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MOS Model 20

Level 2002.2

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Abstract:

The model description for the compact high-voltage MOS transistor model called MOS Model 20 (MM20) is presented. MM20 has been developed for circuit simulation of power integrated circuits. MM20 describes the electrical behaviour of a high-voltage MOS device, like a Lateral Double-diffused MOS (LDMOS) device or an extended-drain MOSFET. The model combines the MOSFET operation of the channel region with that of the drift region of such high-voltage devices.

Since MM20 is a surface-potential–based model, it gives an accurate description in all operation regimes, ranging from sub-threshold to above threshold, in both the linear and saturation regime. MM20 includes strong inversion, depletion, and accumulation, in both the channel region and the drift region of the device. In addition to the previous MM20 model (level = 2001), in this MM20 model (level = 2002), quasi-saturation is included, an effect which is typical for high-voltage LDMOS devices.

The objective of this report is to present the full definition of MM20, level = 2002, 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 parameter extraction strategy is briefly explained.

Preface and History of Model and Documentation

Preface

The first version of the compact LDMOS model, MOS Model 20, became available in October 2003. 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 values of m and of λ_{D}, and the
implementation of the noise transfer function.
May 2005 : Introduction of MOS Model 20, level 2002.
This update includes velocity saturation in the drift region.
August 2006 : Update of MOS Model 20, level 2002.
This update includes some practical changes, like the clip-low
values of W and W_D, and improved avalanche-current modelling.
February 2007 : Update of MOS Model 20, level 2002.
Release of version 2002.2, which includes self-heating.
March 2008 : Update of MOS Model 20, level 2002.
Several minor bugs fixed in version 2002.2 of the model.

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 the 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}, and the clip-low values of m and of λ_{D}.
May 2005 : Introduction of MOS Model 20, level 2002.
This update includes velocity saturation in the drift region.
August 2006 : Update of documentation of MOS Model 20, level 2002.
This update takes into account the contribution of both the channel and
drift regions to the weak-avalanche current.
March 2007 : Update of documentation of MOS Model 20, level 2002.
This update includes a section on the parameter extraction strategy.
March 2008 : Update of documentation of MOS Model 20, level 2002.
This update details aspects new to version 2002.2 and corrects minor errors.
May 2009 : Update of documentation of MOS Model 20, level 2002.
This update corrects minor errors related to self-heating and temperature scaling.

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1 Introduction

MOS Model 20 (MM20) is a 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.

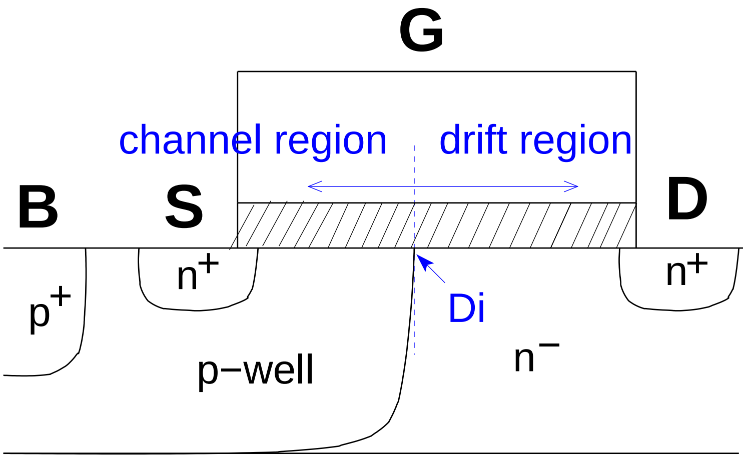


Figure 1: *The region under the thin gate oxide of an n-channel LDMOS device, described by MOS Model 20.*

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 (node 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 a function of the terminal voltages is obtained by the explicit expression as derived in Ref. [3] and used in MOS Model 11 (MM11), level 1101 [4]. Additionally, several important physical effects have been included in the model: mobility reduction, velocity saturation, drain-induced barrier lowering, static feedback, channel length modulation, and weak avalanche (or impact ionization).

MOS Model 20 only provides a model for the intrinsic MOSFET behaviour of the region under the thin gate oxide of a high-voltage MOS device, as well as the gate/source- and gate/drain overlap regions. Junction charges, junction leakage currents, interconnect capacitances, and parasitic bipolar transistors are not included; they should be covered by separate models. For instance, to describe the electrical behaviour due to the pn-junction between the backgate (B) and drain (D), an additional diode model for this pn-junction has to be added; see Figure 2. Furthermore, for very high-voltage MOS transistors with an additional thick field oxide, like in Figure 3, MOS Model

20 can be used in series with a separate model for the drift region under the thick field oxide. In the case of the SOI-LDMOS transistor in Figure 3, MOS Model 40 (MM40) [1] has been used to model the part of the drift region underneath the thick oxide. Finally, self-heating of the device, which may significantly affect the electrical behaviour, is now included via a thermal network as of version 2002.2 of the model.

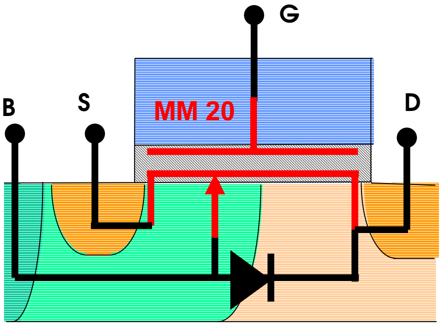


Figure 2: *Macro model for an LDMOS transistor.*

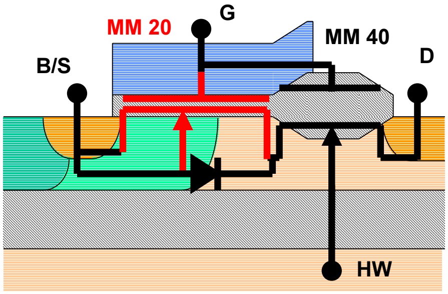


Figure 3: *Macro model for an SOI-LDMOS transistor with a thick field oxide.*

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 is 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 as the *miniset*. This miniset forms the input for the so-called *electrical model*, from which the actual parameters for an arbitrary temperature are obtained by applying the temperature scaling rules. These temperature scaling rules thus describe the dependencies of the actual parameters on the temperature of the device.

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

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

- **Clipping:** To prevent the scaling rules from generating actual parameters that are outside a physically realistic range or that create numerical difficulties (such as 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 ranges for the actual parameters are taken as those 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 those 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 can be separated into 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 can be separated into 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 the 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 4 the implemented equations are listed. Finally the operating point output 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 types of transistor 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 types of transistor 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 for both n- and p-type transistors.

