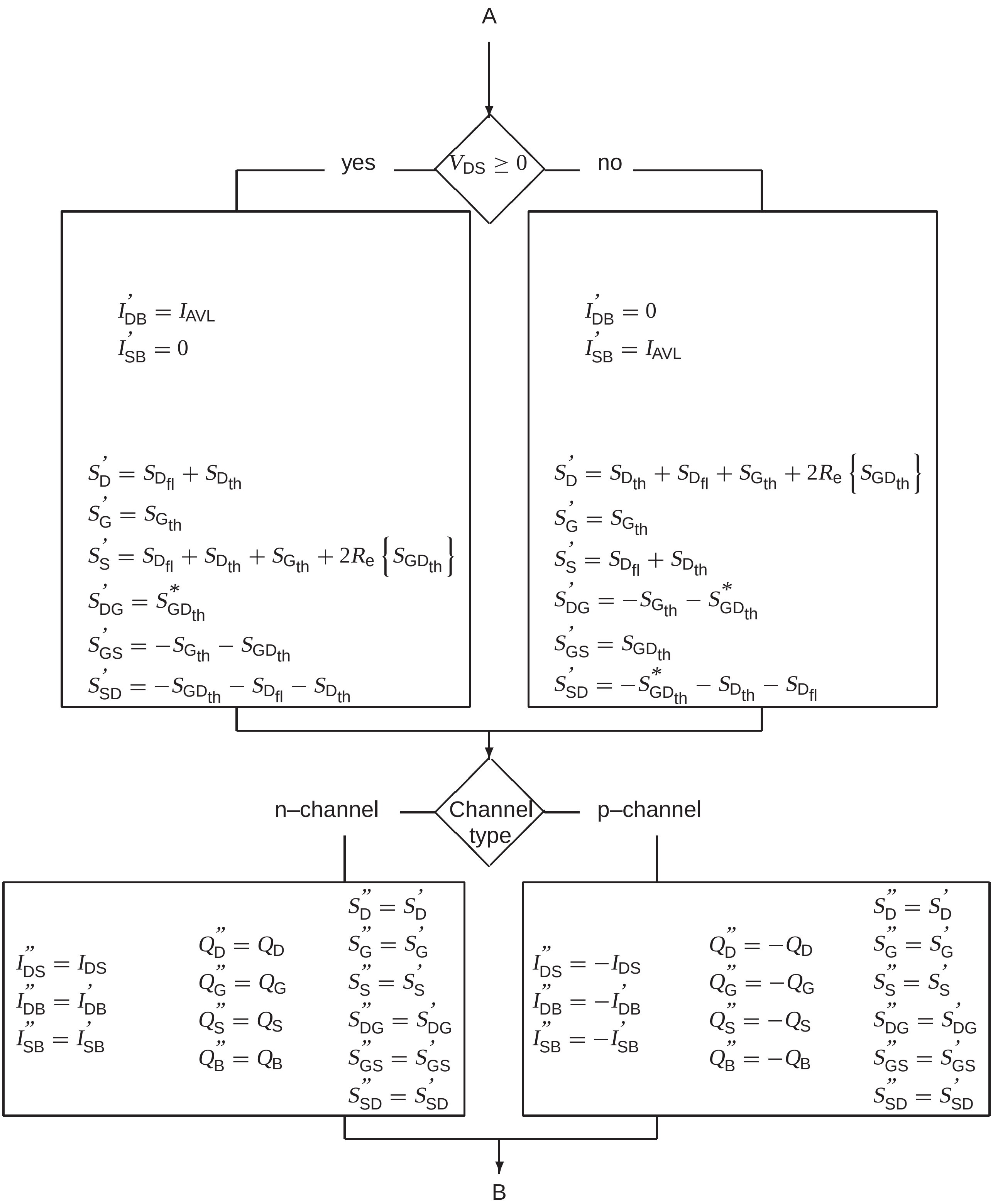
Step 2 Based on *n*– or *p*–channel devices, calculate the modified voltages V_{DS}, V_{GS} and V_{SB}. From here onwards only *n*–channel behaviour needs to be considered.

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.


$V^e_D,\ V^e_G,\ V^e_S,\ V^e_B$
$V''_{DS} = V^e_D - V^e_S$
$V''_{GS} = V^e_G - V^e_S$
$V''_{SB} = V^e_S - V^e_B$
$V''_{DG} = V^e_D - V^e_G$
$V''_{SG} = V^e_S - V^e_G$
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
$I'_{DB} = I_{AVL}$
$I'_{SB} = 0$
$S'_{D} = S_{D_{fl}} + S_{D_{th}}$
$S'_{G} = S_{G_{th}}$
$S'_{S} = S_{D_{fl}} + S_{D_{th}} + S_{G_{th}} + 2R_e \left\{ S_{GD_{th}} \right\}$
$S'_{DG} = S^{*}_{GD_{th}}$
$S'_{GS} = -S_{G_{th}} - S_{GD_{th}}$
$S'_{SD} = -S_{GD_{th}} - S_{D_{fl}} - S_{D_{th}}$
$I'_{DB} = 0$
$I'_{SB} = I_{AVL}$
$S'_{D} = S_{D_{th}} + S_{D_{fl}} + S_{G_{th}} + 2R_e \left\{ S_{GD_{th}} \right\}$
$S'_{G} = S_{G_{th}}$
$S'_{S} = S_{D_{fl}} + S_{D_{th}}$
$S'_{DG} = -S_{G_{th}} - S^{*}_{GD_{th}}$
$S'_{GS} = S_{GD_{th}}$
$S'_{SD} = -S^{*}_{GD_{th}} - S_{D_{th}} - S_{D_{fl}}$
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

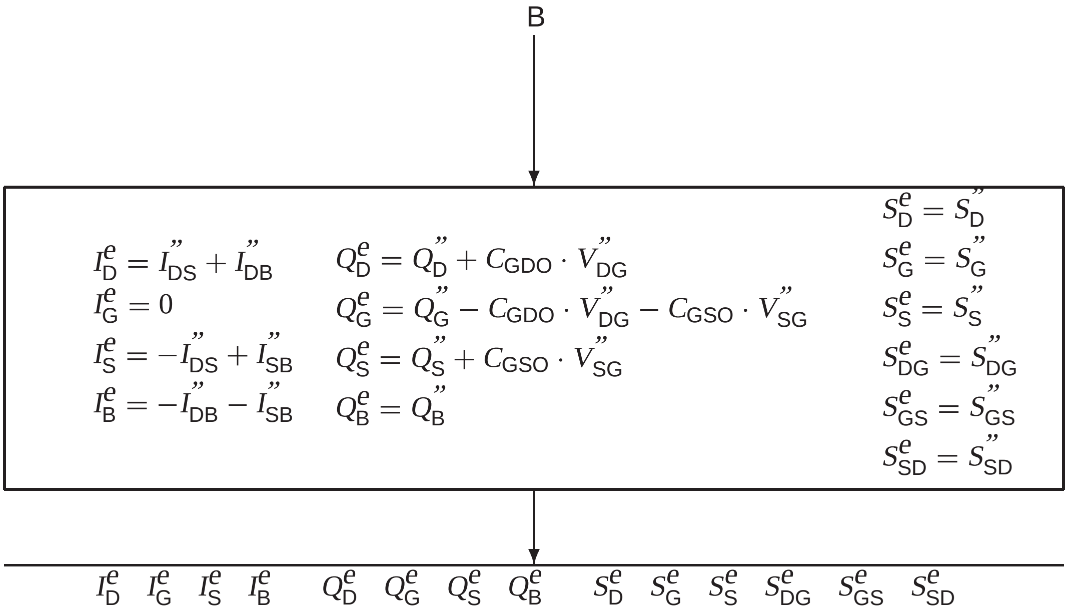


Figure 5: Transformation scheme

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 in the simulator.

3 Nomenclature

3.1 Input Variables and Quantities:

3.1.1 List of Numerical Constants:

No.	Constant	Program name	Value
1	A	LN_MINDOUBLE	-800

3.1.2 List of Physical Constants:

No.	Constant	Program name	Value	Units
1	T_0	KELVIN_CONVERSION	273.15	K
	Offset for conversion from Celsius to Kelvin temperature scale			
2	k_B	K_BOLTZMANN	$1.3806226 \cdot 10^{-23}$	JK^{-1}
	Boltzmann constant			
3	q	Q_ELECTRON	$1.6021918 \cdot 10^{-19}$	C
	Elementary unit charge			
4	ϵ_{ox}	PHY_EPSOX	$3.4531438 \cdot 10^{-11}$	Fm^{-1}
	Absolute permittivity of the oxide layer			

3.1.3 List of Circuit Simulator Variables:

No.	Symbol	Program name	Units	Description
1	T_a	Ta	°C	*Ambient circuit temperature*
2	f	F	Hz	*Operation frequency*

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 are listed in Section 3.2.1, while its scaling rules are listed in Section 3.2.3. For simplicity, in the geometrical MOS Model 20 both the n-channel and p-channel devices have been assigned the same default parameter values.

3.2.1 List of Geometrical Model Parameters

No.	Parameter	Symbol	Units	Meaning
0	LEVEL	level	-	Must be 2001
1	W	W	m	Drawn width of the channel region
2	WVAR	ΔW	m	Width offset of the channel region
3	WD	W_{D}	m	Drawn width of the drift region
4	WDVAR	ΔW_{D}	m	Width offset of the drift region
5	TREF	T_{ref}	$^{\mathrm{o}}$C	Reference temperature
6	VFB	V_{FB}	V	Flatband voltage of the channel region, at reference temperature
7	STVFB	$S_{T;V_{\mathrm{FB}}}$	VK^{-1}	Temperature scaling coefficient for V_{FB}
8	VFBD	V_{FBD}	V	Flatband voltage of the drift region, at reference temperature
9	STVFBD	$S_{T;V_{\mathrm{FBD}}}$	VK^{-1}	Temperature scaling coefficient for V_{FBD}
10	KOR	$k_{0\mathrm{R}}$	V$^{1/2}$	Body factor of the channel region of an infinitely wide transistor
11	SWKO	$S_{W;k_0}$	-	Width scaling coefficient for k_0
12	KODR	$k_{0\mathrm{DR}}$	V$^{1/2}$	Body factor of the drift region of an infinitely wide transistor
13	SWKOD	$S_{W;k_{0\mathrm{D}}}$	-	Width scaling coefficient for $k_{0\mathrm{D}}$
14	PHIB	ϕ_{B}	V	Surface potential at the onset of strong inversion in the channel region, at reference temperature
15	STPHIB	$S_{T;\phi_{\mathrm{B}}}$	VK^{-1}	Temperature scaling coefficient for ϕ_{B}
16	PHIBD	ϕ_{BD}	V	Surface potential at the onset of strong inversion in the drift region, at reference temperature
17	STPHIBD	$S_{T;\phi_{\mathrm{BD}}}$	VK^{-1}	Temperature scaling coefficient for ϕ_{BD}
18	BETW	β_W	AV^{-2}	Gain factor of a channel region of 1 μm wide, at reference temperature
19	ETABET	η_β	-	Temperature scaling exponent for β

No.	Parameter	Symbol	Units	Meaning
20	BETACCW	β_{acc_W}	AV^{-2}	Gain factor of a drift region of 1 μm wide, at reference temperature
21	ETABETACC	$\eta_{\beta_{\mathrm{acc}}}$	-	Temperature scaling exponent for β_{acc}
22	RDW	R_{D_W}	Ω	On-resistance of a drift region of 1 μm wide, at reference temperature
23	ETARD	$\eta_{R_{\mathrm{D}}}$	-	Temperature scaling exponent for R_{D}
24	LAMD	λ_{D}	-	Quotient of the depletion layer thickness to the effective thickness of the drift region at $V_{\mathrm{SB}} = 0$ V
25	THE1R	$\theta_{1\mathrm{R}}$	V^{-1}	Mobility reduction coefficient of an infinitly wide transistor, due to vertical strong-inversion field in channel region
26	SWTHE1	$S_{W;\theta_1}$	-	Width scaling coefficient for θ_1
27	THE1ACC	$\theta_{1\mathrm{acc}}$	V^{-1}	Mobility reduction coefficient in the drift region due to the vertical electrical field caused by accumulation
28	THE2R	$\theta_{2\mathrm{R}}$	$\mathrm{V}^{-1/2}$	Mobility reduction coefficient for $V_{\mathrm{SB}} > 0$ of an infinitly wide transistor, due to the vertical depletion field in the channel region
29	SWTHE2	$S_{W;\theta_2}$	-	Width scaling coefficient for θ_2
30	THE3R	$\theta_{3\mathrm{R}}$	V^{-1}	Mobility reduction coefficient in a channel region of an infinitly wide transistor, due to velocity saturation
31	ETATHE3	η_{θ_3}	-	Temperature scaling exponent for θ_3
32	SWTHE3	$S_{W;\theta_3}$	-	Width scaling coefficient for θ_3
33	MEXP	m	-	Smoothing factor for transition from linear to saturation regime
34	ALP	α	-	Factor for channel length modulation
35	VP	V_{P}	V	Characteristic voltage of channel length modulation
36	SDIBL	σ_{dibl}	$\mathrm{V}^{-1/2}$	Factor for drain-induced barrier lowering
37	MSDIBL	$m_{\sigma_{\mathrm{dibl}}}$	-	Exponent for the drain-induced barrier lowering dependence on the backgate bias
38	MO	m_0	V	Parameter for the (short-channel) sub-threshold slope
39	SSF	σ_{sf}	$\mathrm{V}^{-1/2}$	Factor for static feedback
40	A1R	$a_{1\mathrm{R}}$	-	Factor of weak avalanche current of an infinitely wide transistor, at reference temperature
41	STA1	$S_{T;a_1}$	K^{-1}	Temperature scaling coefficient for a_1
42	SWA1	$S_{W;a_1}$	-	Width scaling coefficient for a_1
43	A2	a_2	V	Exponent of weak avalanche current
44	A3	a_3	-	Factor of the drain-source voltage above which weak avalanche occurs

No.	Parameter	Symbol	Units	Meaning
45	COXW	C_{ox_W}	F	Oxide capacitance for an intrinsic channel region of 1 μm wide
46	COXDW	C_{oxD_W}	F	Oxide capacitance for an intrinsic drift region of 1 μm wide
47	CGDOW	C_{GDO_W}	F	Gate-to-drain overlap capacitance for a drift region of 1 μm wide
48	CGSOW	C_{GSO_W}	F	Gate-to-source overlap capacitance for a channel region of 1 μm wide
49	NT	N_T	J	Coefficient of thermal noise, at reference temperature
50	NFAW	$N_{f\mathrm{A}_W}$	$\mathrm{V}^{-1}\mathrm{m}^{-4}$	First coefficient of flicker noise for a channel region of 1 μm wide
51	NFBW	$N_{f\mathrm{B}_W}$	$\mathrm{V}^{-1}\mathrm{m}^{-2}$	Second coefficient of flicker noise for a channel region of 1 μm wide
52	NFCW	$N_{f\mathrm{C}_W}$	V^{-1}	Third coefficient of flicker noise for a channel region of 1 μm wide
53	TOX	t_{ox}	m	Thickness of the oxide above the channel region
54	DTA	ΔT_{a}	K	Temperature offset to the ambient temperature
55	MULT	M	-	Number of devices in parallel