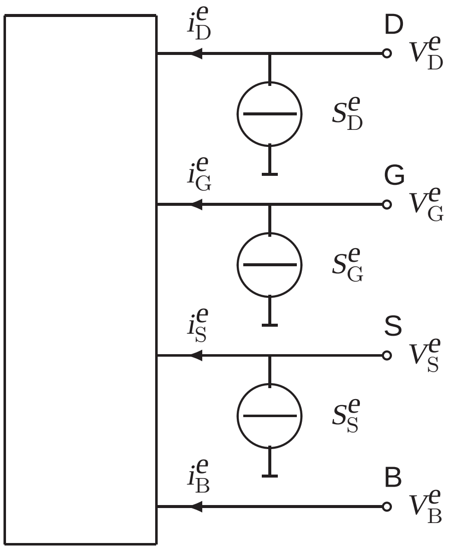
Since a DMOS transistor is an asymmetric device, no source-drain interchange is applied in case the external voltage mapped onto an n-channel transistor is negative. Thus, in MOS Model 20, the DC currents and charges are calculated by use of the externally applied voltages mapped onto an equivalent n-channel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

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

2.1 External Electrical Quantities and Variables

No.	**Variable**	**Program Name**	**Units**	**Description**
1	$V_{\mathrm{D}}^{\mathrm{e}}$	VDE	V	Potential applied to the drain node
2	$V_{\mathrm{G}}^{\mathrm{e}}$	VGE	V	Potential applied to the gate node
3	$V_{\mathrm{S}}^{\mathrm{e}}$	VSE	V	Potential applied to the source node
4	$V_{\mathrm{B}}^{\mathrm{e}}$	VBE	V	Potential applied to the bulk node
5	$I_{\mathrm{D}}^{\mathrm{e}}$	IDE	A	DC current into the drain
6	$I_{\mathrm{G}}^{\mathrm{e}}$	IGE	A	DC current into the gate
7	$I_{\mathrm{S}}^{\mathrm{e}}$	ISE	A	DC current into the source
8	$I_{\mathrm{B}}^{\mathrm{e}}$	IBE	A	DC current into the bulk
9	$Q_{\mathrm{D}}^{\mathrm{e}}$	QDE	C	Charge in the device attributed to the drain node
10	$Q_{\mathrm{G}}^{\mathrm{e}}$	QGE	C	Charge in the device attributed to the gate node
11	$Q_{\mathrm{S}}^{\mathrm{e}}$	QSE	C	Charge in the device attributed to the source node
12	$Q_{\mathrm{B}}^{\mathrm{e}}$	QBE	C	Charge in the device attributed to the bulk node
13	$S_{\mathrm{D}}^{\mathrm{e}}$	SDE	A^2s	Spectral density of the noise current into the drain
14	$S_{\mathrm{G}}^{\mathrm{e}}$	SGE	A^2s	Spectral density of the noise current into the gate
15	$S_{\mathrm{S}}^{\mathrm{e}}$	SSE	A^2s	Spectral density of the noise current into the source
16	$S_{\mathrm{DG}}^{\mathrm{e}}$	SDGE	A^2s	Cross spectral density between the drain and the gate noise currents
17	$S_{\mathrm{GS}}^{\mathrm{e}}$	SGSE	A^2s	Cross spectral density between the gate and the source noise currents
18	$S_{\mathrm{SD}}^{\mathrm{e}}$	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.



$$i_D^e = I_D^e + \frac{\mathrm{d}Q_D^e}{\mathrm{d}t}$$

$$i_G^e = I_G^e + \frac{\mathrm{d}Q_G^e}{\mathrm{d}t}$$

$$i_S^e = I_S^e + \frac{\mathrm{d}Q_S^e}{\mathrm{d}t}$$

$$i_B^e = I_B^e + \frac{\mathrm{d}Q_B^e}{\mathrm{d}t}$$

Figure 4: Definition of the external electrical quantities and variables.

2.2 Internal Electrical Quantities and Variables

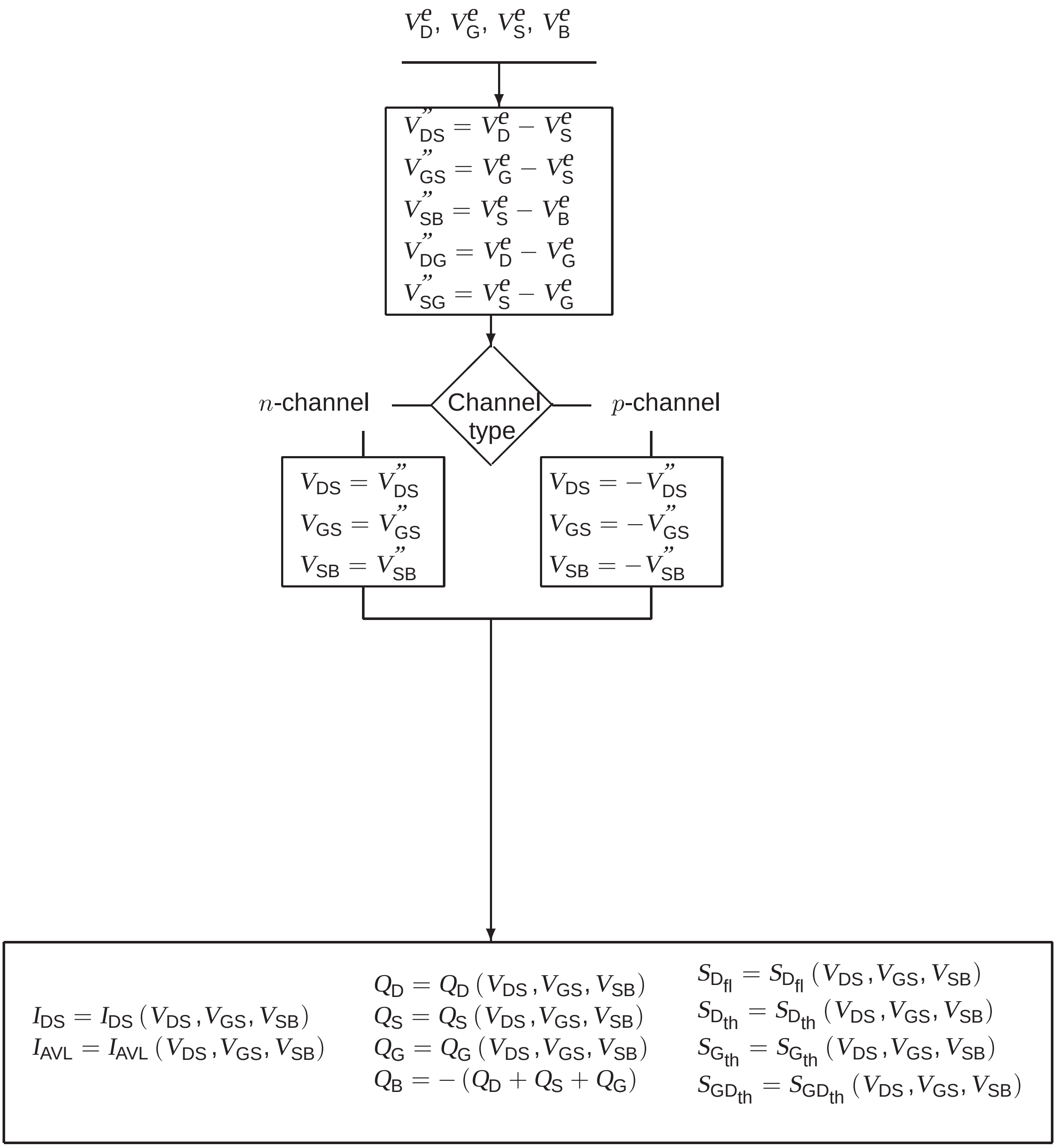
No.	Variable	Program Name	Units	Description
1	V_{DS}	VDS	V	Drain-to-source voltage applied to the equivalent n-MOST
2	V_{GS}	VGS	V	Gate-to-source voltage applied to the equivalent n-MOST
3	V_{SB}	VSB	V	Source-to-bulk voltage applied to the equivalent n-MOST
4	I_{DS}	IDS	A	DC current through the channel 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