3.2.2 Default and Clipping Values of Geometrical Model Parameters

No.	Parameter	Symbol	Units	Default	Clip low	Clip high
0	LEVEL	level	-	2001	-	-
1	W	W	m	20×10^{-6}	1.0×10^{-10}	-
2	WVAR	ΔW	m	0	-	-
3	WD	$W_{\rm D}$	m	20×10^{-6}	1.0×10^{-10}	-
4	WDVAR	$\Delta W_{\rm D}$	m	0		-
5	TREF	$T_{\rm ref}$	$^{\rm o}$C	25	-273	-
6	VFB	$V_{\rm FB}$	V	-1.0	-	-
7	STVFB	$S_{T;V_{\rm FB}}$	VK^{-1}	0	-	-
8	VFBD	$V_{\rm FBD}$	V	-0.1	-	-
9	STVFBD	$S_{T;V_{\rm FBD}}$	VK^{-1}	0	-	-
10	KOR	$k_{\rm 0R}$	V$^{1/2}$	1.6	-	-
11	SWKO	$S_{W;k_0}$	-	0	-	-
12	KODR	$k_{\rm 0DR}$	V$^{1/2}$	1.0	-	-
13	SWKOD	$S_{W;k_{\rm 0D}}$	-	0	-	-
14	PHIB	$\phi_{\rm B}$	V	0.86	-	-
15	STPHIB	$S_{T;\phi_{\rm B}}$	VK^{-1}	-1.2×10^{-3}	-	-
16	PHIBD	$\phi_{\rm BD}$	V	0.78	-	-
17	STPHIBD	$S_{T;\phi_{\rm BD}}$	VK^{-1}	-1.2×10^{-3}	-	-
18	BETW	β_W	AV^{-2}	7.0×10^{-5}	-	-
19	ETABET	η_β	-	1.6	-	-
20	BETACCW	$\beta_{{\rm acc}_W}$	AV^{-2}	7.0×10^{-5}	-	-
21	ETABETACC	$\eta_{\beta_{\rm acc}}$	-	1.5	-	-
22	RDW	$R_{{\rm D}_W}$	Ω	4.0×10^{3}	-	-
23	ETARD	$\eta_{R_{\rm D}}$	-	1.5	-	-
24	LAMD	$\lambda_{\rm D}$	-	0.2	-	-
25	THE1R	$\theta_{\rm 1R}$	V^{-1}	0.09	-	-
26	SWTHE1	$S_{W;\theta_1}$	-	0	-	-
27	THE1ACC	$\theta_{\rm 1acc}$	V^{-1}	0.02	-	-
28	THE2R	$\theta_{\rm 2R}$	V$^{-1/2}$	0.03	-	-
29	SWTHE2	$S_{W;\theta_2}$	-	0	-	-
30	THE3R	$\theta_{\rm 3R}$	V^{-1}	0.4	-	-
31	ETATHE3	η_{θ_3}	-	1.0	-	-
32	SWTHE3	$S_{W;\theta_3}$	-	0	-	-
33	MEXP	m	-	2.0	-	-

No.	Parameter	Symbol	Units	Default	Clip low	Clip high
34	ALP	α	-	2.0×10^{-3}	-	-
35	VP	V_{P}	V	0.05	-	-
36	SDIBL	σ_{dibl}	$\mathrm{V}^{-1/2}$	1.0×10^{-3}	-	-
37	MSDIBL	$m_{\sigma_{\mathrm{dibl}}}$	-	3.0	-	-
38	MO	m_0	V	0.0	-	-
39	SSF	σ_{sf}	$\mathrm{V}^{-1/2}$	1.0×10^{-12}	-	-
40	A1R	$a_{1\mathrm{R}}$	-	1.5×10^{1}	-	-
41	STA1	$S_{T;a_1}$	K^{-1}	0	-	-
42	SWA1	$S_{W;a_1}$	-	0	-	-
43	A2	a_2	V	7.3×10^{1}	-	-
44	A3	a_3	-	0.8	-	-
45	COXW	C_{ox_W}	F	0.75×10^{-15}	-	-
46	COXDW	C_{oxD_W}	F	0.75×10^{-15}	-	-
47	CGDOW	C_{GDO_W}	F	0	-	-
48	CGSOW	C_{GSO_W}	F	0	-	-
49	NT	N_T	J	1.645×10^{-20}	-	-
50	NFAW	$N_{f\mathrm{A}_W}$	$\mathrm{V}^{-1}\mathrm{m}^{-4}$	1.4×10^{25}	-	-
51	NFBW	$N_{f\mathrm{B}_W}$	$\mathrm{V}^{-1}\mathrm{m}^{-2}$	2.0×10^{8}	-	-
52	NFCW	$N_{f\mathrm{C}_W}$	V^{-1}	0	-	-
53	TOX	t_{ox}	m	3.8×10^{-8}	-	-
54	DTA	ΔT_{a}	K	0	-	-
55	MULT	M	-	1.0	0	-

3.2.3 Geometry and Temperature Scaling

Effective temperature and dimensions:

$$T_{\mathrm{K_{dev}}} = T_0 + T_{\mathrm{a}} + \Delta T_{\mathrm{a}} \tag{3.1}$$

$$T_{\mathrm{K_{ref}}} = T_0 + T_{\mathrm{ref}} \tag{3.2}$$

$$\Delta T = T_{\mathrm{K_{dev}}} - T_{\mathrm{K_{ref}}} \tag{3.3}$$

$$W_{\mathrm{E}} = W + \Delta W \tag{3.4}$$

$$W_{\mathrm{ED}} = W_{\mathrm{D}} + \Delta W_{\mathrm{D}} \tag{3.5}$$

$$W_{\mathrm{EN}} = 1.0 \times 10^{-6}\ (\mathrm{m}) \tag{3.6}$$

Actual parameters:

$$\phi_T = \frac{k_{\mathrm{B}} \cdot T_{\mathrm{K_{dev}}}}{q} \tag{3.7}$$

$$V_{\mathrm{FB}_T} = V_{\mathrm{FB}} + \Delta T \cdot S_{T;V_{\mathrm{FB}}} \tag{3.8}$$

$$V_{\mathrm{FBD}_T} = V_{\mathrm{FBD}} + \Delta T \cdot S_{T;V_{\mathrm{FBD}}} \tag{3.9}$$

$$k_0 = k_{0\mathrm{R}} \cdot \left(1 + \frac{W_{\mathrm{EN}}}{W_{\mathrm{E}}} \cdot S_{W;k_0}\right) \tag{3.10}$$

$$k_{0\mathrm{D}} = k_{0\mathrm{DR}} \cdot \left(1 + \frac{W_{\mathrm{EN}}}{W_{\mathrm{ED}}} \cdot S_{W;k_{0\mathrm{D}}}\right) \tag{3.11}$$

$$\phi_{\mathrm{B}_T} = \phi_{\mathrm{B}} + \Delta T \cdot S_{T;\phi_{\mathrm{B}}} \tag{3.12}$$

$$\phi_{\mathrm{BD}_T} = \phi_{\mathrm{BD}} + \Delta T \cdot S_{T;\phi_{\mathrm{BD}}} \tag{3.13}$$

$$\beta_T = \beta_W \cdot \frac{W_{\mathrm{E}}}{W_{\mathrm{EN}}} \cdot \left(\frac{T_{\mathrm{K_{ref}}}}{T_{\mathrm{K_{dev}}}}\right)^{\eta_\beta} \tag{3.14}$$

$$\beta_{\mathrm{acc}_T} = \beta_{\mathrm{acc}_W} \cdot \frac{W_{\mathrm{ED}}}{W_{\mathrm{EN}}} \cdot \left(\frac{T_{\mathrm{K_{ref}}}}{T_{\mathrm{K_{dev}}}}\right)^{\eta_{\beta\mathrm{acc}}} \tag{3.15}$$

$$R_{\mathrm{D}_T} = R_{\mathrm{D}_W} \cdot \frac{W_{\mathrm{EN}}}{W_{\mathrm{ED}}} \cdot \left(\frac{T_{\mathrm{K_{dev}}}}{T_{\mathrm{K_{ref}}}}\right)^{\eta_{R_{\mathrm{D}}}} \tag{3.16}$$

$$\theta_1 = \theta_{1\mathrm{R}} \cdot \left(1 + \frac{W_{\mathrm{EN}}}{W_{\mathrm{E}}} \cdot S_{W;\theta_1}\right) \tag{3.17}$$

$$\theta_2 = \theta_{2\mathrm{R}} \cdot \left(1 + \frac{W_{\mathrm{EN}}}{W_{\mathrm{E}}} \cdot S_{W;\theta_2}\right) \tag{3.18}$$

$$\theta_{3_T} = \theta_{3_\mathrm{R}} \cdot \left(\frac{T_{\mathrm{K}_\mathrm{ref}}}{T_{\mathrm{K}_\mathrm{dev}}}\right)^{\eta_{\theta_3}} \cdot \left(1 + \frac{W_\mathrm{EN}}{W_\mathrm{E}} \cdot S_{W;\theta_3}\right) \tag{3.19}$$

$$a_{1_T} = a_{1\mathrm{R}} \cdot \left(1 + \Delta T \cdot S_{T;a_1}\right) \cdot \left(1 + \frac{W_\mathrm{EN}}{W_\mathrm{E}} \cdot S_{W;a_1}\right) \tag{3.20}$$

$$C_\mathrm{ox} = C_{\mathrm{ox}_W} \cdot \frac{W_\mathrm{E}}{W_\mathrm{EN}} \tag{3.21}$$

$$C_\mathrm{oxD} = C_{\mathrm{oxD}_W} \cdot \frac{W_\mathrm{ED}}{W_\mathrm{EN}} \tag{3.22}$$

$$C_\mathrm{GDO} = C_{\mathrm{GDO}_W} \cdot \frac{W_\mathrm{ED}}{W_\mathrm{EN}} \tag{3.23}$$

$$C_\mathrm{GSO} = C_{\mathrm{GSO}_W} \cdot \frac{W_\mathrm{E}}{W_\mathrm{EN}} \tag{3.24}$$

$$N_{T_T} = N_T \cdot \frac{T_{\mathrm{K}_\mathrm{dev}}}{T_{\mathrm{K}_\mathrm{ref}}} \tag{3.25}$$

$$N_{f\mathrm{A}} = N_{f\mathrm{A}_W} \cdot \frac{W_\mathrm{EN}}{W_\mathrm{E}} \tag{3.26}$$

$$N_{f\mathrm{B}} = N_{f\mathrm{B}_W} \cdot \frac{W_\mathrm{EN}}{W_\mathrm{E}} \tag{3.27}$$

$$N_{f\mathrm{C}} = N_{f\mathrm{C}_W} \cdot \frac{W_\mathrm{EN}}{W_\mathrm{E}} \tag{3.28}$$

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 are listed in Section 3.3.1, while its temperature scaling rules are listed in Section 3.3.3. For simplicity, in the electrical MOS Model 20 both the *n*-channel and *p*-channel devices have been assigned the same default parameter values.

3.3.1 List of Electrical Model Parameters

No.	Parameter	Symbol	Units	Meaning
0	LEVEL	level	-	Must be 2001
1	TREF	T_{ref}	$^{\text{o}}$C	Reference temperature
2	VFB	V_{FB}	V	Flatband voltage of the channel region, at reference temperature
3	STVFB	$S_{T;\text{V}_{\text{FB}}}$	VK^{-1}	Temperature scaling coefficient for V_{FB}
4	VFBD	V_{FBD}	V	Flatband voltage of the drift region, at reference temperature
5	STVFBD	$S_{T;\text{V}_{\text{FBD}}}$	VK^{-1}	Temperature scaling coefficient for V_{FBD}
6	KO	k_0	V$^{1/2}$	Body factor of the channel region
7	KOD	$k_{0\text{D}}$	V$^{1/2}$	Body factor of the drift region
8	PHIB	ϕ_{B}	V	Surface potential at the onset of strong inversion in the channel region, at reference temperature
9	STPHIB	$S_{T;\phi_{\text{B}}}$	VK^{-1}	Temperature scaling coefficient for ϕ_{B}
10	PHIBD	ϕ_{BD}	V	Surface potential at the onset of strong inversion in the drift region, at reference temperature
11	STPHIBD	$S_{T;\phi_{\text{BD}}}$	VK^{-1}	Temperature scaling coefficient for ϕ_{BD}
12	BET	β	AV^{-2}	Gain factor of the channel region, at reference temperature
13	ETABET	η_{β}	-	Temperature scaling exponent for β
14	BETACC	β_{acc}	AV^{-2}	Gain factor for accumulation in the drift region, at reference temperature
15	ETABETACC	$\eta_{\beta_{\text{acc}}}$	-	Temperature scaling exponent for β_{acc}
16	RD	R_{D}	Ω	On-resistance of the drift region, at reference temperature
17	ETARD	$\eta_{R_{\text{D}}}$	-	Temperature scaling exponent for R_{D}
18	LAMD	λ_{D}	-	Quotient of the depletion layer thickness at $V_{\text{SB}} > 0$, to the effective thickness of the drift region at $V_{\text{SB}} = 0$ V
19	THE1	θ_1	V^{-1}	Mobility reduction coefficient in channel region due to vertical electrical field caused by strong inversion

No.	Parameter	Symbol	Units	Meaning
20	THE1ACC	θ_{1acc}	V^{-1}	Mobility reduction coefficient in the drift region due to the vertical electrical field caused by accumulation
21	THE2	θ_2	$V^{-1/2}$	Mobility reduction coefficient at $V_{SB} > 0$ in the channel region due to the vertical electrical field caused by depletion
22	THE3	θ_3	V^{-1}	Mobility reduction coefficient in the channel region due to the horizontal electrical field caused by velocity saturation
23	ETATHE3	η_{θ_3}	-	Temperature scaling exponent for θ_3
24	MEXP	m	-	Smoothing factor for transition from linear to saturation regime
25	ALP	α	-	Factor for channel length modulation
26	VP	V_P	V	Characteristic voltage of channel length modulation
27	SDIBL	σ_{dibl}	$V^{-1/2}$	Factor for drain-induced barrier lowering
28	MSDIBL	$m_{\sigma_{dibl}}$	-	Exponent for the drain-induced barrier lowering dependence on backgate bias
29	MO	m_0	V	Parameter for the (short-channel) sub-threshold slope
30	SSF	σ_{sf}	$V^{-1/2}$	Factor for static feedback
31	A1	a_1	-	Factor of weak avalanche current, at reference temperature
32	STA1	$S_{T;a_1}$	K^{-1}	Temperature scaling coefficient for a_1
33	A2	a_2	V	Exponent of weak avalanche current
34	A3	a_3	-	Factor of drain-source voltage above which weak avalanche occurs
35	COX	C_{ox}	F	Oxide capacitance for the intrinsic channel region
36	COXD	C_{oxD}	F	Oxide capacitance for the intrinsic drift region
37	CGDO	C_{GDO}	F	Gate to drain overlap capacitance
38	CGSO	C_{GSO}	F	Gate to source overlap capacitance
39	NT	N_T	J	Coefficient of thermal noise, at reference temperature
40	NFA	N_{fA}	$V^{-1}m^{-4}$	First coefficient of flicker noise
41	NFB	N_{fB}	$V^{-1}m^{-2}$	Second coefficient of flicker noise
42	NFC	N_{fC}	V^{-1}	Third coefficient of flicker noise
43	TOX	t_{ox}	m	Thickness of the oxide above the channel region
44	DTA	ΔT_a	K	Temperature offset to the ambient temperature
45	MULT	M	-	Number of devices in parallel