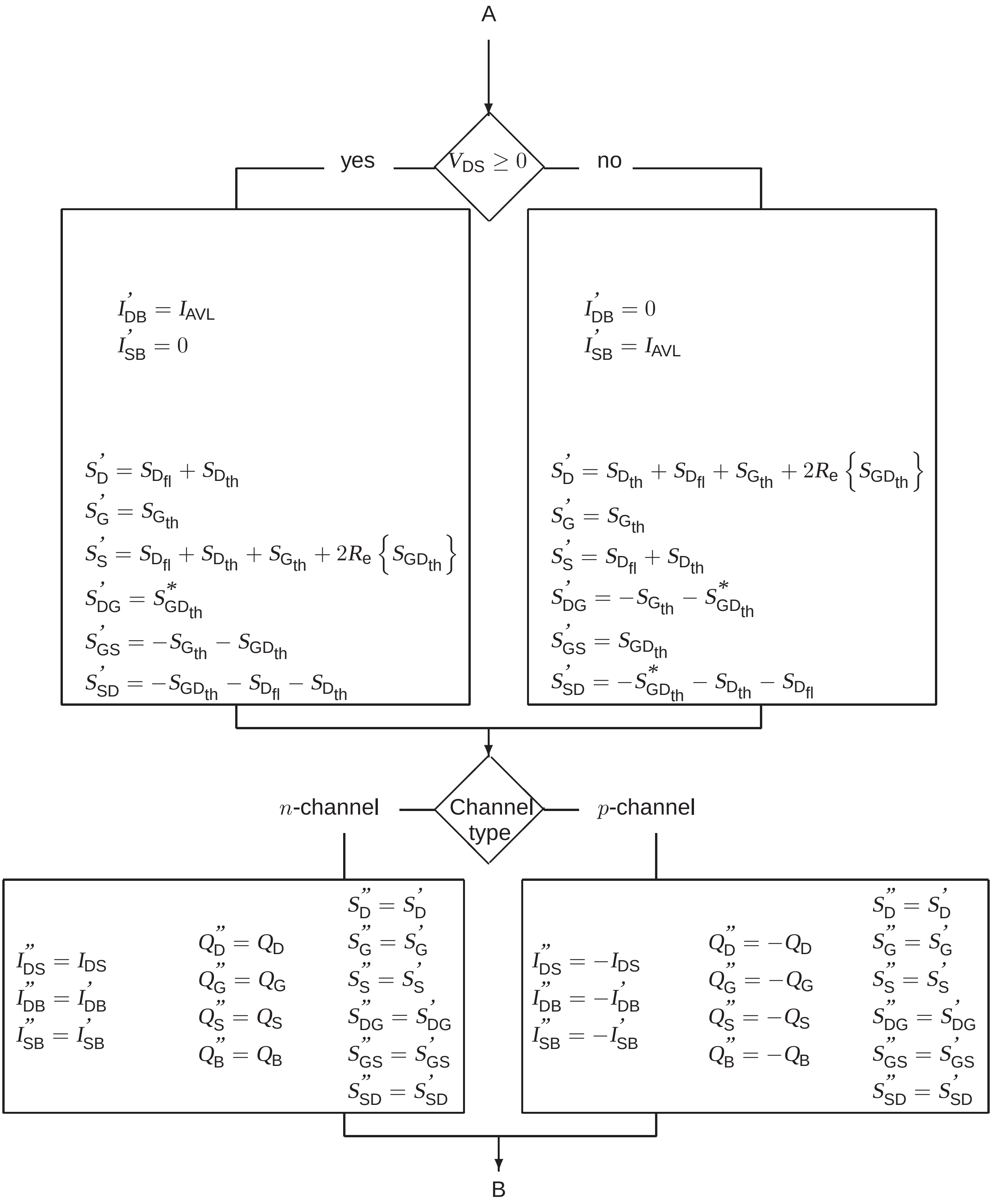
10	$S_{\mathrm{D_{th}}}$	SDTH	$\mathrm{A^2s}$	Spectral density of the thermal-noise current of the channel region
11	$S_{\mathrm{D_{fl}}}$	SDFL	$\mathrm{A^2s}$	Spectral density of the flicker-noise current of the channel region
12	$S_{\mathrm{G_{th}}}$	SGTH	$\mathrm{A^2s}$	Spectral density of the thermal-noise current induced in the gate
13	$S_{\mathrm{GD_{th}}}$	SGDTH	$\mathrm{A^2s}$	Cross spectral density of the thermal-noise current induced in the gate and the thermal-noise current of the channel

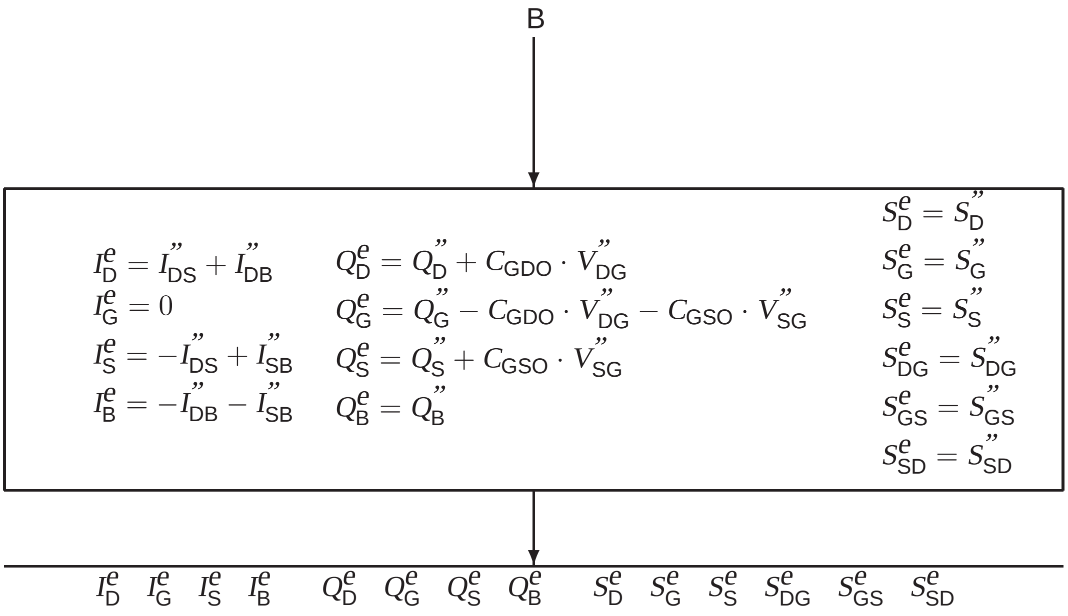
2.3 Embedding Procedure of MOS Model 20 in a Circuit Simulator

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^{e}_{D}, V^{e}_{G}, V^{e}_{S}, and V^{e}_{B} 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. The following steps are taken:

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.
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.
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.
4. Correct for a possible p-channel transformation.
5. Change from branch current to nodal currents, establishing the external current output quantities. Add the overlap charges to the nodal charges, thus forming the external charge output quantities.