3.3.2 Default and Clipping Values of Electrical Model Parameters

No.	Parameter	Symbol	Units	Default	Clip low	Clip high
0	LEVEL	level	-	2001	-	-
1	TREF	T_{ref}	$^{\mathrm{o}}$C	25	-273	-
2	VFB	V_{FB}	V	-1.0	-	-
3	STVFB	$S_{T;\mathrm{V_{FB}}}$	VK^{-1}	0	-	-
4	VFBD	V_{FBD}	V	-0.1	-	-
5	STVFBD	$S_{T;\mathrm{V_{FBD}}}$	VK^{-1}	0	-	-
6	KO	k_0	$\mathrm{V}^{1/2}$	1.6	1.0×10^{-12}	-
7	KOD	$k_{0\mathrm{D}}$	$\mathrm{V}^{1/2}$	1.0	1.0×10^{-12}	-
8	PHIB	ϕ_{B}	V	0.86	1.0×10^{-12}	-
9	STPHIB	$S_{T;\phi_{\mathrm{B}}}$	VK^{-1}	-1.2×10^{-3}	-	-
10	PHIBD	ϕ_{BD}	V	0.78	1.0×10^{-12}	-
11	STPHIBD	$S_{T;\phi_{\mathrm{BD}}}$	VK^{-1}	-1.2×10^{-3}	-	-
12	BET	β	AV^{-2}	1.4×10^{-3}	1.0×10^{-12}	-
13	ETABET	η_{β}	-	1.6	-	-
14	BETACC	β_{acc}	AV^{-2}	1.4×10^{-3}	1.0×10^{-12}	-
15	ETABETACC	$\eta_{\beta_{\mathrm{acc}}}$	-	1.5	-	-
16	RD	R_{D}	Ω	2.0×10^{2}	1.0×10^{-12}	-
17	ETARD	$\eta_{R_{\mathrm{D}}}$	-	1.5	-	-
18	LAMD	λ_{D}	-	0.2	1.0×10^{-12}	-
19	THE1	θ_1	V^{-1}	0.09	0	-
20	THE1ACC	$\theta_{1\mathrm{acc}}$	V^{-1}	0.02	0	-
21	THE2	θ_2	$\mathrm{V}^{-1/2}$	0.03	0	-
22	THE3	θ_3	V^{-1}	0.4	0	-
23	ETATHE3	η_{θ_3}	-	1.0	-	-
24	MEXP	m	-	2.0	0.05	-
25	ALP	α	-	2.0×10^{-3}	0	-
26	VP	V_{P}	V	0.05	1.0×10^{-12}	-
27	SDIBL	σ_{dibl}	$\mathrm{V}^{-1/2}$	1.0×10^{-3}	0	-
28	MSDIBL	$m_{\sigma_{\mathrm{dibl}}}$	-	3.0	0	-
29	MO	m_0	V	0.0	0	0.5
30	SSF	σ_{sf}	$\mathrm{V}^{-1/2}$	1.0×10^{-12}	1.0×10^{-12}	-
31	A1	a_1	-	1.5×10^{1}	0	-
32	STA1	$S_{T;a_1}$	K^{-1}	0	-	-
33	A2	a_2	V	7.3×10^{1}	1.0×10^{-12}	-

No.	Parameter	Symbol	Units	Default	Clip low	Clip high
34	A3	a_3	-	0.8	0	-
35	COX	C_{ox}	F	15×10^{-15}	0	-
36	COXD	C_{oxD}	F	15×10^{-15}	0	-
37	CGDO	C_{GDO}	F	0	0	-
38	CGSO	C_{GSO}	F	0	0	-
39	NT	N_T	J	1.645×10^{-20}	0	-
40	NFA	$N_{f\mathrm{A}}$	$\mathrm{V}^{-1}\mathrm{m}^{-4}$	7.0×10^{23}	0	-
41	NFB	$N_{f\mathrm{B}}$	$\mathrm{V}^{-1}\mathrm{m}^{-2}$	1.0×10^{7}	0	-
42	NFC	$N_{f\mathrm{C}}$	V^{-1}	0	0	-
43	TOX	t_{ox}	m	3.8×10^{-8}	1.0×10^{-12}	-
44	DTA	ΔT_{a}	K	0	-	-
45	MULT	M	-	1.0	0	-

3.3.3 Temperature Scaling

Effective temperature:

$$T_{\mathrm{K_{dev}}} = T_0 + T_{\mathrm{a}} + \Delta T_{\mathrm{a}} \tag{3.29}$$

$$T_{\mathrm{K_{ref}}} = T_0 + T_{\mathrm{ref}} \tag{3.30}$$

$$\Delta T = T_{\mathrm{K_{dev}}} - T_{\mathrm{K_{ref}}} \tag{3.31}$$

Actual parameters:

$$\phi_T = \frac{k_{\mathrm{B}} \cdot T_{\mathrm{K_{dev}}}}{q} \tag{3.32}$$

$$V_{\mathrm{FB}_T} = V_{\mathrm{FB}} + \Delta T \cdot S_{T;V_{\mathrm{FB}}} \tag{3.33}$$

$$V_{\mathrm{FBD}_T} = V_{\mathrm{FBD}} + \Delta T \cdot S_{T;V_{\mathrm{FBD}}} \tag{3.34}$$

$$\phi_{\mathrm{B}_T} = \phi_{\mathrm{B}} + \Delta T \cdot S_{T;\phi_{\mathrm{B}}} \tag{3.35}$$

$$\phi_{\mathrm{BD}_T} = \phi_{\mathrm{BD}} + \Delta T \cdot S_{T;\phi_{\mathrm{BD}}} \tag{3.36}$$

$$\beta_T = \beta \cdot \left(\frac{T_{\mathrm{K_{ref}}}}{T_{\mathrm{K_{dev}}}}\right)^{\eta_\beta} \tag{3.37}$$

$$\beta_{\mathrm{acc}_T} = \beta_{\mathrm{acc}} \cdot \left(\frac{T_{\mathrm{K_{ref}}}}{T_{\mathrm{K_{dev}}}}\right)^{\eta_{\beta\mathrm{acc}}} \tag{3.38}$$

$$R_{\mathrm{D}_T} = R_{\mathrm{D}} \cdot \left(\frac{T_{\mathrm{K_{dev}}}}{T_{\mathrm{K_{ref}}}}\right)^{\eta_{R_{\mathrm{D}}}} \tag{3.39}$$

$$\theta_{3_T} = \theta_3 \cdot \left(\frac{T_{\mathrm{K_{ref}}}}{T_{\mathrm{K_{dev}}}}\right)^{\eta_{\theta_3}} \tag{3.40}$$

$$a_{1_T} = a_1 \cdot \left(1 + \Delta T \cdot S_{T;a_1}\right) \tag{3.41}$$

$$N_{T_T} = N_T \cdot \frac{T_{\mathrm{K_{dev}}}}{T_{\mathrm{K_{ref}}}} \tag{3.42}$$

3.4 Postprocessing

3.4.1 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

$$\beta_T \rightarrow \beta_T \cdot M \tag{3.43}$$

$$\beta_{\mathrm{acc}_T} \rightarrow \beta_{\mathrm{acc}_T} \cdot M \tag{3.44}$$

$$R_{\mathrm{D}_T} \rightarrow R_{\mathrm{D}_T} \cdot \frac{1}{M} \tag{3.45}$$

$$C_{\mathrm{ox}} \rightarrow C_{\mathrm{ox}} \cdot M \tag{3.46}$$

$$C_{\mathrm{oxD}} \rightarrow C_{\mathrm{oxD}} \cdot M \tag{3.47}$$

$$C_{\mathrm{GDO}} \rightarrow C_{\mathrm{GDO}} \cdot M \tag{3.48}$$

$$C_{\mathrm{GSO}} \rightarrow C_{\mathrm{GSO}} \cdot M \tag{3.49}$$

$$N_{f\mathrm{A}} \rightarrow N_{f\mathrm{A}} \cdot \frac{1}{M} \tag{3.50}$$

$$N_{f\mathrm{B}} \rightarrow N_{f\mathrm{B}} \cdot \frac{1}{M} \tag{3.51}$$

$$N_{f\mathrm{C}} \rightarrow N_{f\mathrm{C}} \cdot \frac{1}{M} \tag{3.52}$$

3.4.2 Clipping of Actual Parameters

After the geometry, temperature and mult- 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 Section 3.3.2.

4 Physical Background

4.1 DC-Current Model

As basis for the dc-model, firstly the current $I_{\rm ch}$ through the inversion channel as well as the current $I_{\rm dr}$ through the drift region are derived, both in terms of the internal drain voltage $V_{\rm Di}$. Next, this internal drain voltage is solved explicitly by equating $I_{\rm ch}$ to $I_{\rm dr}$. In this way, the internal drain voltage, is expressed explicitly in terms of the applied voltages $V_{\rm D}$, $V_{\rm G}$, $V_{\rm S}$ and $V_{\rm B}$ at the drain, gate, source and backgate terminal, respectively. Finally, the dc-current $I_{\rm DS}$ is calculated by use of surface potential formulations which are valid in all operating regimes, ranging from weak to strong inversion.

Thus, to obtain an accurate and continuous description of the dc-current and its derivatives in all operation regimes, a charge sheet MOSFET model approach based on surface potential formulations is taken. The surface potentials $\psi_{\rm s0}$ at the source $x = 0$ and $\psi_{\rm sL}$ at the internal drain $x = L$ are calculated according to [3], so that they are expressed explicitly in terms of the voltage differences $V_{\rm SB}$ and $V_{\rm GB}$, and of $V_{\rm DiB}$ and $V_{\rm GB}$, respectively.

With the electron mobility denoted by μ, the channel current is given by

$$I_{\rm ch} = \frac{W \cdot \mu}{L} \cdot \left(\int_{\psi_{\rm s0}}^{\psi_{\rm sL}} \left(-Q'_{\rm inv}\right) d\psi_{\rm s} + \phi_T \cdot \left(Q'_{\rm invL} - Q'_{\rm inv0}\right) \right), \tag{4.1}$$

where

$$Q'_{\rm inv} = -C'_{\rm ox} \cdot \left(V_{\rm GB} - V_{\rm FB} - \psi_{\rm s} - k_0 \cdot \sqrt{\psi_{\rm s}} \right), \tag{4.2}$$

is the strong inversion charge per unit area in the channel region. Here, $C'_{\rm ox} = \epsilon_{\rm ox}/t_{\rm ox}$ is the oxide capacitance per unit area, with $\epsilon_{\rm ox}$ the permitivity of oxide and $t_{\rm ox}$ the oxide thickness. Notice that, for simplicity, the body factor k_0 is taken independent of the position along the channel, which means that the effect of the doping gradient is neglected. By substituting (4.2) into (4.1), we arrive at

$$I_{\rm ch} = \frac{W \cdot \mu \cdot C'_{\rm ox}}{L} \cdot \left(V_{\rm inv0} - \tfrac{1}{2} \cdot \xi \cdot \Delta\psi_{\rm s} + \xi \cdot \phi_T \right) \cdot \Delta\psi_{\rm s}, \tag{4.3}$$

after Taylor expansions have been taken which have led to

$$\xi = 1 + \frac{k_0}{2 \cdot \sqrt{V_1 + \psi_{\rm s0}}}. \tag{4.4}$$

The potential drop $\Delta\psi_s$ is given by $\psi_{\rm sL} - \psi_{\rm s0}$. Inclusion of mobility reduction due to the vertical electrical field as well as the horizontal electrical field according to

$$\mu = \frac{\mu_0}{\left(1 + \theta_1 \cdot V_{\rm inv0} + \theta_2 \cdot \left(\sqrt{\phi_{\rm B} + V_{\rm SB}} - \sqrt{\phi_{\rm B}}\right)\right) \cdot (1 + \theta_3 \cdot \Delta\psi_{\rm s})} \tag{4.5}$$

yields the following expression for the channel current in terms of the surface potentials $\psi_{\rm s0}$ and $\psi_{\rm sL}$

$$I_{\rm ch} = \beta \cdot \frac{\left(V_{\rm inv0} - \frac{1}{2} \cdot \xi \cdot \Delta\psi_{\rm s} + \xi \cdot \phi_T \right) \cdot \Delta\psi_{\rm s}}{\left(1 + \theta_1 \cdot V_{\rm inv0} + \theta_2 \cdot \left(\sqrt{\phi_{\rm B} + V_{\rm SB}} - \sqrt{\phi_{\rm B}}\right)\right) \cdot (1 + \theta_3 \cdot \Delta\psi_{\rm s})}, \tag{4.6}$$

where

$$\beta = \frac{W \cdot \mu_0 \cdot C'_{\text{ox}}}{L} \tag{4.7}$$

is the gain factor of the channel region.

In case of strong inversion in the channel region, the potential drop $\Delta\psi_{\text{s}}$ approximately equals V_{DiS}. Hence, in the linear operating regime, the potential drop $V_{\text{DiS}} = V_{\text{DiS}_0}$ is obtained by solving $I_{\text{ch}} = I_{\text{dr}}$, in which the mobility reduction term due to the horizontal electrical field is neglected, i.e. θ_3 is set to zero.

Under the assumption that in the linear operating regime only accumulation (and thus no depletion) underneath the gate oxide of the drift region occurs, the drift region current I_{dr} is given by

$$I_{\text{dr}} = \frac{W_{\text{D}} \cdot \mu_{\text{dr}}}{L_{\text{D}}} \cdot \int_{V_{\text{Di}}}^{V_{\text{D}}} \left(-Q'_{\text{b}}\right) dV_{\text{C}} + \frac{W_{\text{D}} \cdot \mu_{\text{acc}}}{L_{\text{D}}} \cdot \int_{V_{\text{Di}}}^{V_{\text{D}}} \left(-Q'_{\text{acc}}\right) dV_{\text{C}}. \tag{4.8}$$

Here, μ_{dr} represents the electron mobility through the bulk of the drift region and μ_{acc} that through the accumulation layer. The accumulation charge Q'_{acc} per unit area is given by

$$Q'_{\text{acc}} = -C'_{\text{ox}} \left(V_{\text{G}} - V_{\text{C}} - V_{\text{FBD}}\right) \tag{4.9}$$

while the charge Q'_{b} per unit area of the bulk of the drift region is approximated by

$$Q'_{\text{b}} = -\left(q \cdot N_D \cdot t_{\text{Si}} - k_b \cdot \sqrt{\phi_0 + V_{\text{SB}}}\right). \tag{4.10}$$

Here, t_{Si} is the thickness of the drift region, N_D is the concentration of donors in the drift region, ϕ_0 is the built-in potential of the pn-junction between backgate and drain, and the constant k_b equals

$$k_b = \sqrt{\frac{2 \cdot q \cdot \epsilon_{\text{Si}} \cdot N_D \cdot N_A}{N_A + N_D}}, \tag{4.11}$$

with N_A the concentration of acceptors in the channel region, and ϵ_{Si} the permitivity of silicon. Thus, $t_{\text{Si}_{\text{eff}}} = t_{\text{Si}} - k_b \cdot \sqrt{\phi_0 + V_{\text{SB}}} \Big/ (q \cdot N_D)$ represents the effective thickness of the drift region, taking into account the depletion layer from the backgate. Finally, by taking the electron mobility in the accumulation layer as

$$\mu_{\text{acc}} = \frac{\mu_{\text{acc0}}}{1 + \theta_{1\text{acc}} \cdot ((V_{\text{GS}} + V_{\text{GD}})/2 - V_{\text{FBD}})} \tag{4.12}$$

we arrive at the following expression for the drift region current

$$\begin{aligned} I_{\text{dr}} = \frac{1}{R_{\text{D}}} \cdot \left(1 - \lambda_{\text{D}} \cdot \frac{\sqrt{\phi_0 + V_{\text{SB}}} - \sqrt{\phi_0}}{\sqrt{\phi_0}}\right) \cdot V_{\text{DDi}} \\ + \frac{1}{2} \cdot \beta_{\text{acc}} \cdot \frac{(V_{\text{GDi}} - V_{\text{FBD}})^2 - (V_{\text{GD}} - V_{\text{FBD}})^2}{1 + \theta_{1\text{acc}} \cdot ((V_{\text{GS}} + V_{\text{GD}})/2 - V_{\text{FBD}})}, \end{aligned} \tag{4.13}$$

where

$$R_{\text{D}} = \frac{L_{\text{D}}}{W_{\text{D}} \cdot \mu_{\text{dr}} \cdot \left(q \cdot N_D \cdot t_{\text{Si}} - k_b \sqrt{\phi_0}\right)} \tag{4.14}$$

is the on-resistance of the drift region at $V_{\text{SB}} = 0$, and

$$\beta_{\text{acc}} = \frac{W_{\text{D}} \cdot \mu_{\text{acc0}} \cdot C'_{\text{ox}}}{L_{\text{D}}} \tag{4.15}$$

is the gain factor of the drift region accumulation layer. Furthermore, the parameter λ_{D}, given by

$$\lambda_{\text{D}} = \frac{k_b \cdot \sqrt{\phi_0}}{q \cdot N_D \cdot t_{\text{Si}} - k_b \cdot \sqrt{\phi_0}}, \tag{4.16}$$

equals the ratio of the depletion layer thickness from the backgate to the effective thickness of the drift region, at $V_{\text{SB}} = 0$. Thus, by equating I_{dr} to $I_{\text{ch}}|_{\theta_3=0}$ the internal potential drop V_{DiS_0} valid in the linear operating regime is derived in terms of the applied terminal voltages.

In the saturated operating regime, on the other hand, where $\partial I_{\text{ch}}/\partial \Delta\psi_{\text{s}} = 0$ holds, the potential drop V_{DiS} equals the saturation potential drop V_{DiSsat} given by

$$V_{\text{DiSsat}} = \frac{2 \cdot (V_{\text{inv0}}/\xi + \phi_T)}{1 + \sqrt{1 + 2 \cdot \theta_3 \cdot (V_{\text{inv0}}/\xi + \phi_T)}}. \tag{4.17}$$

Next, the effective potential drop $V_{\text{DiS}_{\text{eff}}}$ to calculate the surface potential ψ_{sL}, is obtained by taking in a smooth way the minimum of V_{DiS_0} and V_{DiSsat}. Finally, the term $\left(Q'_{\text{invL}} - Q'_{\text{inv0}}\right)$ in (4.1) due to diffusion is calculated according to [3]. A comparison between dc-measurements and the model can be found in [5].

4.2 Nodal Charge Model

To determine the nodal charges, all different stadia of strong inversion, depletion and accumulation in both the drift region and the channel region have to be taken into account. The gate charge Q_{G} of the whole device consists of the gate charge $Q_{\text{G}_{\text{ch}}}$ of the channel region and the gate charge $Q_{\text{G}_{\text{dr}}}$ of the drift region, according to

$$Q_{\text{G}} = Q_{\text{G}_{\text{ch}}} + Q_{\text{G}_{\text{dr}}}, \tag{4.18}$$

where

$$Q_{\text{G}_{\text{ch}}} = -W \int_0^L \left(Q'_{\text{inv}} + Q'_{\text{dep}} + Q'_{\text{acc}}\right) dx \tag{4.19}$$

and

$$Q_{\text{G}_{\text{dr}}} = -W_{\text{D}} \int_L^{L+L_{\text{dr}}} \left(Q'_{\text{inv}} + Q'_{\text{dep}} + Q'_{\text{acc}}\right) dx \tag{4.20}$$

Similarly, the backgate charge Q_{B} of the whole device consists of the backgate charge $Q_{\text{B}_{\text{ch}}}$ of the channel region and the backgate charge $Q_{\text{B}_{\text{dr}}}$ of the drift region, according to

$$Q_{\text{B}} = Q_{\text{B}_{\text{ch}}} + Q_{\text{B}_{\text{dr}}}, \tag{4.21}$$

where

$$Q_{\mathrm{B_{ch}}} = W \int_0^L \left(Q'_{\mathrm{dep}} + Q'_{\mathrm{acc}} \right) dx, \tag{4.22}$$

and

$$Q_{\mathrm{B_{dr}}} = W_{\mathrm{D}} \int_L^{L+L_{\mathrm{dr}}} Q'_{\mathrm{inv}} dx. \tag{4.23}$$

To determine how the charge $-(Q_{\mathrm{G}} + Q_{\mathrm{B}})$ is distributed underneath the thin gate oxide, two limits are identified. The first limit is for well above threshold (i.e. for the gate voltage sufficiently large), and the drain charge Q_{D} is approximated by

$$Q_{\mathrm{D}} = W \int_0^L \frac{x}{L + L_{\mathrm{dr}}} Q'_{\mathrm{inv}} dx + W_{\mathrm{D}} \int_L^{L+L_{\mathrm{dr}}} \frac{x}{L + L_{\mathrm{dr}}} Q'_{\mathrm{acc}} dx + W_{\mathrm{D}} \int_L^{L+L_{\mathrm{dr}}} Q'_{\mathrm{dep}} dx, \tag{4.24}$$

as one would expect from the Ward-Dutton charge partioning scheme [6] (valid in case of a uniform MOSFET). Notice that all depletion charge of the drift region is attributed to the drain. The second limit is for below threshold (i.e. for the gate voltage sufficiently small), and the drain charge Q_{D} is approximated by

$$Q_{\mathrm{D}} = W \int_0^L \frac{x}{L + L_{\mathrm{dr}}} Q'_{\mathrm{inv}} dx + W_{\mathrm{D}} \int_L^{L+L_{\mathrm{dr}}} Q'_{\mathrm{acc}} dx + W_{\mathrm{D}} \int_L^{L+L_{\mathrm{dr}}} Q'_{\mathrm{dep}} dx, \tag{4.25}$$

which means that also all accumulation charge of the drift region is attributed to the drain. This second limit is calculated in case $Q'_{\mathrm{invL}} = 0$.

For the channel region $0 < x < L$, the charges are calculated by using the potential drop $\Delta\psi_{\mathrm{s}}$ over the channel region, according to [4]. For the drift region $L < x < L + L_{\mathrm{dr}}$, the effective potentials are recalculated in order to include depletion and saturation in the drift region. To include depletion, the drift region current I_{dr} is extended to

$$\begin{aligned} I_{\mathrm{dr}} = \frac{1}{R_{\mathrm{D}}} \cdot \left(1 - \lambda_{\mathrm{D}} \cdot \frac{\sqrt{\phi_0 + V_{\mathrm{SB}}} - \sqrt{\phi_0}}{\sqrt{\phi_0}} \right) \cdot V_{\mathrm{DDi}} \\ + \frac{1}{2} \cdot \beta_{\mathrm{acc}} \cdot \frac{F[V_{\mathrm{GDi}} - V_{\mathrm{FBD}}] - F[V_{\mathrm{GD}} - V_{\mathrm{FBD}}]}{1 + \theta_{1\mathrm{acc}} \cdot ((V_{\mathrm{GS}} + V_{\mathrm{GD}})/2 - V_{\mathrm{FBD}})}, \end{aligned} \tag{4.26}$$

where the function F distinguishes between accumulation and depletion, according to

$$F[V] = \begin{cases} V^2, & V \geq 0, \\ 2 \cdot k_{0\mathrm{D}} \cdot \left(\frac{2}{3} \left(\left(\left(\frac{k_{0\mathrm{D}}}{2} \right)^2 - V \right)^{3/2} - \left(\frac{k_{0\mathrm{D}}}{2} \right)^3 \right) + \frac{k_{0\mathrm{D}}}{2} \cdot V \right), & V < 0. \end{cases} \tag{4.27}$$

To include saturation in the drift region, the potentials $V_{\mathrm{GD}} - V_{\mathrm{FBD}}$ and $V_{\mathrm{GDi}} - V_{\mathrm{FBD}}$ in (4.26) are bounded by

$$V_{\mathrm{pinch}} = -V_{\mathrm{oxp0}} \cdot \left(1 + \frac{V_{\mathrm{oxp0}}}{k_{0\mathrm{D}}^2} \right), \tag{4.28}$$

where

$$V_{\text{oxp0}} = \frac{k_b}{C'_{\text{ox}}} \cdot \frac{\sqrt{\phi_0}}{\lambda_{\text{D}}} \cdot \left(1 - \lambda_{\text{D}} \cdot \frac{\sqrt{\phi_0 + V_{\text{SB}}} - \sqrt{\phi_0}}{\sqrt{\phi_0}}\right). \tag{4.29}$$

Thus, $V_{\text{oxp0}} = q \cdot N_D \cdot t_{\text{Si}_{\text{eff}}} \big/ C'_{\text{ox}}$ approximates the voltage over the thin gate oxide for which the drift region pinches off, and V_{pinch} is the potential $V_{\text{GC}} - V_{\text{FBD}}$ for which the depletion layer thickness underneath the gate oxide equals the effective drift region layer thickness $t_{\text{Si}_{\text{eff}}}$. By solving numerically $I_{\text{dr}} = I_{\text{DS}}$ for given I_{DS}, by means of the Newton-Rhapson iteration procedure, the internal potential drop $V_{\text{DiS}_{\text{dr,eff}}}$ is calculated, also valid in case saturation and depletion occurs in the drift region.

5 Implemented Equations

In the following sections a function is denoted by $F\left[variable,\ldots\right]$, 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.

5.1 Internal Parameters

$$\epsilon_1 = 2\cdot 10^{-2}$$

$$\epsilon_2 = 1\cdot 10^{-2}$$

$$\epsilon_3 = 4\cdot 10^{-2}$$

$$\epsilon_4 = 1\cdot 10^{-1}$$

$$\epsilon_5 = 1\cdot 10^{-4}$$

$$\epsilon_6 = 1\cdot 10^{-5}$$

$$\epsilon_7 = 2\cdot 10^{-1}$$

$$V_1 = 1$$

$$V_{\text{limit}} = 4\cdot\phi_T$$

$$\phi_0 = \tfrac{1}{2}\left(\phi_{\text{B}_T} + \phi_{\text{BD}_T}\right)$$

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

$$Acc_{\text{D}} = \frac{1}{1 + k_{0\text{D}}\Big/\sqrt{2\cdot\phi_T}}$$

$$F_L = \frac{C_{\text{ox}}}{C_{\text{ox}} + C_{\text{oxD}}}$$

5.2 Current Equations

$$V_{\text{GB}_{\text{t0}}} = V_{\text{GS}} + V_{\text{SB}} - V_{\text{FB}_T} \tag{5.1}$$

$$V_{\text{GB}_{\text{eff0}}} = \text{hyp}\left[V_{\text{GB}_{\text{t0}}};\epsilon_1\right] \tag{5.2}$$

$$\psi_{\text{sat}_0} = \left(\frac{V_{\text{GB}_{\text{eff0}}}}{k_0\big/2 + \sqrt{V_{\text{GB}_{\text{eff0}}} + \left(k_0\big/2\right)^2}}\right)^2 \tag{5.3}$$

$$V_{\text{SB}_{\text{t}}} = \text{hyp}\left[V_{\text{SB}} + 0.9\cdot\phi_{\text{B}_T};\epsilon_2\right] + 0.1\cdot\phi_{\text{B}_T} \tag{5.4}$$

Drain induced barrier lowering and static feedback:

$$D_{\text{dibl}} = \sigma_{\text{dibl}} \cdot \sqrt{\phi_{\text{B}_T}} \cdot \left(\frac{\sqrt{V_{\text{SB}_\text{t}}}}{\sqrt{\phi_{\text{B}_T}}} \right)^{m_{\sigma_{\text{dibl}}}} \tag{5.5}$$

$$D_{\text{sf}} = \sigma_{\text{sf}} \cdot \sqrt{\text{hyp}\left[\psi_{\text{sat}_0} - V_{\text{SB}_\text{t}}; \epsilon_3\right]} \tag{5.6}$$

$$D = D_{\text{dibl}} + \text{hyp}\left[D_{\text{sf}} - D_{\text{dibl}}; \epsilon_4 \cdot \sigma_{\text{sf}}\right] \tag{5.7}$$

$$V_{\text{DS}_1} = \begin{cases} V_{\text{DS}}, & V_{\text{DS}} \geq 0, \\ \text{hypm}\left[V_{\text{DS}}, V_{\text{SB}_\text{t}}; m\right], & V_{\text{DS}} < 0 \end{cases} \tag{5.8}$$

$$V_{\text{DS}_{\text{eff}}} = \frac{{V_{\text{DS}_1}}^4}{\left({V_{\text{limit}}}^2 + {V_{\text{DS}_1}}^2\right)^{3/2}} \tag{5.9}$$

$$\Delta V_{\text{G}} = D \cdot V_{\text{DS}_{\text{eff}}} \tag{5.10}$$

Surface potential at source side:

$$V_{\text{GB}_\text{t}} = V_{\text{GB}_{\text{t0}}} + \Delta V_{\text{G}} \tag{5.11}$$

$$V_{\text{GB}_{\text{eff}}} = \text{hyp}\left[V_{\text{GB}_\text{t}}; \epsilon_1\right] \tag{5.12}$$

$$\Delta_{\text{acc}} = \phi_T \cdot \left(\exp\left[-\frac{Acc \cdot \left(V_{\text{GB}_{\text{eff}}} - \epsilon_1\right)}{\phi_T} \right] - 1 \right) \tag{5.13}$$

$$\Psi_{\text{sat}}\left[V_{\text{GB}_{\text{eff}}}, \Delta_{\text{acc}}; k\right] = \left(\frac{V_{\text{GB}_{\text{eff}}} + \Delta_{\text{acc}}}{k/2 + \sqrt{V_{\text{GB}_{\text{eff}}} + \Delta_{\text{acc}} + (k/2)^2}} \right)^2 - \Delta_{\text{acc}} \tag{5.14}$$

$$\psi_{\text{sat}} = \Psi_{\text{sat}}\left[V_{\text{GB}_{\text{eff}}}, \Delta_{\text{acc}}; k_0\right] \tag{5.15}$$

$$f_1\left[\psi_{\text{sat}}, V_{\text{CB}_\text{t}}\right] = \psi_{\text{sat}} - \text{hyp}\left[\psi_{\text{sat}} - V_{\text{CB}_\text{t}}; \epsilon_1\right] \tag{5.16}$$

$$f_2\left[\psi_{\text{sat}}, V_{\text{CB}_\text{t}}\right] = f_1\left[\psi_{\text{sat}}, V_{\text{CB}_\text{t}}\right] + \frac{\psi_{\text{sat}} - f_1\left[\psi_{\text{sat}}, V_{\text{CB}_\text{t}}\right]}{\sqrt{1 + \frac{\left(\psi_{\text{sat}} - f_1\left[\psi_{\text{sat}}, V_{\text{CB}_\text{t}}\right]\right)^2}{16 \cdot {\phi_T}^2}}} \tag{5.17}$$

$$f_3\left[\psi_{\text{sat}}, V_{\text{CB}_\text{t}}, V_{\text{GB}_{\text{eff}}}\right] = V_{\text{GB}_{\text{eff}}} - f_2\left[\psi_{\text{sat}}, V_{\text{CB}_\text{t}}\right] \tag{5.18}$$

$$\Psi_{\mathrm{s}}\left[V_{\mathrm{GB_{eff}}}, \psi_{\mathrm{sat}}, \Delta_{\mathrm{acc}}, V_{\mathrm{CB_t}}; k, m_0\right] = f_1\left[\psi_{\mathrm{sat}}, V_{\mathrm{CB_t}}\right] + \phi_T \cdot (1 + m_0) \cdot \ln\left[1 + \frac{\left(\frac{f_3\left[\psi_{\mathrm{sat}}, V_{\mathrm{CB_t}}, V_{\mathrm{GB_{eff}}}\right]}{k}\right)^2 - f_1\left[\psi_{\mathrm{sat}}, V_{\mathrm{CB_t}}\right] - \Delta_{\mathrm{acc}}}{\phi_T}\right] \tag{5.19}$$

$$\psi_{\mathrm{s0}} = \Psi_{\mathrm{s}}\left[V_{\mathrm{GB_{eff}}}, \psi_{\mathrm{sat}}, \Delta_{\mathrm{acc}}, V_{\mathrm{SB_t}}; k_0, m_0\right] \tag{5.20}$$