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


A
$V_{\rm DS} \geq 0$
yes
no
$I'_{\rm DB} = I_{\rm AVL}$
$I'_{\rm SB} = 0$
$S'_{\rm D} = S_{\rm D_{fl}} + S_{\rm D_{th}}$
$S'_{\rm G} = S_{\rm G_{th}}$
$S'_{\rm S} = S_{\rm D_{fl}} + S_{\rm D_{th}} + S_{\rm G_{th}} + 2\Re\left\{S_{\rm GD_{th}}\right\}$
$S'_{\rm DG} = S^{*}_{\rm GD_{th}}$
$S'_{\rm GS} = -S_{\rm G_{th}} - S_{\rm GD_{th}}$
$S'_{\rm SD} = -S_{\rm GD_{th}} - S_{\rm D_{fl}} - S_{\rm D_{th}}$
$I'_{\rm DB} = 0$
$I'_{\rm SB} = I_{\rm AVL}$
$S'_{\rm D} = S_{\rm D_{th}} + S_{\rm D_{fl}} + S_{\rm G_{th}} + 2\Re\left\{S_{\rm GD_{th}}\right\}$
$S'_{\rm G} = S_{\rm G_{th}}$
$S'_{\rm S} = S_{\rm D_{fl}} + S_{\rm D_{th}}$
$S'_{\rm DG} = -S_{\rm G_{th}} - S^{*}_{\rm GD_{th}}$
$S'_{\rm GS} = S_{\rm GD_{th}}$
$S'_{\rm SD} = -S^{*}_{\rm GD_{th}} - S_{\rm D_{th}} - S_{\rm D_{fl}}$
n-channel
Channel type
p-channel
$I''_{\rm DS} = I_{\rm DS}$
$I''_{\rm DB} = I'_{\rm DB}$
$I''_{\rm SB} = I'_{\rm SB}$
$Q''_{\rm D} = Q_{\rm D}$
$Q''_{\rm G} = Q_{\rm G}$
$Q''_{\rm S} = Q_{\rm S}$
$Q''_{\rm B} = Q_{\rm B}$
$S''_{\rm D} = S'_{\rm D}$
$S''_{\rm G} = S'_{\rm G}$
$S''_{\rm S} = S'_{\rm S}$
$S''_{\rm DG} = S'_{\rm DG}$
$S''_{\rm GS} = S'_{\rm GS}$
$S''_{\rm SD} = S'_{\rm SD}$
$I''_{\rm DS} = -I_{\rm DS}$
$I''_{\rm DB} = -I'_{\rm DB}$
$I''_{\rm SB} = -I'_{\rm SB}$
$Q''_{\rm D} = -Q_{\rm D}$
$Q''_{\rm G} = -Q_{\rm G}$
$Q''_{\rm S} = -Q_{\rm S}$
$Q''_{\rm B} = -Q_{\rm B}$
$S''_{\rm D} = S'_{\rm D}$
$S''_{\rm G} = S'_{\rm G}$
$S''_{\rm S} = S'_{\rm S}$
$S''_{\rm DG} = S'_{\rm DG}$
$S''_{\rm GS} = S'_{\rm GS}$
$S''_{\rm SD} = S'_{\rm SD}$
B



$$I^e_{\mathrm{D}} = I^{”}_{\mathrm{DS}} + I^{”}_{\mathrm{DB}} \qquad Q^e_{\mathrm{D}} = Q^{”}_{\mathrm{D}} + C_{\mathrm{GDO}} \cdot V^{”}_{\mathrm{DG}}$$

$$I^e_{\mathrm{G}} = 0 \qquad Q^e_{\mathrm{G}} = Q^{”}_{\mathrm{G}} - C_{\mathrm{GDO}} \cdot V^{”}_{\mathrm{DG}} - C_{\mathrm{GSO}} \cdot V^{”}_{\mathrm{SG}}$$

$$I^e_{\mathrm{S}} = -I^{”}_{\mathrm{DS}} + I^{”}_{\mathrm{SB}} \qquad Q^e_{\mathrm{S}} = Q^{”}_{\mathrm{S}} + C_{\mathrm{GSO}} \cdot V^{”}_{\mathrm{SG}}$$

$$I^e_{\mathrm{B}} = -I^{”}_{\mathrm{DB}} - I^{”}_{\mathrm{SB}} \qquad Q^e_{\mathrm{B}} = Q^{”}_{\mathrm{B}}$$

$$S^e_{\mathrm{D}} = S^{”}_{\mathrm{D}}, \quad S^e_{\mathrm{G}} = S^{”}_{\mathrm{G}}, \quad S^e_{\mathrm{S}} = S^{”}_{\mathrm{S}}, \quad S^e_{\mathrm{DG}} = S^{”}_{\mathrm{DG}}, \quad S^e_{\mathrm{GS}} = S^{”}_{\mathrm{GS}}, \quad S^e_{\mathrm{SD}} = S^{”}_{\mathrm{SD}}$$

$$I^e_{\mathrm{D}} \; I^e_{\mathrm{G}} \; I^e_{\mathrm{S}} \; I^e_{\mathrm{B}} \quad Q^e_{\mathrm{D}} \; Q^e_{\mathrm{G}} \; Q^e_{\mathrm{S}} \; Q^e_{\mathrm{B}} \quad S^e_{\mathrm{D}} \; S^e_{\mathrm{G}} \; S^e_{\mathrm{S}} \; S^e_{\mathrm{DG}} \; S^e_{\mathrm{GS}} \; S^e_{\mathrm{SD}}$$

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 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 set to 2002
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	°C	Reference temperature
6	VFB	V_FB	V	Flat-band 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	Flat-band 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_0R	$\mathrm{V}^{1/2}$	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_0DR	$\mathrm{V}^{1/2}$	Body factor of the drift region of an infinitely wide transistor
13	SWKOD	$S_{W;k_\mathrm{0D}}$	-	Width scaling coefficient for k_0D
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 width, at reference temperature
19	ETABET	η_β	-	Temperature scaling exponent for β

No.	Parameter	Symbol	Units	Meaning
20	BETACCW	$\beta_{\mathrm{acc}W}$	AV^{-2}	Gain factor of a drift region of 1 μm width, at reference temperature
21	ETABETACC	$\eta_{\beta_{\mathrm{acc}}}$	-	Temperature scaling exponent for β_{acc}
22	RDW	$R_{\mathrm{D}W}$	Ω	On-resistance of a drift region of 1 μm width, 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 infinitely wide transistor, due to the vertical strong-inversion field in the 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	$\theta_{2\mathrm{R}}$	V$^{-1/2}$	Mobility reduction coefficient for $V_{\mathrm{SB}} > 0$ of an infinitely 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 the channel region of an infinitely 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 the transition from the linear to the saturation regime
34	THE3DR	$\theta_{3\mathrm{DR}}$	V^{-1}	Mobility reduction coefficient in the drift region of an infinitely wide transistor, due to velocity saturation
35	ETATHE3D	$\eta_{\theta_{3\mathrm{D}}}$	-	Temperature scaling exponent for $\theta_{3\mathrm{D}}$
36	SWTHE3D	$S_{W;\theta_{3\mathrm{D}}}$	-	Width scaling coefficient for $\theta_{3\mathrm{D}}$
37	MEXPD	m_{D}	-	Smoothing factor for the transition from the linear to the quasi-saturation regime
38	ALP	α	-	Factor for channel-length modulation
39	VP	V_{P}	V	Characteristic voltage of channel-length modulation
40	SDIBL	σ_{dibl}	V$^{-1/2}$	Factor for drain-induced barrier lowering
41	MSDIBL	$m_{\sigma_{\mathrm{dibl}}}$	-	Exponent for the drain-induced barrier lowering dependence on the backgate bias
42	MO	m_0	V	Parameter for the (short-channel) sub-threshold slope
43	SSF	σ_{sf}	V$^{-1/2}$	Factor for static feedback