Internal drain saturation voltage:

$$\mathcal{V}_{\mathrm{inv}}\left[V_{\mathrm{GB_{eff}}}, \psi_{\mathrm{s}}, \Delta_{\mathrm{acc}}; k\right] = \mathrm{hyp}\left[V_{\mathrm{GB_{eff}}} - \psi_{\mathrm{s}} - k \cdot \sqrt{\mathrm{hyp}\left[\psi_{\mathrm{s}} + \Delta_{\mathrm{acc}}; \epsilon_2\right]}; \epsilon_5\right] \tag{5.21}$$

$$V_{\mathrm{inv0}} = \mathcal{V}_{\mathrm{inv}}\left[V_{\mathrm{GB_{eff}}}, \psi_{\mathrm{s0}}, \Delta_{\mathrm{acc}}; k_0\right] \tag{5.22}$$

$$\mathcal{V}_{\mathrm{dep}}\left[\psi_{\mathrm{s}}, \Delta_{\mathrm{acc}}; k, \epsilon\right] = k \cdot \sqrt{\mathrm{hyp}\left[\psi_{\mathrm{s}} + \Delta_{\mathrm{acc}}; \epsilon\right]} \tag{5.23}$$

$$V_{\mathrm{dep0}} = \mathcal{V}_{\mathrm{dep}}\left[\psi_{\mathrm{s0}}, \Delta_{\mathrm{acc}}; k_0, \epsilon_2\right] \tag{5.24}$$

$$V_{\mathrm{SB_{t0}}} = \mathrm{hyp}\left[0.9 \cdot \phi_{\mathrm{B}_T}; \epsilon_2\right] + 0.1 \cdot \phi_{\mathrm{B}_T} \tag{5.25}$$

$$\psi_{\mathrm{s0_0}} = \Psi_{\mathrm{s}}\left[V_{\mathrm{GB_{eff}}}, \psi_{\mathrm{sat}}, \Delta_{\mathrm{acc}}, V_{\mathrm{SB_{t0}}}; k_0, m_0\right] \tag{5.26}$$

$$V_{\mathrm{dep0_0}} = \mathcal{V}_{\mathrm{dep}}\left[\psi_{\mathrm{s0_0}}, \Delta_{\mathrm{acc}}; k_0, \epsilon_2\right] \tag{5.27}$$

$$F_{\mathrm{mob}} = 1 + \theta_1 \cdot V_{\mathrm{inv0}} + \theta_2 \cdot \frac{\mathrm{hyp}\left[V_{\mathrm{dep0}} - V_{\mathrm{dep0_0}}; \epsilon_5\right]}{k_0} \tag{5.28}$$

$$\delta = \frac{k_0}{2 \cdot \sqrt{V_1 + \mathrm{hyp}\left[\psi_{\mathrm{s0}} + \Delta_{\mathrm{acc}}; \epsilon_5\right]}} \tag{5.29}$$

$$\xi = 1 + \delta \tag{5.30}$$

$$V_{\mathrm{DiSsat_0}} = V_{\mathrm{limit}} + \frac{V_{\mathrm{inv0}}}{\xi} \tag{5.31}$$

$$V_{\mathrm{DiSsat}} = \frac{2 \cdot V_{\mathrm{DiSsat_0}}}{1 + \sqrt{1 + 2 \cdot \theta_{3_T} \cdot V_{\mathrm{DiSsat_0}}}} \tag{5.32}$$

$$V_{\mathrm{DiSsat_{eff}}} = V_{\mathrm{limit}} + \mathrm{hyp}\left[V_{\mathrm{DiSsat}} - V_{\mathrm{limit}}; \epsilon_3\right] \tag{5.33}$$

Internal drain voltage, without velocity saturation:

$$V_{\mathrm{GS_t}} = V_{\mathrm{GS}} - V_{\mathrm{FBD}_T} \tag{5.34}$$

$$V_{\mathrm{GD_t}} = V_{\mathrm{GS_t}} - V_{\mathrm{DS_1}} \tag{5.35}$$

$$V_{\mathrm{GS_{t0}}} = V_{\mathrm{limit}} + \mathrm{hyp}\left[V_{\mathrm{GS_t}} - V_{\mathrm{limit}}; \epsilon_3\right] \tag{5.36}$$

$$V_{\mathrm{GD_{t0}}} = V_{\mathrm{GS_{t0}}} - \mathrm{hypm}\left[V_{\mathrm{DS_1}}, V_{\mathrm{GS_{t0}}}; 8\right] \tag{5.37}$$

$$\mathcal{F}_{\mathrm{mobacc}}\left[V_{\mathrm{GDi_t}}, V_{\mathrm{GD_t}}\right] = 1 + \frac{1}{2}\cdot\theta_{\mathrm{1acc}}\cdot\left(\mathrm{hyp}\left[V_{\mathrm{GDi_t}}; \epsilon_2\right] + \mathrm{hyp}\left[V_{\mathrm{GD_t}}; \epsilon_2\right]\right) \tag{5.38}$$

$$F_{\mathrm{mobacc}} = \mathcal{F}_{\mathrm{mobacc}}\left[V_{\mathrm{GS_t}}, V_{\mathrm{GD_t}}\right] \tag{5.39}$$

$$f_{\mathrm{acc}} = \frac{\beta_{\mathrm{acc}_T}\cdot R_{\mathrm{D}_T}}{F_{\mathrm{mobacc}}} \tag{5.40}$$

$$f_{\mathrm{lin}} = \mathrm{hyp}\left[1 - \lambda_{\mathrm{D}}\cdot\frac{\sqrt{\phi_0 + \mathrm{hyp}\left[V_{\mathrm{SB}}; \epsilon_1\right]} - \sqrt{\phi_0}}{\sqrt{\phi_0}}; \epsilon_2\right] \tag{5.41}$$

$$f_\xi = \frac{\beta_T\cdot\xi\cdot R_{\mathrm{D}_T}}{F_{\mathrm{mob}}} \tag{5.42}$$

$$f_{\mathrm{inv0}} = f_\xi\cdot V_{\mathrm{DiSsat_0}} \tag{5.43}$$

$$V_{\mathrm{dr}} = \left\{f_{\mathrm{lin}} + \frac{1}{2}\cdot f_{\mathrm{acc}}\cdot\left(V_{\mathrm{GS_{t0}}} + V_{\mathrm{GD_{t0}}}\right)\right\}\cdot\left(V_{\mathrm{GS_{t0}}} - V_{\mathrm{GD_{t0}}}\right) \tag{5.44}$$

$$V_{\mathrm{ch_{sat0}}} = \left(f_{\mathrm{inv0}} - \frac{1}{2}\cdot f_\xi\cdot V_{\mathrm{DiSsat_0}}\right)\cdot V_{\mathrm{DiSsat_0}} \tag{5.45}$$

$$V_{\mathrm{dr_{sat}}} = V_{\mathrm{ch_{sat0}}} + \left(f_{\mathrm{lin}} + f_{\mathrm{acc}}\cdot V_{\mathrm{GS_{t0}}}\right)\cdot V_{\mathrm{DiSsat_0}} - \frac{1}{2}\cdot f_{\mathrm{acc}}\cdot V^2_{\mathrm{DiSsat_0}} \tag{5.46}$$

$$N = \begin{cases} f_{\mathrm{lin}} + f_{\mathrm{acc}}\cdot V_{\mathrm{GS_{t0}}} + f_\xi\cdot V_{\mathrm{DiSsat_0}}, & V_{\mathrm{dr}} \le V_{\mathrm{dr_{sat}}} \\ f_{\mathrm{lin}} + f_{\mathrm{acc}}\cdot V_{\mathrm{GS_{t0}}}, & V_{\mathrm{dr}} > V_{\mathrm{dr_{sat}}} \end{cases} \tag{5.47}$$

$$V_{\mathrm{DiS_0}} = \begin{cases} \dfrac{2\cdot V_{\mathrm{dr}}}{N + \sqrt{N^2 - 2\cdot(f_{\mathrm{acc}} + f_\xi)\cdot V_{\mathrm{dr}}}}, & V_{\mathrm{dr}} \le V_{\mathrm{dr_{sat}}} \\ \dfrac{2\cdot(V_{\mathrm{dr}} - \frac{1}{2}\cdot f_\xi\cdot V^2_{\mathrm{DiSsat_0}})}{N + \sqrt{N^2 - 2\cdot f_{\mathrm{acc}}\cdot(V_{\mathrm{dr}} - \frac{1}{2}\cdot f_\xi\cdot V^2_{\mathrm{DiSsat_0}})}}, & V_{\mathrm{dr}} > V_{\mathrm{dr_{sat}}} \end{cases} \tag{5.48}$$

$$V_{\mathrm{GDi_{t0}}} = V_{\mathrm{GS_{t0}}} - V_{\mathrm{DiS_0}} \tag{5.49}$$

Surface potential at internal drain:

$$V_{\mathrm{DiS_{eff}}} = \mathrm{hypm}\left[V_{\mathrm{DiS_0}}, V_{\mathrm{DiSsat_{eff}}}; m\right] \tag{5.50}$$

$$V_{\mathrm{DiB_{t,eff}}} = \mathrm{hyp}\left[V_{\mathrm{SB}} + V_{\mathrm{DiS_{eff}}} + 0.9 \cdot \phi_{\mathrm{B}_T}; \epsilon_2\right] + 0.1 \cdot \phi_{\mathrm{B}_T} \tag{5.51}$$

$$\psi_{\mathrm{sL}} = \Psi_{\mathrm{s}}\left[V_{\mathrm{GB_{eff}}}, \psi_{\mathrm{sat}}, \Delta_{\mathrm{acc}}, V_{\mathrm{DiB_{t,eff}}}; k_0, m_0\right] \tag{5.52}$$

Drain-source current:

$$\mathcal{V}_{\mathrm{inv_{ex}}}\left[\psi_{\mathrm{s}}, \Delta_{\mathrm{acc}}, V_{\mathrm{CB_t}}; k, m_0\right] = k \cdot \frac{\phi_T \cdot \exp\left[\dfrac{\psi_{\mathrm{s}} - V_{\mathrm{CB_t}}}{(1+m_0)\cdot\phi_T}\right]}{\sqrt{\mathrm{hyp}\left[\psi_{\mathrm{s}} + \Delta_{\mathrm{acc}}; \epsilon_5\right] + \phi_T \cdot \exp\left[\dfrac{\psi_{\mathrm{s}} - V_{\mathrm{CB_t}}}{(1+m_0)\cdot\phi_T}\right]} + \sqrt{\mathrm{hyp}\left[\psi_{\mathrm{s}} + \Delta_{\mathrm{acc}}; \epsilon_5\right]}} \tag{5.53}$$

$$V_{\mathrm{inv_{ex0}}} = \mathcal{V}_{\mathrm{inv_{ex}}}\left[\psi_{\mathrm{s0}}, \Delta_{\mathrm{acc}}, V_{\mathrm{SB_t}}; k_0, m_0\right] \tag{5.54}$$

$$V_{\mathrm{inv_{exL}}} = \mathcal{V}_{\mathrm{inv_{ex}}}\left[\psi_{\mathrm{sL}}, \Delta_{\mathrm{acc}}, V_{\mathrm{DiB_{t,eff}}}; k_0, m_0\right] \tag{5.55}$$

$$\Delta\psi_{\mathrm{s}} = \psi_{\mathrm{sL}} - \psi_{\mathrm{s0}} \tag{5.56}$$

$$\overline{V_{\mathrm{inv}}} = V_{\mathrm{inv0}} - \tfrac{1}{2}\cdot\xi\cdot\Delta\psi_{\mathrm{s}} \tag{5.57}$$

$$F_{\mathrm{mobsat}} = 1 + \theta_{3_T}\cdot\Delta\psi_{\mathrm{s}} \tag{5.58}$$

$$G_{\mathrm{mob}} = F_{\mathrm{mob}}\cdot F_{\mathrm{mobsat}} \tag{5.59}$$

$$G_{\Delta L} = \mathrm{hyp}\left[1 - \alpha\cdot\ln\left[\frac{V_{\mathrm{DS_1}} - V_{\mathrm{DiS_{eff}}} + \sqrt{(V_{\mathrm{DS_1}} - V_{\mathrm{DiS_{eff}}})^2 + V_P^2}}{V_P}\right]; \epsilon_5\right] \tag{5.60}$$

$$x_0 = 2\cdot\frac{\psi_{\mathrm{sat}} + \phi_T - V_{\mathrm{SB_t}}}{\phi_T} \tag{5.61}$$

$$x_L = 2\cdot\frac{\psi_{\mathrm{sat}} + \phi_T - V_{\mathrm{DiB_{t,eff}}}}{\phi_T} \tag{5.62}$$

$$G = \begin{cases} \dfrac{\exp[x_0] + \exp[x_L]}{1 + \exp[x_0] + \exp[x_L]}, & x_0 \le 80 \wedge x_L \le 80, \\ 1, & x_0 > 80 \vee x_L > 80 \end{cases} \tag{5.63}$$