No.	**Parameter**	**Symbol**	**Units**	**Meaning**
44	A1CHR	$a_{1ch\mathrm{R}}$	-	Factor of weak-avalanche current of an infinitely wide transistor, at reference temperature, accounting for the contribution of the channel region to the total avalanche current
45	STA1CH	$S_{T;a_{1ch}}$	K^{-1}	Temperature scaling coefficient for a_{1ch}
46	SWA1CH	$S_{W;a_{1ch}}$	-	Width scaling coefficient for a_{1ch}
47	A2CH	a_{2ch}	V	Exponent of channel-related weak-avalanche current
48	A3CH	a_{3ch}	-	Factor of the internal-drain–source voltage above which weak avalanche occurs
49	A1DRR	$a_{1dr\mathrm{R}}$	-	Factor of weak-avalanche current of an infinitely wide transistor, at reference temperature, accounting for the contribution of the drift region to the total avalanche current
50	STA1DR	$S_{T;a_{1dr}}$	K^{-1}	Temperature scaling coefficient for a_{1dr}
51	SWA1DR	$S_{W;a_{1dr}}$	-	Width scaling coefficient for a_{1dr}
52	A2DR	a_{2dr}	V	Exponent of drift-region weak-avalanche current
53	A3DR	a_{3dr}	-	Factor of the drain-source voltage above which weak avalanche occurs
54	COXW	$C_{\mathrm{ox}W}$	F	Oxide capacitance for an intrinsic channel region of 1 μm width
55	COXDW	$C_{\mathrm{oxD}W}$	F	Oxide capacitance for an intrinsic drift region of 1 μm width
56	CGDOW	$C_{\mathrm{GDO}W}$	F	Gate-to-drain overlap capacitance for a drift region of 1 μm width
57	CGSOW	$C_{\mathrm{GSO}W}$	F	Gate-to-source overlap capacitance for a channel region of 1 μm width
58	NT	N_T	J	Coefficient of thermal noise, at reference temperature
59	NFAW	$N_{f\mathrm{A}_W}$	$\mathrm{V}^{-1}\mathrm{m}^{-4}$	First coefficient of flicker noise for a channel region of 1 μm width
60	NFBW	$N_{f\mathrm{B}_W}$	$\mathrm{V}^{-1}\mathrm{m}^{-2}$	Second coefficient of flicker noise for a channel region of 1 μm width
61	NFCW	$N_{f\mathrm{C}_W}$	V^{-1}	Third coefficient of flicker noise for a channel region of 1 μm width
62	TOX	t_{ox}	m	Thickness of the oxide above the channel region
63	DTA	ΔT_{a}	K	Temperature offset to the ambient temperature
64	MULT	M	-	Number of devices in parallel

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

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

The parameter MULT for all level-2002 models is detailed here:

No.	**Parameter**	**Symbol**	**Units**	**Meaning**
67	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	-	2002	-	-
1	W	W	m	20×10^{-6}	1.0×10^{-9}	-
2	WVAR	ΔW	m	0	-	-
3	WD	$W_{\rm D}$	m	20×10^{-6}	1.0×10^{-9}	-
4	WDVAR	$\Delta W_{\rm D}$	m	0		-
5	TREF	$T_{\rm ref}$	°C	25	-273	-
6	VFB	$V_{\rm FB}$	V	-1.0	-	-
7	STVFB	$S_{T;V_{\rm FB}}$	$\rm VK^{-1}$	0	-	-
8	VFBD	$V_{\rm FBD}$	V	-0.1	-	-
9	STVFBD	$S_{T;V_{\rm FBD}}$	$\rm VK^{-1}$	0	-	-
10	KOR	$k_{0\rm R}$	$\rm V^{1/2}$	1.6	-	-
11	SWKO	$S_{W;k_0}$	-	0	-	-
12	KODR	$k_{0\rm DR}$	$\rm V^{1/2}$	1.0	-	-
13	SWKOD	$S_{W;k_{0\rm D}}$	-	0	-	-
14	PHIB	$\phi_{\rm B}$	V	0.86	-	-
15	STPHIB	$S_{T;\phi_{\rm B}}$	$\rm VK^{-1}$	-1.2×10^{-3}	-	-
16	PHIBD	$\phi_{\rm BD}$	V	0.78	-	-
17	STPHIBD	$S_{T;\phi_{\rm BD}}$	$\rm VK^{-1}$	-1.2×10^{-3}	-	-
18	BETW	β_W	$\rm AV^{-2}$	7.0×10^{-5}	-	-
19	ETABET	η_β	-	1.6	-	-
20	BETACCW	$\beta_{{\rm acc}W}$	$\rm AV^{-2}$	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	$\theta_{1\rm R}$	$\rm V^{-1}$	0.09	-	-
26	SWTHE1	$S_{W;\theta_1}$	-	0	-	-
27	THE1ACC	$\theta_{1\rm acc}$	$\rm V^{-1}$	0.02	-	-
28	THE2R	$\theta_{2\rm R}$	$\rm V^{-1/2}$	0.03	-	-
29	SWTHE2	$S_{W;\theta_2}$	-	0	-	-
30	THE3R	$\theta_{3\rm R}$	$\rm V^{-1}$	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	THE3DR	$\theta_{3\mathrm{DR}}$	V^{-1}	0.0	-	-
35	ETATHE3D	$\eta_{\theta_{3\mathrm{D}}}$	-	1.0	-	-
36	SWTHE3D	$S_{W;\theta_{3\mathrm{D}}}$	-	0	-	-
37	MEXPD	m_{D}	-	2.0	-	-
38	ALP	α	-	2.0×10^{-3}	-	-
39	VP	V_{P}	V	0.05	-	-
40	SDIBL	σ_{dibl}	$\mathrm{V}^{-1/2}$	1.0×10^{-3}	-	-
41	MSDIBL	$m_{\sigma_{\mathrm{dibl}}}$	-	3.0	-	-
42	MO	m_0	V	0.0	-	-
43	SSF	σ_{sf}	$\mathrm{V}^{-1/2}$	1.0×10^{-12}	-	-
44	A1CHR	$a_{1ch\mathrm{R}}$	-	1.5×10^{1}	-	-
45	STA1CH	$S_{T;a_{1ch}}$	K^{-1}	0	-	-
46	SWA1CH	$S_{W;a_{1ch}}$	-	0	-	-
47	A2CH	a_{2ch}	V	7.3×10^{1}	-	-
48	A3CH	a_{3ch}	-	0.8	-	-
49	A1DRR	$a_{1dr\mathrm{R}}$	-	1.5×10^{1}	-	-
50	STA1DR	$S_{T;a_{1dr}}$	K^{-1}	0	-	-
51	SWA1DR	$S_{W;a_{1dr}}$	-	0	-	-
52	A2DR	a_{2dr}	V	7.3×10^{1}	-	-
53	A3DR	a_{3dr}	-	0.8	-	-
54	COXW	$C_{\mathrm{ox}W}$	F	0.75×10^{-15}	-	-
55	COXDW	$C_{\mathrm{oxD}W}$	F	0.75×10^{-15}	-	-
56	CGDOW	$C_{\mathrm{GDO}W}$	F	0	-	-
57	CGSOW	$C_{\mathrm{GSO}W}$	F	0	-	-
58	NT	N_T	J	1.645×10^{-20}	-	-
59	NFAW	$N_{f\mathrm{A}_W}$	$\mathrm{V}^{-1}\mathrm{m}^{-4}$	1.4×10^{25}	-	-
60	NFBW	$N_{f\mathrm{B}_W}$	$\mathrm{V}^{-1}\mathrm{m}^{-2}$	2.0×10^{8}	-	-
61	NFCW	$N_{f\mathrm{C}_W}$	V^{-1}	0	-	-
62	TOX	t_{ox}	m	3.8×10^{-8}	-	-
63	DTA	ΔT_{a}	K	0	-	-
64	RTH	R_{TH}	°C/W	300.0	0	-
65	CTH	C_{TH}	J/°C	3.0×10^{-9}	0	-
66	ATH	A_{TH}	-	0.0	-	-
67	MULT	M	-	1.0	0	-

3.2.3 Geometry and Temperature Scaling

Effective temperature and dimensions:

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

$$T_{\mathrm{Kdev}} = T_0 + T_{\mathrm{a}} + \Delta T_{\mathrm{a}} + V_{\mathrm{dT}} \tag{3.2}$$

$$T_{\mathrm{Kref}} = T_0 + T_{\mathrm{ref}} \tag{3.3}$$

$$\Delta T = T_{\mathrm{Kdev}} - T_{\mathrm{Kref}} \tag{3.4}$$

$$W_{\mathrm{E}} = W + \Delta W \tag{3.5}$$

$$W_{\mathrm{ED}} = W_{\mathrm{D}} + \Delta W_{\mathrm{D}} \tag{3.6}$$

$$W_{\mathrm{EN}} = 1.0 \times 10^{-6}\ \text{(m)} \tag{3.7}$$

Actual parameters:

$$\phi_T = \frac{k_{\mathrm{B}} \cdot T_{\mathrm{Kdev}}}{q} \tag{3.8}$$

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

$$V_{\mathrm{FBD}T} = V_{\mathrm{FBD}} + \Delta T \cdot S_{T;V_{\mathrm{FBD}}} \tag{3.10}$$

$$k_0 = k_{0\mathrm{R}} \cdot \left(1 + \frac{W_{\mathrm{EN}}}{W_{\mathrm{E}}} \cdot S_{W;k_0}\right) \tag{3.11}$$

$$k_{0\mathrm{D}} = k_{0\mathrm{DR}} \cdot \left(1 + \frac{W_{\mathrm{EN}}}{W_{\mathrm{ED}}} \cdot S_{W;k_{0\mathrm{D}}}\right) \tag{3.12}$$

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

$$\phi_{\mathrm{BD}T} = \phi_{\mathrm{BD}} + \Delta T \cdot S_{T;\phi_{\mathrm{BD}}} \tag{3.14}$$

$$\beta_T = \beta_W \cdot \frac{W_{\mathrm{E}}}{W_{\mathrm{EN}}} \cdot \left(\frac{T_{\mathrm{Kref}}}{T_{\mathrm{Kdev}}}\right)^{\eta_\beta} \tag{3.15}$$

$$\beta_{\mathrm{acc}T} = \beta_{\mathrm{acc}W} \cdot \frac{W_{\mathrm{ED}}}{W_{\mathrm{EN}}} \cdot \left(\frac{T_{\mathrm{Kref}}}{T_{\mathrm{Kdev}}}\right)^{\eta_{\beta_{\mathrm{acc}}}} \tag{3.16}$$

$$R_{\mathrm{D}T} = R_{\mathrm{D}W} \cdot \frac{W_{\mathrm{EN}}}{W_{\mathrm{ED}}} \cdot \left(\frac{T_{\mathrm{Kdev}}}{T_{\mathrm{Kref}}}\right)^{\eta_{R_{\mathrm{D}}}} \tag{3.17}$$

$$\theta_1 = \theta_{1\mathrm{R}} \cdot \left(1 + \frac{W_{\mathrm{EN}}}{W_{\mathrm{E}}} \cdot S_{W;\theta_1}\right) \tag{3.18}$$

$$\theta_2 = \theta_{2\mathrm{R}} \cdot \left(1 + \frac{W_{\mathrm{EN}}}{W_{\mathrm{E}}} \cdot S_{W;\theta_2}\right) \tag{3.19}$$

$$\theta_{3T} = \theta_{3\mathrm{R}} \cdot \left(\frac{T_{\mathrm{Kref}}}{T_{\mathrm{Kdev}}}\right)^{\eta_{\theta_3}} \cdot \left(1 + \frac{W_{\mathrm{EN}}}{W_{\mathrm{E}}} \cdot S_{W;\theta_3}\right) \tag{3.20}$$

$$\theta_{3\mathrm{D}T} = \theta_{3\mathrm{DR}} \cdot \left(\frac{T_{\mathrm{Kref}}}{T_{\mathrm{Kdev}}}\right)^{\eta_{\theta_{3\mathrm{D}}}} \cdot \left(1 + \frac{W_{\mathrm{EN}}}{W_{\mathrm{ED}}} \cdot S_{W;\theta_{3\mathrm{D}}}\right) \tag{3.21}$$

$$a_{1chT} = a_{1ch\mathrm{R}} \cdot (1 + \Delta T \cdot S_{T;a_{1ch}}) \cdot \left(1 + \frac{W_{\mathrm{EN}}}{W_{\mathrm{E}}} \cdot S_{W;a_{1ch}}\right) \tag{3.22}$$

$$a_{1drT} = a_{1dr\mathrm{R}} \cdot (1 + \Delta T \cdot S_{T;a_{1dr}}) \cdot \left(1 + \frac{W_{\mathrm{EN}}}{W_{\mathrm{ED}}} \cdot S_{W;a_{1dr}}\right) \tag{3.23}$$

$$C_{\mathrm{ox}} = C_{\mathrm{ox}W} \cdot \frac{W_{\mathrm{E}}}{W_{\mathrm{EN}}} \tag{3.24}$$

$$C_{\mathrm{oxD}} = C_{\mathrm{oxD}W} \cdot \frac{W_{\mathrm{ED}}}{W_{\mathrm{EN}}} \tag{3.25}$$

$$C_{\mathrm{GDO}} = C_{\mathrm{GDO}W} \cdot \frac{W_{\mathrm{ED}}}{W_{\mathrm{EN}}} \tag{3.26}$$

$$C_{\mathrm{GSO}} = C_{\mathrm{GSO}W} \cdot \frac{W_{\mathrm{E}}}{W_{\mathrm{EN}}} \tag{3.27}$$

$$N_{T_T} = N_T \cdot \frac{T_{\mathrm{Kdev}}}{T_{\mathrm{Kref}}} \tag{3.28}$$

$$N_{f\mathrm{A}} = N_{f\mathrm{A}_W} \cdot \frac{W_{\mathrm{EN}}}{W_{\mathrm{E}}} \tag{3.29}$$

$$N_{f\mathrm{B}} = N_{f\mathrm{B}_W} \cdot \frac{W_{\mathrm{EN}}}{W_{\mathrm{E}}} \tag{3.30}$$

$$N_{f\mathrm{C}} = N_{f\mathrm{C}_W} \cdot \frac{W_{\mathrm{EN}}}{W_{\mathrm{E}}} \tag{3.31}$$

$$R_{\mathrm{TH}_T} = R_{\mathrm{TH}} \cdot \left(\frac{T_{\mathrm{Kamb}}}{T_{\mathrm{Kref}}}\right)^{A_{\mathrm{TH}}} \tag{3.32}$$

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 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 set to 2002
1	TREF	T_{ref}	°C	Reference temperature
2	VFB	V_{FB}	V	Flat-band voltage of the channel region, at reference temperature
3	STVFB	$S_{T;\mathrm{V_{FB}}}$	VK^{-1}	Temperature scaling coefficient for V_{FB}
4	VFBD	V_{FBD}	V	Flat-band voltage of the drift region, at reference temperature
5	STVFBD	$S_{T;\mathrm{V_{FBD}}}$	VK^{-1}	Temperature scaling coefficient for V_{FBD}
6	KO	k_0	$\mathrm{V}^{1/2}$	Body factor of the channel region
7	KOD	$k_{0\mathrm{D}}$	$\mathrm{V}^{1/2}$	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	$S_{T;\phi_{\mathrm{B}}}$	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	$S_{T;\phi_{\mathrm{BD}}}$	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	$\eta_{\beta_{\mathrm{acc}}}$	-	Temperature scaling exponent for β_{acc}
16	RD	R_{D}	Ω	On-resistance of the drift region, at reference temperature
17	ETARD	$\eta_{R_{\mathrm{D}}}$	-	Temperature scaling exponent for R_{D}
18	LAMD	λ_{D}	-	Quotient of the depletion layer thickness at $V_{\mathrm{SB}} > 0$ to the effective thickness of the drift region at $V_{\mathrm{SB}} = 0$ V
19	THE1	θ_1	V^{-1}	Mobility reduction coefficient in the channel region due to the vertical electrical field caused by strong inversion