$$I_{\mathrm{drift}} = \beta_T\cdot G\cdot\frac{\overline{V_{\mathrm{inv}}}\cdot\Delta\psi_{\mathrm{s}}}{G_{\mathrm{mob}}\cdot G_{\Delta L}} \tag{5.64}$$

$$I_{\mathrm{diff}} = \beta_T\cdot\phi_T\cdot\frac{V_{\mathrm{inv_{ex0}}} - V_{\mathrm{inv_{exL}}}}{G_{\mathrm{mob}}\cdot G_{\Delta L}} \tag{5.65}$$

$$I_{\mathrm{DS}} = I_{\mathrm{drift}} + I_{\mathrm{diff}} \tag{5.66}$$

Avalanche current:

$$F_{\text{mobsat}_{\text{sat}}} = 1 + \theta_{3_T} \cdot V_{\text{DiSsat}_{\text{eff}}} \tag{5.67}$$

$$G_{\text{mob}_{\text{sat}}} = F_{\text{mob}} \cdot F_{\text{mobsat}_{\text{sat}}} \tag{5.68}$$

$$\overline{V_{\text{inv}_{\text{sat}}}} = \text{hyp}\left[V_{\text{inv0}} - \tfrac{1}{2} \cdot \xi \cdot V_{\text{DiSsat}_{\text{eff}}}; \epsilon_2\right] \tag{5.69}$$

$$I_{\text{sat}} = \beta_T \cdot G \cdot \frac{\overline{V_{\text{inv}_{\text{sat}}}} \cdot V_{\text{DiSsat}_{\text{eff}}}}{G_{\text{mob}_{\text{sat}}}} \tag{5.70}$$

$$V_{\text{ch}_{\text{sat}}} = R_{\text{D}_T} \cdot I_{\text{sat}} \tag{5.71}$$

$$V_{\text{oxp}} = \frac{f_{\text{lin}}}{f_{\text{acc}}} \tag{5.72}$$

$$V_{\text{DSsat}} = V_{\text{oxp}} + V_{\text{GS}_{\text{t}}} - \sqrt{\text{hyp}\left[\left(V_{\text{oxp}} + V_{\text{GS}_{\text{t}}} - V_{\text{DiSsat}_{\text{eff}}}\right)^2 - \frac{2 \cdot V_{\text{ch}_{\text{sat}}}}{f_{\text{acc}}}; \epsilon_5\right]} \tag{5.73}$$

$$V_{\text{DSsat}_{\text{eff}}} = V_{\text{limit}} + \text{hyp}\left[V_{\text{DSsat}} - V_{\text{limit}}; \epsilon_3\right] \tag{5.74}$$

$$I_{\text{AVL}} = \begin{cases} a_{1_T} \cdot |I_{\text{DS}}| \cdot \exp\left[-\dfrac{a_2}{\left|V_{\text{DS}_1}\right| - a_3 \cdot V_{\text{DSsat}_{\text{eff}}}}\right], & \left|V_{\text{DS}_1}\right| - a_3 \cdot V_{\text{DSsat}_{\text{eff}}} > -\dfrac{a_2}{A}, \\ 0, & \left|V_{\text{DS}_1}\right| - a_3 \cdot V_{\text{DSsat}_{\text{eff}}} \leq -\dfrac{a_2}{A} \end{cases} \tag{5.75}$$

Internal drain voltage, including saturation in the drift region:

$$V_{\text{oxp0}} = f_{\text{lin}} \cdot \frac{k_0 \cdot k_{0\text{D}}}{\sqrt{k_0^2 + k_{0\text{D}}^2}} \cdot \frac{\sqrt{\phi_0}}{\lambda_{\text{D}}} \tag{5.76}$$

$$V_{\text{pinch}} = -V_{\text{oxp0}} \cdot \left(1 + \frac{V_{\text{oxp0}}}{k_{0\text{D}}^2}\right) \tag{5.77}$$

$$V_{\text{TS}_{\text{t}}} = V_{\text{FB}_T} + \phi_{\text{B}_T} - V_{\text{FBD}_T} + k_0 \cdot \sqrt{V_{\text{SB}_{\text{t}}}} \tag{5.78}$$

$$V_{\text{DSsat}_{\text{dr}}} = V_{\text{TS}_{\text{t}}} - V_{\text{pinch}} \tag{5.79}$$

$$V_{\text{DSsat}_{\text{dr,eff}}} = V_{\text{limit}} + \text{hyp}\left[V_{\text{DSsat}_{\text{dr}}} - V_{\text{limit}}; \epsilon_3\right] \tag{5.80}$$

$$V_{\text{DS}_{\text{dr,eff}}} = \text{hypm}\left[V_{\text{DS}_1}, V_{\text{DSsat}_{\text{dr,eff}}}; m\right] \tag{5.81}$$

$$V_{\text{GD}_{\text{t,eff}}} = V_{\text{GS}_{\text{t}}} - V_{\text{DS}_{\text{dr,eff}}} \tag{5.82}$$

$$V_{\mathrm{GD_{t,eff0}}} = V_{\mathrm{pinch}} + \mathrm{hyp}\left[V_{\mathrm{GD_{t,eff}}} - V_{\mathrm{pinch}}; \epsilon_7\right] \tag{5.83}$$

$$V_{\mathrm{ch}} = R_{\mathrm{D}_T} \cdot I_{\mathrm{DS}} \tag{5.84}$$

$$F[V] = \begin{cases} V^2, & V \geq 0 \\ 2 \cdot k_{\mathrm{0D}} \cdot \left(\frac{2}{3}\left(\left(\left(\frac{k_{\mathrm{0D}}}{2}\right)^2 - V\right)^{3/2} - \left(\frac{k_{\mathrm{0D}}}{2}\right)^3\right) + \frac{k_{\mathrm{0D}}}{2} \cdot V\right), & V < 0 \end{cases} \tag{5.85}$$

$$F'[V] = \begin{cases} 2 \cdot V, & V \geq 0 \\ -2 \cdot k_{\mathrm{0D}} \cdot \left(-\frac{k_{\mathrm{0D}}}{2} + \sqrt{\left(\frac{k_{\mathrm{0D}}}{2}\right)^2 - V}\right), & V < 0 \end{cases} \tag{5.86}$$

$$H\left[V_{\mathrm{GDi_t}}\right] = 2 \cdot V_{\mathrm{oxp}} \cdot \left(V_{\mathrm{GDi_t}} - V_{\mathrm{GD_{t,eff0}}}\right) + F\left[V_{\mathrm{GDi_t}}\right] - F\left[V_{\mathrm{GD_{t,eff0}}}\right] - \frac{2 \cdot V_{\mathrm{ch}}}{f_{\mathrm{acc}}} \tag{5.87}$$

$$H'\left[V_{\mathrm{GDi_t}}\right] = 2 \cdot V_{\mathrm{oxp}} + F'\left[V_{\mathrm{GDi_t}}\right] \tag{5.88}$$

$$\left\{V_{\mathrm{GDi_{t,eff0}}}\right\}_0 = V_{\mathrm{GD_{t,eff0}}}$$

$$\{\mathrm{error}\}_0 = 1$$

for $(n = 1, \ldots, 20)$ and $\left(\{\mathrm{error}\}_{n-1} < 1 \times 10^{-6} \cdot \phi_T\right)$
do begin

$$\left\{V_{\mathrm{GDi_{t,eff0}}}\right\}_n = \left\{V_{\mathrm{GDi_{t,eff0}}}\right\}_{n-1} - \frac{H\left[\left\{V_{\mathrm{GDi_{t,eff0}}}\right\}_{n-1}\right]}{H'\left[\left\{V_{\mathrm{GDi_{t,eff0}}}\right\}_{n-1}\right]} \tag{5.89}$$

$$\{\mathrm{error}\}_n = \left|\left\{V_{\mathrm{GDi_{t,eff0}}}\right\}_n - \left\{V_{\mathrm{GDi_{t,eff0}}}\right\}_{n-1}\right|$$

end

$$V_{\mathrm{GDi_{t,eff0}}} = \left\{V_{\mathrm{GDi_{t,eff0}}}\right\}_n$$

$$V_{\mathrm{DDi_{eff}}} = V_{\mathrm{GDi_{t,eff0}}} - V_{\mathrm{GD_{t,eff0}}} \tag{5.90}$$

$$V_{\mathrm{DiS_{dr,eff}}} = V_{\mathrm{DS_{dr,eff}}} - V_{\mathrm{DDi_{eff}}} \tag{5.91}$$

$$V_{\mathrm{GDi_{t,eff}}} = V_{\mathrm{GS_t}} - V_{\mathrm{DiS_{dr,eff}}} \tag{5.92}$$

5.3 Charge Equations

Recalculation of factor ξ:

$$\delta = \frac{k_0}{2 \cdot \sqrt{\mathrm{hyp}\left[\frac{\psi_{\mathrm{s0}} + \psi_{\mathrm{sL}}}{2} + \Delta_{\mathrm{acc}}; \epsilon_5\right]}} \tag{5.93}$$

$$\xi = 1 + \delta \tag{5.94}$$

Surface potential for accumulation in the channel region:

$$f_{1acc}\left[V_{GB_t}, V_{GB_{eff}}; Acc\right] = Acc \cdot \left(V_{GB_t} - V_{GB_{eff}}\right) \tag{5.95}$$

$$f_{2acc}\left[V_{GB_t}, V_{GB_{eff}}; Acc\right] = \frac{f_{1acc}\left[V_{GB_t}, V_{GB_{eff}}; Acc\right]}{\sqrt{1 + \frac{f_{1acc}^2\left[V_{GB_t}, V_{GB_{eff}}; Acc\right]}{16 \cdot {\phi_T}^2}}} \tag{5.96}$$

$$f_{3acc}\left[V_{GB_t}, V_{GB_{eff}}; Acc\right] = V_{GB_t} - V_{GB_{eff}} - f_{2acc}\left[V_{GB_t}, V_{GB_{eff}}; Acc\right] \tag{5.97}$$

$$\Psi_{sacc}\left[V_{GB_t}, V_{GB_{eff}}; k, Acc\right] = -\phi_T \cdot \ln\left[1 + \frac{\left(\frac{f_{3acc}\left[V_{GB_t}, V_{GB_{eff}}; Acc\right]}{k}\right)^2 - f_{2acc}\left[V_{GB_t}, V_{GB_{eff}}; Acc\right]}{\phi_T}\right] \tag{5.98}$$

$$\psi_{sacc} = \Psi_{sacc}\left[V_{GB_t}, V_{GB_{eff}}; k_0, Acc\right] \tag{5.99}$$

Charges in the channel region:

$$V_{ox} = V_{GB_t} - \tfrac{1}{2} \cdot (\psi_{s0} + \psi_{sL}) - \psi_{sacc} \tag{5.100}$$

$$V_{GT0} = \mathcal{V}_{inv}\left[V_{GB_{eff}}, \psi_{s0}, \Delta_{acc}; k_0\right] \tag{5.101}$$

$$V_{GTL} = \mathcal{V}_{inv}\left[V_{GB_{eff}}, \psi_{sL}, \Delta_{acc}; k_0\right] \tag{5.102}$$

$$\Delta V_{GT} = V_{GT0} - V_{GTL} \tag{5.103}$$

$$\overline{V_{GT}} = \tfrac{1}{2} \cdot (V_{GT0} + V_{GTL}) \tag{5.104}$$

$$F_j = \frac{\Delta V_{GT}}{\overline{V_{GT}} + \xi \cdot \phi_T} \tag{5.105}$$

$$Q_{G_{mos}} = C_{ox} \cdot \left(V_{ox} + \frac{F_j}{12 \cdot \xi} \cdot \Delta V_{GT}\right) \tag{5.106}$$

$$Q_{D_{mos}} = -\frac{C_{ox}}{2} \cdot \left(\overline{V_{GT}} - \frac{\Delta V_{GT}}{6} \cdot \left\{1 - \frac{F_j}{2} - \frac{F_j^2}{20}\right\}\right) \tag{5.107}$$

$$Q_{S_{mos}} = -\frac{C_{ox}}{2} \cdot \left(\overline{V_{GT}} + \frac{\Delta V_{GT}}{6} \cdot \left\{1 + \frac{F_j}{2} - \frac{F_j^2}{20}\right\}\right) \tag{5.108}$$

$$Q_{\mathrm{B_{mos}}} = -\left(Q_{\mathrm{G_{mos}}} + Q_{\mathrm{D_{mos}}} + Q_{\mathrm{S_{mos}}}\right) \tag{5.109}$$

$$Q_{\mathrm{G_{ch}}} = Q_{\mathrm{G_{mos}}} \tag{5.110}$$

$$Q_{\mathrm{D_{ch}}} = F_L \cdot Q_{\mathrm{D_{mos}}} \tag{5.111}$$

$$Q_{\mathrm{S_{ch}}} = Q_{\mathrm{S_{mos}}} + (1 - F_L) \cdot Q_{\mathrm{D_{mos}}} \tag{5.112}$$

$$Q_{\mathrm{B_{ch}}} = -\left(Q_{\mathrm{G_{ch}}} + Q_{\mathrm{D_{ch}}} + Q_{\mathrm{S_{ch}}}\right) \tag{5.113}$$

Surface potentials in the drift region:

$$V_{\mathrm{DG_{eff}}} = \mathrm{hyp}\left[-V_{\mathrm{GD_{t,eff}}}; \epsilon_7\right] \tag{5.114}$$

$$\Delta_{\mathrm{acc_D}} = \phi_T \cdot \left(\exp\left[-\frac{Acc_{\mathrm{D}}\left(V_{\mathrm{DG_{eff}}} - \epsilon_7\right)}{\phi_T}\right] - 1\right) \tag{5.115}$$

$$\psi_{\mathrm{sat_D}} = \Psi_{\mathrm{sat}}\left[V_{\mathrm{DG_{eff}}}, \Delta_{\mathrm{acc_D}}; k_{0\mathrm{D}}\right] \tag{5.116}$$

$$V_{\mathrm{DB_t}} = \mathrm{hyp}\left[V_{\mathrm{SB}} + V_{\mathrm{DS_{dr,eff}}} + 0.9 \cdot \phi_{\mathrm{BD}_T}; \epsilon_2\right] + 0.1 \cdot \phi_{\mathrm{BD}_T} \tag{5.117}$$

$$\psi_{\mathrm{sD}} = \Psi_{\mathrm{s}}\left[V_{\mathrm{DG_{eff}}}, \psi_{\mathrm{sat_D}}, \Delta_{\mathrm{acc_D}}, V_{\mathrm{DB_t}}; k_{0\mathrm{D}}, m_0\right] \tag{5.118}$$

$$\psi_{\mathrm{sacc_D}} = \Psi_{\mathrm{sacc}}\left[-V_{\mathrm{GD_{t,eff}}}, V_{\mathrm{DG_{eff}}}; k_{0\mathrm{D}}, Acc_{\mathrm{D}}\right] \tag{5.119}$$

$$V_{\mathrm{DiG_{eff}}} = \mathrm{hyp}\left[-V_{\mathrm{GDi_{t,eff}}}; \epsilon_7\right] \tag{5.120}$$

$$\Delta_{\mathrm{acc_{Di}}} = \phi_T \cdot \left(\exp\left[-\frac{Acc_{\mathrm{D}}\left(V_{\mathrm{DiG_{eff}}} - \epsilon_7\right)}{\phi_T}\right] - 1\right) \tag{5.121}$$

$$\psi_{\mathrm{sat_{Di}}} = \Psi_{\mathrm{sat}}\left[V_{\mathrm{DiG_{eff}}}, \Delta_{\mathrm{acc_{Di}}}; k_{0\mathrm{D}}\right] \tag{5.122}$$

$$V_{\mathrm{DiB_t}} = \mathrm{hyp}\left[V_{\mathrm{SB}} + V_{\mathrm{DiS_{dr,eff}}} + 0.9 \cdot \phi_{\mathrm{BD}_T}; \epsilon_2\right] + 0.1 \cdot \phi_{\mathrm{BD}_T} \tag{5.123}$$

$$\psi_{\mathrm{sDi}} = \Psi_{\mathrm{s}}\left[V_{\mathrm{DiG_{eff}}}, \psi_{\mathrm{sat_{Di}}}, \Delta_{\mathrm{acc_{Di}}}, V_{\mathrm{DiB_t}}; k_{0\mathrm{D}}, m_0\right] \tag{5.124}$$

$$\psi_{\mathrm{sacc_{Di}}} = \Psi_{\mathrm{sacc}}\left[-V_{\mathrm{GDi_{t,eff}}}, V_{\mathrm{DiG_{eff}}}; k_{0\mathrm{D}}, Acc_{\mathrm{D}}\right] \tag{5.125}$$

Charges in the drift region:

$$V_{\mathrm{ox_{dr}}} = \tfrac{1}{2} \cdot \left(V_{\mathrm{GD_t}} + V_{\mathrm{GDi_t}} + \psi_{\mathrm{sD}} + \psi_{\mathrm{sDi}} + \psi_{\mathrm{sacc_D}} + \psi_{\mathrm{sacc_{Di}}}\right) \tag{5.126}$$

$$V_{\mathrm{GDi_{acc}}} = V_{\mathrm{DiG_{eff}}} + V_{\mathrm{GDi_{t,eff}}} \tag{5.127}$$

$$V_{\mathrm{GD_{acc}}} = V_{\mathrm{DG_{eff}}} + V_{\mathrm{GD_{t,eff}}} \tag{5.128}$$

$$\Delta V_{\mathrm{acc}} = V_{\mathrm{GDi_{acc}}} - V_{\mathrm{GD_{acc}}} \tag{5.129}$$

$$\overline{V_{\mathrm{acc}}} = \tfrac{1}{2} \cdot \left(V_{\mathrm{GDi_{acc}}} + V_{\mathrm{GD_{acc}}}\right) \tag{5.130}$$

$$F_{j_{\mathrm{acc}}} = \frac{\Delta V_{\mathrm{acc}}}{\overline{V_{\mathrm{acc}}} + V_{\mathrm{oxp}}} \tag{5.131}$$

$$Q_{\mathrm{G_{dr}}} = C_{\mathrm{oxD}} \cdot \left(V_{\mathrm{ox_{dr}}} + \frac{F_{j_{\mathrm{acc}}}}{12} \cdot \Delta V_{\mathrm{acc}}\right) \tag{5.132}$$

$$Q_{\mathrm{D_{acc}}} = -\frac{C_{\mathrm{oxD}}}{2} \cdot \left(\overline{V_{\mathrm{acc}}} - \frac{\Delta V_{\mathrm{acc}}}{6} \cdot \left\{1 - \frac{F_{j_{\mathrm{acc}}}}{2} - \frac{F_{j_{\mathrm{acc}}}^2}{20}\right\}\right) \tag{5.133}$$

$$Q_{\mathrm{S_{acc}}} = -\frac{C_{\mathrm{oxD}}}{2} \cdot \left(\overline{V_{\mathrm{acc}}} + \frac{\Delta V_{\mathrm{acc}}}{6} \cdot \left\{1 + \frac{F_{j_{\mathrm{acc}}}}{2} - \frac{F_{j_{\mathrm{acc}}}^2}{20}\right\}\right) \tag{5.134}$$

$$V_{\mathrm{T_t}} = V_{\mathrm{FB}_T} + \phi_{\mathrm{B}_T} - V_{\mathrm{FBD}_T} + k_0 \cdot \sqrt{V_{\mathrm{DiB_{t,eff}}}} \tag{5.135}$$

$$V_{\mathrm{GDi_{lim}}} = V_{\mathrm{GDi_{t,eff}}} + \mathrm{hyp}\left[V_{\mathrm{T_t}} - V_{\mathrm{GDi_{t,eff}}}; \epsilon_7\right] \tag{5.136}$$

$$V_{\mathrm{GD_{lim}}} = V_{\mathrm{GDi_{lim}}} - V_{\mathrm{DDi_{eff}}} \tag{5.137}$$

$$V_{\mathrm{GD_{acc,lim}}} = \mathrm{hyp}\left[V_{\mathrm{GD_{lim}}}; \epsilon_7\right] \tag{5.138}$$

$$V_{\mathrm{GDi_{acc,lim}}} = \mathrm{hyp}\left[V_{\mathrm{GDi_{lim}}}; \epsilon_7\right] \tag{5.139}$$

$$\Delta V_{\mathrm{acc,lim}} = V_{\mathrm{GDi_{acc,lim}}} - V_{\mathrm{GD_{acc,lim}}} \tag{5.140}$$

$$\overline{V_{\mathrm{acc,lim}}} = \tfrac{1}{2} \cdot \left(V_{\mathrm{GDi_{acc,lim}}} + V_{\mathrm{GD_{acc,lim}}}\right) \tag{5.141}$$

$$F_{j_{\mathrm{acc,lim}}} = \frac{\Delta V_{\mathrm{acc,lim}}}{\overline{V_{\mathrm{acc,lim}}} + V_{\mathrm{oxp}}} \tag{5.142}$$

$$Q_{\mathrm{S_{acc,lim}}} = -\frac{C_{\mathrm{oxD}}}{2} \cdot \left(\overline{V_{\mathrm{acc,lim}}} + \frac{\Delta V_{\mathrm{acc,lim}}}{6} \cdot \left\{1 + \frac{F_{j_{\mathrm{acc,lim}}}}{2} - \frac{F_{j_{\mathrm{acc,lim}}}^2}{20}\right\}\right) \tag{5.143}$$

$$V_{\mathrm{dep_D}} = \mathcal{V}_{\mathrm{dep}}\left[\psi_{\mathrm{sD}}, \Delta_{\mathrm{acc_D}}; k_{\mathrm{0D}}, \epsilon_6\right] \tag{5.144}$$

$$V_{\mathrm{dep_{Di}}} = \mathcal{V}_{\mathrm{dep}}\left[\psi_{\mathrm{sDi}}, \Delta_{\mathrm{acc_{Di}}}; k_{\mathrm{0D}}, \epsilon_6\right] \tag{5.145}$$

$$Q_{\mathrm{G_{dep}}} = -\frac{C_{\mathrm{oxD}}}{2} \cdot \left(V_{\mathrm{dep_D}} + V_{\mathrm{dep_{Di}}}\right) \tag{5.146}$$

$$V_{\mathrm{inv_D}} = V_{\mathrm{DG_{eff}}} - \psi_{\mathrm{sD}} - V_{\mathrm{dep_D}} \tag{5.147}$$

$$V_{\mathrm{inv_{Di}}} = V_{\mathrm{DiG_{eff}}} - \psi_{\mathrm{sDi}} - V_{\mathrm{dep_{Di}}} \tag{5.148}$$

$$Q_{\mathrm{B_{dr}}} = \frac{C_{\mathrm{oxD}}}{2} \cdot \left(V_{\mathrm{inv_D}} + V_{\mathrm{inv_{Di}}}\right) \tag{5.149}$$

$$Q_{\mathrm{D_{dr}}} = Q_{\mathrm{D_{acc}}} + F_L \cdot Q_{\mathrm{S_{acc}}} + (1 - F_L) \cdot Q_{\mathrm{S_{acc,lim}}} - Q_{\mathrm{G_{dep}}} \tag{5.150}$$

$$Q_{\mathrm{S_{dr}}} = -\left(Q_{\mathrm{G_{dr}}} + Q_{\mathrm{D_{dr}}} + Q_{\mathrm{B_{dr}}}\right) \tag{5.151}$$

Total charges:

$$Q_{\mathrm{G}} = Q_{\mathrm{G_{ch}}} + Q_{\mathrm{G_{dr}}} \tag{5.152}$$

$$Q_{\mathrm{D}} = Q_{\mathrm{D_{ch}}} + Q_{\mathrm{D_{dr}}} \tag{5.153}$$

$$Q_{\mathrm{S}} = Q_{\mathrm{S_{ch}}} + Q_{\mathrm{S_{dr}}} \tag{5.154}$$

$$Q_{\mathrm{B}} = -\left(Q_{\mathrm{G}} + Q_{\mathrm{D}} + Q_{\mathrm{S}}\right) \tag{5.155}$$

5.4 Noise Equations

Noise transfer function:

$$g_{\mathrm{m_{ch}}} = \max\left[\beta_T \cdot \frac{\Delta\psi_{\mathrm{s}}}{G_{\mathrm{mob}}} \cdot \left(1 - \theta_1 \cdot \frac{\overline{V_{\mathrm{inv}}}}{F_{\mathrm{mob}}}\right), 1 \times 10^{-10}\right] \tag{5.156}$$

$$g_{\mathrm{ds_{ch}}} = \max\left[\beta_T \cdot \frac{V_{\mathrm{inv0}} + \xi \cdot V_{\mathrm{limit}} - \xi \cdot \Delta\psi_{\mathrm{s}} - \frac{1}{2} \cdot \theta_{3_T} \cdot \xi \cdot (\Delta\psi_{\mathrm{s}})^2}{G_{\mathrm{mob}} \cdot F_{\mathrm{mobsat}}}, 0\right] \tag{5.157}$$

$$g_{\mathrm{m_{dr}}} = \max\left[\frac{f_{\mathrm{acc}}}{R_{\mathrm{D}_T}} \cdot \left(V_{\mathrm{GDi_{t0}}} - V_{\mathrm{GD_{t0}}}\right), 1 \times 10^{-10}\right] \tag{5.158}$$

$$g_{\mathrm{ds_{dr}}} = \max\left[\frac{f_{\mathrm{lin}}}{R_{\mathrm{D}_T}} + \frac{f_{\mathrm{acc}}}{R_{\mathrm{D}_T}} \cdot V_{\mathrm{GD_{t0}}}, 1 \times 10^{-10}\right] \tag{5.159}$$

$$g_{\mathrm{transfer}} = \frac{g_{\mathrm{ds_{dr}}} + g_{\mathrm{m_{dr}}}}{g_{\mathrm{ds_{ch}}} + g_{\mathrm{ds_{dr}}} + g_{\mathrm{m_{dr}}}} \tag{5.160}$$

Flicker noise:

$$N_0 = \frac{\epsilon_{ox}}{q \cdot t_{ox}} \cdot V_{inv_{ex0}} \tag{5.161}$$

$$N_L = \frac{\epsilon_{ox}}{q \cdot t_{ox}} \cdot V_{inv_{exL}} \tag{5.162}$$

$$N^* = \frac{\epsilon_{ox}}{q \cdot t_{ox}} \cdot \xi \cdot \phi_T \tag{5.163}$$

$$\begin{aligned} S_{D_{fl0}} = \frac{q \cdot \phi_T^2 \cdot t_{ox} \cdot \beta_T \cdot I_{DS}}{\epsilon_{ox} \cdot N^* \cdot G_{mob}} \Big\{ \left(N_{fA} - N^* \cdot N_{fB} + N^{*2} \cdot N_{fC} \right) \cdot \ln \left[\frac{N_0 + N^*}{N_L + N^*} \right] \\ + \left(N_{fB} - N^* \cdot N_{fC} \right) \cdot (N_0 - N_L) + \frac{N_{fC}}{2} \cdot \left({N_0}^2 - {N_L}^2 \right) \Big\} \\ + \phi_T \cdot I_{DS}^2 \cdot (1 - G_{\Delta L}) \cdot \frac{N_{fA} + N_{fB} \cdot N_L + N_{fC} \cdot N_L^2}{(N_L + N^*)^2} \end{aligned} \tag{5.164}$$

$$S_{D_{fl}} = g_{transfer}^2 \cdot \frac{\max\left[S_{D_{fl0}}, 0\right]}{f} \tag{5.165}$$

Thermal noise:

$$\begin{aligned} S_{D_{th0}} = \beta_T \cdot \Big\{ \frac{F_{mobsat} \cdot G_{\Delta L}}{F_{mob}} \cdot \left(\overline{V_{inv}} + \frac{\xi^2}{12} \cdot \frac{\Delta\psi_s{}^2}{\overline{V_{inv}} + \xi \cdot \phi_T} \right) \\ - \frac{\theta_{3_T} \cdot \overline{V_{inv}} \cdot \Delta\psi_s}{F_{mob}} \cdot \left(2 - \frac{\theta_{3_T} \cdot \Delta\psi_s}{F_{mobsat} \cdot G_{\Delta L}} \right) \Big\} \end{aligned} \tag{5.166}$$

$$S_{D_{th}} = g_{transfer}^2 \cdot N_{T_T} \cdot \max\left[S_{D_{th0}}, 0\right] \tag{5.167}$$

$$S_{G_{th}} = N_{T_T} \cdot \frac{(2 \cdot \pi \cdot C_{ox})^2}{3 \cdot g_{m_{ch}}} \cdot f^2 \tag{5.168}$$

$$S_{GD_{th}} = 0.4 \cdot \mathrm{j} \cdot \sqrt{S_{G_{th}} \cdot S_{D_{th}}} \tag{5.169}$$

6 Parameter Extraction Strategy

The parameter extraction strategy for MOS Model 20 *ex*cluding 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:

1. measurements
2. extraction of miniset parameters (including temperature scaling parameters)
3. 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.

6.1 Measurements

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

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

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

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

• **Measurement II (subvt):** Sub-threshold 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

[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 III (idvd):** I_D and g_{DS} versus V_{DS} characteristics:
n–channel : $V_{DS} = 0, \ldots, V_{DS,\,max}$
$V_{GS} = V_T + 0.1$ 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 : $V_{DS} = 0, \ldots, -V_{DS,\,max}$
$V_{GS} = V_T - 0.1$ V, $V_T - 1.1$ V, $V_T - 2.1$ V, $V_T - 3.1$ V.
$V_{BS} = 0, -2$ and -4 V

• **Measurement IV (idvdh):** I_D and g_{DS} versus V_{DS} characteristics:
n–channel : $V_{DS} = 0 \ldots V_{DS,\,max}$
V_{GS} = 4 values starting from $(V_{DS,\,max}/4)$ to $V_{DS,\,max}$
$V_{SB} = 0$ V

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

• **Measurement V (ibvg):** I_D and I_B versus V_{GS} characteristics in high-field operation regions:
n–channel : $V_{GS} = 0, \ldots, V_{GS,\,max}$.
$V_{DS} = V_{GS,\,max} - 4\ V$, $V_{GS,\,max} - 2\ V$ and $-V_{GS,\,max}$
$V_{SB} = 0$ V

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

• **Measurement VI (Cvg):** C_{gg}, C_{sg}, C_{dg} and C_{bg} versus V_{GS} characteristics:
n/p–channel : $V_{GS} = -V_{GS,\,max}, \ldots, V_{GS,\,max}$
$V_{DS} = 0$ V
$V_{SB} = 0$ V

The values of transconductance g_m and output conductance g_{DS} are determined 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 $T_{min} = -40^oC$ to $T_{max} = 125^oC$. Finally, to determine the width scaling parameters, the measurements at room temperature need to be performed for a narrow and broad transistor.