No.	**Parameter**	**Symbol**	**Units**	**Meaning**
20	THE1ACC	$\theta_{1\mathrm{acc}}$	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 $V_{\mathrm{SB}} > 0$ 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 the transition from the linear to the saturation regime
25	THE3D	$\theta_{3\mathrm{D}}$	V^{-1}	Mobility reduction coefficient in the drift region due to the horizontal electrical field caused by velocity saturation
26	ETATHE3D	$\eta_{\theta_{3\mathrm{D}}}$	-	Temperature scaling exponent for $\theta_{3\mathrm{D}}$
27	MEXPD	m_{D}	-	Smoothing factor for the transition from the linear to the quasi-saturation regime
28	ALP	α	-	Factor for channel-length modulation
29	VP	V_{P}	V	Characteristic voltage of channel-length modulation
30	SDIBL	σ_{dibl}	V$^{-1/2}$	Factor for drain-induced barrier lowering
31	MSDIBL	$m_{\sigma_{\mathrm{dibl}}}$	-	Exponent for the drain-induced barrier lowering dependence on backgate bias
32	MO	m_0	V	Parameter for the (short-channel) sub-threshold slope
33	SSF	σ_{sf}	V$^{-1/2}$	Factor for static feedback
34	A1CH	a_{1ch}	-	Factor of weak-avalanche current, at reference temperature, accounting for the contribution of the channel region to the total avalanche current
35	STA1CH	$S_{T;a_{1ch}}$	K^{-1}	Temperature scaling coefficient for a_{1ch}
36	A2CH	a_{2ch}	V	Exponent of channel-related weak-avalanche current
37	A3CH	a_{3ch}	-	Factor of internal drain-source voltage above which weak avalanche occurs
38	A1DR	a_{1dr}	-	Factor of weak-avalanche current, at reference temperature, accounting for the contribution of the drift region to the total avalanche current
39	STA1DR	$S_{T;a_{1dr}}$	K^{-1}	Temperature scaling coefficient for a_{1dr}
40	A2DR	a_{2dr}	V	Exponent of drift-region weak-avalanche current
41	A3DR	a_{3dr}	-	Factor of drain-source voltage above which weak avalanche occurs
42	COX	C_{ox}	F	Oxide capacitance for the intrinsic channel region

No.	**Parameter**	**Symbol**	**Units**	**Meaning**
43	COXD	C_{oxD}	F	Oxide capacitance for the intrinsic drift region
44	CGDO	C_{GDO}	F	Gate-to-drain overlap capacitance
45	CGSO	C_{GSO}	F	Gate-to-source overlap capacitance
46	NT	N_T	J	Coefficient of thermal noise, at reference temperature
47	NFA	$N_{f\mathrm{A}}$	$\mathrm{V}^{-1}\mathrm{m}^{-4}$	First coefficient of flicker noise
48	NFB	$N_{f\mathrm{B}}$	$\mathrm{V}^{-1}\mathrm{m}^{-2}$	Second coefficient of flicker noise
49	NFC	$N_{f\mathrm{C}}$	V^{-1}	Third coefficient of flicker noise
50	TOX	t_{ox}	m	Thickness of the oxide above the channel region
51	DTA	ΔT_{a}	K	Temperature offset to the ambient temperature
52	RTH	R_{TH}	°C/W	Thermal resistance
53	CTH	C_{TH}	J/°C	Thermal capacitance
54	ATH	A_{TH}	-	Thermal coefficient of the thermal resistance
55	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	-	2002	-	-
1	TREF	$T_{\rm ref}$	°C	25	-273	-
2	VFB	$V_{\rm FB}$	V	-1.0	-	-
3	STVFB	$S_{T;\rm V_{FB}}$	$\rm VK^{-1}$	0	-	-
4	VFBD	$V_{\rm FBD}$	V	-0.1	-	-
5	STVFBD	$S_{T;\rm V_{FBD}}$	$\rm VK^{-1}$	0	-	-
6	KO	k_0	$\rm V^{1/2}$	1.6	1.0×10^{-12}	-
7	KOD	$k_{0\rm D}$	$\rm V^{1/2}$	1.0	1.0×10^{-12}	-
8	PHIB	$\phi_{\rm B}$	V	0.86	1.0×10^{-12}	-
9	STPHIB	$S_{T;\phi_{\rm B}}$	$\rm VK^{-1}$	-1.2×10^{-3}	-	-
10	PHIBD	$\phi_{\rm BD}$	V	0.78	1.0×10^{-12}	-
11	STPHIBD	$S_{T;\phi_{\rm BD}}$	$\rm VK^{-1}$	-1.2×10^{-3}	-	-
12	BET	β	$\rm AV^{-2}$	1.4×10^{-3}	1.0×10^{-12}	-
13	ETABET	η_β	-	1.6	-	-
14	BETACC	$\beta_{\rm acc}$	$\rm AV^{-2}$	1.4×10^{-3}	1.0×10^{-12}	-
15	ETABETACC	$\eta_{\beta_{\rm acc}}$	-	1.5	-	-
16	RD	$R_{\rm D}$	Ω	2.0×10^{2}	1.0×10^{-12}	-
17	ETARD	$\eta_{R_{\rm D}}$	-	1.5	-	-
18	LAMD	$\lambda_{\rm D}$	-	0.2	1.0×10^{-12}	-
19	THE1	θ_1	$\rm V^{-1}$	0.09	0	-
20	THE1ACC	$\theta_{1\rm acc}$	$\rm V^{-1}$	0.02	0	-
21	THE2	θ_2	$\rm V^{-1/2}$	0.03	0	-
22	THE3	θ_3	$\rm V^{-1}$	0.4	0	-
23	ETATHE3	η_{θ_3}	-	1.0	-	-
24	MEXP	m	-	2.0	0.05	-
25	THE3D	$\theta_{3\rm D}$	$\rm V^{-1}$	0.0	0	-
26	ETATHE3D	$\eta_{\theta_{3\rm D}}$	-	1.0	-	-
27	MEXPD	$m_{\rm D}$	-	2.0	0.05	-
28	ALP	α	-	2.0×10^{-3}	0	-
29	VP	$V_{\rm P}$	V	0.05	1.0×10^{-12}	-
30	SDIBL	$\sigma_{\rm dibl}$	$\rm V^{-1/2}$	1.0×10^{-3}	0	-
31	MSDIBL	$m_{\sigma_{\rm dibl}}$	-	3.0	0	-
32	MO	m_0	V	0.0	0	0.5
33	SSF	$\sigma_{\rm sf}$	$\rm V^{-1/2}$	1.0×10^{-12}	1.0×10^{-12}	-

No.	**Parameter**	**Symbol**	**Units**	**Default**	**Clip low**	**Clip high**
34	A1CH	a_{1ch}	-	1.5×10^1	0	-
35	STA1CH	$S_{T;a_{1ch}}$	K^{-1}	0	-	-
36	A2CH	a_{2ch}	V	7.3×10^1	1.0×10^{-12}	-
37	A3CH	a_{3ch}	-	0.8	0	-
38	A1DR	a_{1dr}	-	1.5×10^1	0	-
39	STA1DR	$S_{T;a_{1dr}}$	K^{-1}	0	-	-
40	A2DR	a_{2dr}	V	7.3×10^1	1.0×10^{-12}	-
41	A3DR	a_{3dr}	-	0.8	0	-
42	COX	C_{ox}	F	15×10^{-15}	0	-
43	COXD	C_{oxD}	F	15×10^{-15}	0	-
44	CGDO	C_{GDO}	F	0	0	-
45	CGSO	C_{GSO}	F	0	0	-
46	NT	N_T	J	1.645×10^{-20}	0	-
47	NFA	$N_{f\mathrm{A}}$	V^{-1}m^{-4}	7.0×10^{23}	0	-
48	NFB	$N_{f\mathrm{B}}$	V^{-1}m^{-2}	1.0×10^7	0	-
49	NFC	$N_{f\mathrm{C}}$	V^{-1}	0	0	-
50	TOX	t_{ox}	m	3.8×10^{-8}	1.0×10^{-12}	-
51	DTA	ΔT_{a}	K	0	-	-
52	RTH	R_{TH}	°C/W	300.0	0	-
53	CTH	C_{TH}	J/°C	3.0×10^{-9}	0	-
54	ATH	A_{TH}	-	0.0	-	-
55	MULT	M	-	1.0	0	-