6.2 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 $\Delta T_{\text{self-heating}}$ 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 $\Delta T_{\text{self-heating}}$ due to self-heating, according to

$$\Delta T_{\text{self-heating}} = R_{\text{th}} \cdot I_{\text{DS}} \cdot V_{\text{DS}}. \tag{6.1}$$

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

$$R_{\text{th}_{\text{SOI}}} = \left(\frac{t_{\text{BOX}}}{k_{\text{ox}}} + \frac{t_{\text{Si}}}{k_{\text{Si}}} \right) \cdot \frac{1}{A}, \qquad \text{or} \qquad R_{\text{th}_{\text{bulk}}} = \frac{t_{\text{Si}}}{k_{\text{Si}}} \cdot \frac{1}{A}, \tag{6.2}$$

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 6. The physical constants k_{Si} and k_{ox} are the thermal conductivity of silicon and oxide, respectively. At $T = 27^{\text{o}}$C these conductivities are given by $k_{\text{ox}} = 1.4$ W/(K·m) and $k_{\text{Si}} = 1.41 \cdot 10^2$ W/(K·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].

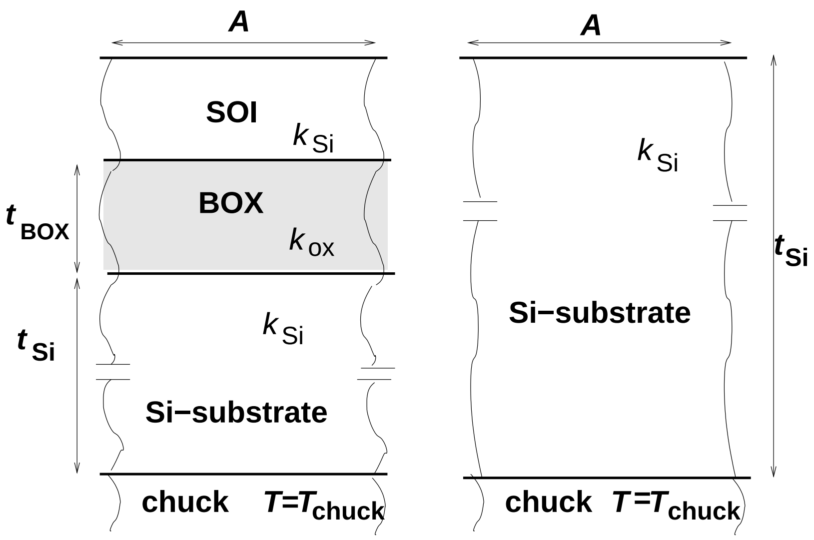


Figure 6: *Geometry for the one-dimensional heat-flow in a transistor in an SOI process (left) and a bulk process (right).*

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:

Parameter	Program Name	Parameter Value	
		NMOS	PMOS
V_{FB}	VFB	-1.0	-1.0
$S_{T;\text{V}_{\text{FB}}}$	STVFB	$-1.0 \cdot 10^{-3}$	$-1.0 \cdot 10^{-3}$
V_{FBD}	VFBD	0.0	0.0
$S_{T;\text{V}_{\text{FB}}}$	STVFB	0.0	0.0
k_0	KO	1.6	1.6
$k_{0\text{D}}$	KOD	1.0	1.0
ϕ_{B}	PHIB	0.9	0.9
$S_{T;\phi_{\text{B}}}$	STPHIB	$-1.0 \cdot 10^{-3}$	$-1.0 \cdot 10^{-3}$
ϕ_{BD}	PHIBD	0.8	0.8
$S_{T;\phi_{\text{BD}}}$	STPHIBD	$-1.0 \cdot 10^{-3}$	$-1.0 \cdot 10^{-3}$
β	BET	$(2.2 \cdot 10^{-12}/t_{\text{ox}}) \cdot (W/L_{\text{ch}})$	$(0.8 \cdot 10^{-12}/t_{\text{ox}}) \cdot (W/L_{\text{ch}})$
η_{β}	ETABET	1.6	1.6
β_{acc}	BETACC	$(2.2 \cdot 10^{-12}/t_{\text{ox}}) \cdot (W/L_{\text{dr}})$	$(0.8 \cdot 10^{-12}/t_{\text{ox}}) \cdot (W/L_{\text{dr}})$
$\eta_{\beta_{\text{acc}}}$	ETABETACC	1.6	1.6
R_{D}	RD	$5.0 \cdot 10^{3} \cdot (L_{\text{dr}}/W)$	$1.5 \cdot 10^{4} \cdot (L_{\text{dr}}/W)$
$\eta_{R_{\text{D}}}$	ETARD	1.5	1.5
λ_{D}	LAMD	0.2	0.2
θ_1	THE1	0.05	0.05
$\theta_{1\text{acc}}$	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
α	ALP	$2.0 \cdot 10^{-3}$	$2.0 \cdot 10^{-3}$
V_{P}	VP	$5.0 \cdot 10^{-2}$	$5.0 \cdot 10^{-2}$
σ_{dibl}	SDIBL	$1.0 \cdot 10^{-3}$	$1.0 \cdot 10^{-3}$
$m_{\sigma_{\text{dibl}}}$	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_1	A1	18	18
$S_{T;a_1}$	STA1	0.0	0.0
a_2	A2	73	73
a_3	A3	1.0	1.0
C_{ox}	COX	$(3.453 \cdot 10^{-11}/t_{\text{ox}}) \cdot W \cdot L_{\text{ch}}$	$(3.453 \cdot 10^{-11}/t_{\text{ox}}) \cdot W \cdot L_{\text{ch}}$
C_{oxD}	COXD	$(3.453 \cdot 10^{-11}/t_{\text{ox}}) \cdot W \cdot L_{\text{dr}}$	$(3.453 \cdot 10^{-11}/t_{\text{ox}}) \cdot W \cdot L_{\text{dr}}$
C_{GDO}	CGDO	$3.0 \cdot 10^{-10} \cdot W$	$3.0 \cdot 10^{-10} \cdot W$
C_{GSO}	CGSO	$3.0 \cdot 10^{-10} \cdot W$	$3.0 \cdot 10^{-10} \cdot W$

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).

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.

Step	Optimised Parameters	Measure-ment	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), $T = T_{min}, \ldots, T_{max}$	I_D	abs	$I_D < 0.1 \cdot I_{D,max_{idvg}}$
4	θ_1, θ_3, η_{θ_3}	IV (idvdh), $T = T_{min}, \ldots, T_{max}$	I_D	abs	in saturation
5	β, η_β	IV (idvdh), $T = T_{min}, \ldots, T_{max}$	I_D	abs	in saturation
6	α, V_P, σ_{sf}	III (idvd), $T = T_{ref}$	g_{DS}	rel	in saturation, $V_{GS} < V_T + 3.1\ V$
7	β, η_β	III (idvd), $T = T_{ref}$	g_{DS}	rel	in saturation, $V_{GS} = V_T + 3.1\ V$
8	β_{acc}, $\eta_{\beta_{acc}}$, R_D	IV (idvdh), $T = T_{min}, \ldots, T_{max}$	I_D	abs	in linear region, $\eta_{R_D} = \eta_{\beta_{acc}}$
9	θ_{1acc}	I (idvg), $T = T_{ref}$	I_D	abs	-
10	θ_2	III (idvd), $T = T_{ref}$	I_D	abs	$V_{SB} > 0$
11	λ_D	I (idvg), $T = T_{ref}$	I_D	abs	$V_{SB} > 0$
12	a_1, a_2, a_3	V (ibvg), $T = T_{ref}$	I_B	abs	-
13	$S_{T;a_1}$	V (ibvg), $T = T_{min}, \ldots, T_{max}$	I_B	abs	-

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

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.

Step	Optimised Parameters	Measure-ment	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), $T = T_{min}, \ldots, T_{max}$	C_{GG}	abs	-

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

6.3 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 3.2.3. 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 3.2.3, 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 6.2.
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.

7 Pstar Specific Items

7.1 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.

7.2 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 $C_{x(y)}$ indicates the derivative of the charge Q at terminal x to the voltage at terminal y, when all other terminals remain constant.

No.	Symbol	Program Name	Units	Description
0	I_{DS}	IDS	A	Drain current, excluding avalanche current
1	I_{AVL}	IAVL	A	Substrate current due to weak-avalanche
2	V_{DS}	VDS	V	Drain-source voltage
3	V_{GS}	VGS	V	Gate-source voltage
4	V_{SB}	VSB	V	Source-bulk voltage
5	V_{T0}	VTO	V	Zero-bias threshold voltage of the channel region (after geometric and temperature scaling): $V_{\mathrm{T0}} = V_{\mathrm{FB}_T} + \phi_{\mathrm{B}_T} + k_0 \cdot \sqrt{\phi_{\mathrm{B}_T}}$
6	V_{TS}	VTS	V	Threshold voltage including back-bias effects: $V_{\mathrm{TS}} = V_{\mathrm{FB}_T} + \phi_{\mathrm{B}_T} + k_0 \cdot \sqrt{V_{\mathrm{SB_t}}}$
7	V_{TH}	VTH	V	Threshold voltage including back-bias and drain-bias effects: $V_{\mathrm{TH}} = V_{\mathrm{FB}_T} + \phi_{\mathrm{B}_T} + k_0 \cdot \sqrt{V_{\mathrm{SB_t}}} - \Delta V_{\mathrm{G}}$
8	V_{GT}	VGT	V	Effective gate drive voltage including back-bias and drain voltage effects: $V_{\mathrm{GT}} = V_{\mathrm{inv_{ex0}}}$
9	V_{TOD}	VTOD	V	Treshold voltage of the drift region: $V_{\mathrm{TOD}} = V_{\mathrm{FBD}_T} - \phi_{\mathrm{BD}_T} - k_{\mathrm{0D}} \cdot \sqrt{\phi_{\mathrm{BD}_T}}$
10	$V_{\mathrm{DiS_{eff}}}$	VDISEFF	V	Effective internal drain to source voltage at actual bias
11	$V_{\mathrm{DiSsat_{eff}}}$	VDISSAT	V	Internal drain saturation voltage at actual bias
12	$V_{\mathrm{DSsat_{eff}}}$	VDSSAT	V	Drain-source saturation voltage at actual bias
13	g_{m}	GM	A/V	Transconductance (assumed $V_{\mathrm{DS}} > 0$): $g_{\mathrm{m}} = \partial I_{\mathrm{DS}} / \partial V_{\mathrm{GS}}$
14	g_{mb}	GMB	A/V	Substrate-transconductance (assumed $V_{\mathrm{DS}} > 0$): $g_{\mathrm{mb}} = \partial I_{\mathrm{DS}} / \partial V_{\mathrm{BS}}$
15	g_{ds}	GDS	A/V	Output conductance: $g_{\mathrm{ds}} = \partial I_{\mathrm{DS}} / \partial V_{\mathrm{DS}}$

No.	Symbol	Program Name	Unit	Description
16	C_{DD}	CDD	F	$C_{DD} = \partial Q_D / \partial V_{DS}$
17	C_{DG}	CDG	F	$C_{DG} = -\partial Q_D / \partial V_{GS}$
18	C_{DS}	CDS	F	$C_{DS} = C_{DD} - C_{DG} - C_{DB}$
19	C_{DB}	CDB	F	$C_{DB} = \partial Q_D / \partial V_{SB}$
20	C_{GD}	CGD	F	$C_{GD} = -\partial Q_G / \partial V_{DS}$
21	C_{GG}	CGG	F	$C_{GG} = \partial Q_G / \partial V_{GS}$
22	C_{GS}	CGS	F	$C_{GS} = C_{GG} - C_{GD} - C_{GB}$
23	C_{GB}	CGB	F	$C_{GB} = \partial Q_G / \partial V_{SB}$
24	C_{SD}	CSD	F	$C_{SD} = -\partial Q_S / \partial V_{DS}$
25	C_{SG}	CSG	F	$C_{SG} = -\partial Q_S / \partial V_{GS}$
26	C_{SS}	CSS	F	$C_{SS} = C_{SG} + C_{SD} + C_{SB}$
27	C_{SB}	CSB	F	$C_{SB} = \partial Q_S / \partial V_{SB}$
28	C_{BD}	CBD	F	$C_{BD} = -\partial Q_B / \partial V_{DS}$
29	C_{BG}	CBG	F	$C_{BG} = -\partial Q_B / \partial V_{GS}$
30	C_{BS}	CBS	F	$C_{BS} = C_{BB} - C_{BD} - C_{BG}$
31	C_{BB}	CBB	F	$C_{BB} = -\partial Q_B / \partial V_{SB}$
32	W_E	WEFF	m	Effective channel region width for geometrical model
33	W_{ED}	WDEFF	m	Effective drift region width for geometrical model
34	u	U	-	Transistor gain: $u = g_m / g_{ds}$
35	R_{out}	ROUT	Ω	Small-signal output resistance: $R_{out} = 1 / g_{ds}$
36	V_{Early}	VEARLY	V	Equivalent Early voltage: $V_{Early} = \lvert I_{DS} \rvert / g_{ds}$
37	β_{eff}	BEFF	A/V^2	Gain factor: $\beta_{eff} = 2 \cdot \lvert I_{DS} \rvert / V_{inv_{ex0}}^2$
38	f_T	FUG	Hz	Unity gain frequency at actual bias: $f_T = \dfrac{g_m}{2 \cdot \pi \cdot (C_{GG} + C_{GSO} + C_{GDO})}$
39	$g_{m_{ch}}$	GMMOS	A/V	Transconductance of channel region
40	$\sqrt{S_{V_{Gth}}}$	SQRTSFW	$V/\sqrt{Hz}$	Input-referred RMS thermal noise voltage density: $\sqrt{S_{V_{Gth}}} = \sqrt{S_{D_{th}}} / g_{m_{ch}}$
41	$\sqrt{S_{V_{Gfl}}}$	SQRTSFF	$V/\sqrt{Hz}$	Input-referred RMS flicker noise voltage density at 1 kHz: $\sqrt{S_{V_{Gfl}}} = \sqrt{S_{D_{fl}}[1kHz]} / g_{m_{ch}}$
42	f_{knee}	FKNEE	Hz	Cross-over frequency above which thermal noise is dominant: $f_{knee} = 1Hz \cdot S_{D_{fl}}[1Hz] / S_{D_{th}}$

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A Auxiliary Functions

The hyp-function:

$$\text{hyp}\,[x;\epsilon] \quad = \quad \frac{1}{2}\cdot\left(x+\sqrt{x^2+4\cdot\epsilon^2}\right) \tag{A.1}$$

The hypm-function:

$$\text{hypm}\left[x,y;m\right] \quad = \quad \frac{x\cdot y}{\left(x^{2\cdot m}+y^{2\cdot m}\right)^{1/(2\cdot m)}} \tag{A.2}$$