3.3.3 Temperature Scaling

Effective temperature:

$$T_{\mathrm{Kamb}} = T_0 + T_{\mathrm{a}} + \Delta T_{\mathrm{a}} \tag{3.33}$$

$$T_{\mathrm{Kdev}} = T_0 + T_{\mathrm{a}} + \Delta T_{\mathrm{a}} + V_{\mathrm{dT}} \tag{3.34}$$

$$T_{\mathrm{Kref}} = T_0 + T_{\mathrm{ref}} \tag{3.35}$$

$$\Delta T = T_{\mathrm{Kdev}} - T_{\mathrm{Kref}} \tag{3.36}$$

Actual parameters:

$$\phi_T = \frac{k_{\mathrm{B}} \cdot T_{\mathrm{Kdev}}}{q} \tag{3.37}$$

$$V_{\mathrm{FB}T} = V_{\mathrm{FB}} + \Delta T \cdot S_{T;V_{\mathrm{FB}}} \tag{3.38}$$

$$V_{\mathrm{FBD}T} = V_{\mathrm{FBD}} + \Delta T \cdot S_{T;V_{\mathrm{FBD}}} \tag{3.39}$$

$$\phi_{\mathrm{B}T} = \phi_{\mathrm{B}} + \Delta T \cdot S_{T;\phi_{\mathrm{B}}} \tag{3.40}$$

$$\phi_{\mathrm{BD}T} = \phi_{\mathrm{BD}} + \Delta T \cdot S_{T;\phi_{\mathrm{BD}}} \tag{3.41}$$

$$\beta_T = \beta \cdot \left(\frac{T_{\mathrm{Kref}}}{T_{\mathrm{Kdev}}} \right)^{\eta_\beta} \tag{3.42}$$

$$\beta_{\mathrm{acc}T} = \beta_{\mathrm{acc}} \cdot \left(\frac{T_{\mathrm{Kref}}}{T_{\mathrm{Kdev}}} \right)^{\eta_{\beta\mathrm{acc}}} \tag{3.43}$$

$$R_{\mathrm{D}T} = R_{\mathrm{D}} \cdot \left(\frac{T_{\mathrm{Kdev}}}{T_{\mathrm{Kref}}} \right)^{\eta_{R_{\mathrm{D}}}} \tag{3.44}$$

$$\theta_{3T} = \theta_3 \cdot \left(\frac{T_{\mathrm{Kref}}}{T_{\mathrm{Kdev}}} \right)^{\eta_{\theta_3}} \tag{3.45}$$

$$\theta_{3\mathrm{D}T} = \theta_{3\mathrm{D}} \cdot \left(\frac{T_{\mathrm{Kref}}}{T_{\mathrm{Kdev}}} \right)^{\eta_{\theta_{3\mathrm{D}}}} \tag{3.46}$$

$$a_{1chT} = a_{1ch} \cdot (1 + \Delta T \cdot S_{T;a_{1ch}}) \tag{3.47}$$

$$a_{1drT} = a_{1dr} \cdot (1 + \Delta T \cdot S_{T;a_{1dr}}) \tag{3.48}$$

$$N_{T_T} = N_T \cdot \frac{T_{\mathrm{Kdev}}}{T_{\mathrm{Kref}}} \tag{3.49}$$

$$R_{\mathrm{TH}_T} = R_{\mathrm{TH}} \cdot \left(\frac{T_{\mathrm{Kamb}}}{T_{\mathrm{Kref}}} \right)^{A_{\mathrm{TH}}} \tag{3.50}$$

3.4 Postprocessing

3.4.1 MULT Scaling

Since equal, parallel-circuited transistors are frequently employed in circuit design, 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

$$\beta_T \rightarrow \beta_T \cdot M \tag{3.51}$$

$$\beta_{\mathrm{acc}T} \rightarrow \beta_{\mathrm{acc}T} \cdot M \tag{3.52}$$

$$R_{\mathrm{D}T} \rightarrow R_{\mathrm{D}T} \cdot \frac{1}{M} \tag{3.53}$$

$$C_{\mathrm{ox}} \rightarrow C_{\mathrm{ox}} \cdot M \tag{3.54}$$

$$C_{\mathrm{oxD}} \rightarrow C_{\mathrm{oxD}} \cdot M \tag{3.55}$$

$$C_{\mathrm{GDO}} \rightarrow C_{\mathrm{GDO}} \cdot M \tag{3.56}$$

$$C_{\mathrm{GSO}} \rightarrow C_{\mathrm{GSO}} \cdot M \tag{3.57}$$

$$N_{f\mathrm{A}} \rightarrow N_{f\mathrm{A}} \cdot \frac{1}{M} \tag{3.58}$$

$$N_{f\mathrm{B}} \rightarrow N_{f\mathrm{B}} \cdot \frac{1}{M} \tag{3.59}$$

$$N_{f\mathrm{C}} \rightarrow N_{f\mathrm{C}} \cdot \frac{1}{M} \tag{3.60}$$

$$R_{\mathrm{TH}} \rightarrow R_{\mathrm{TH}} \cdot \frac{1}{M} \tag{3.61}$$

$$C_{\mathrm{TH}} \rightarrow C_{\mathrm{TH}} \cdot \frac{1}{M} \tag{3.62}$$

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 those for the electrical model parameters, as listed in Section 3.3.2.

4 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.

4.1 Internal Parameters

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

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

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

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

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

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

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

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

$$\epsilon_8 = 3 \cdot 10^{-2}$$

$$V_1 = 1$$

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

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

$$Acc = \frac{1}{1 + k_0 \left/ \sqrt{2 \cdot \phi_T}\right.}$$

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

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

4.2 Current Equations

Effective potentials:

$$V_{\mathrm{GB_{t0}}} = V_{\mathrm{GS}} + V_{\mathrm{SB}} - V_{\mathrm{FB}T} \tag{4.1}$$

$$V_{\mathrm{SB_t}} = \text{hyp}\left[V_{\mathrm{SB}} + 0.9 \cdot \phi_{\mathrm{B}T}; \epsilon_2\right] + 0.1 \cdot \phi_{\mathrm{B}T} \tag{4.2}$$

$$V_{\mathrm{DS1}} = \begin{cases} V_{\mathrm{DS}}, & V_{\mathrm{DS}} \geq 0 \\ \text{hypm}\left[V_{\mathrm{DS}}, V_{\mathrm{SB_t}}; m\right], & V_{\mathrm{DS}} < 0 \end{cases} \tag{4.3}$$

$$V_{\mathrm{GS_t}} = V_{\mathrm{GS}} - V_{\mathrm{FBD}T} \tag{4.4}$$

$$V_{\mathrm{GD_t}} = V_{\mathrm{GS_t}} - V_{\mathrm{DS1}} \tag{4.5}$$

Channel-region quantities:

$$V_{\mathrm{inv0}} = \text{hyp}\left[V_{\mathrm{GB_{t0}}} - V_{\mathrm{SB_t}} - k_0 \cdot \sqrt{V_{\mathrm{SB_t}}}; \epsilon_2\right] \tag{4.6}$$

$$\delta = \frac{k_0}{2 \cdot \sqrt{V_1 + V_{\mathrm{SB_t}}}} \tag{4.7}$$

$$\xi = 1 + \delta \tag{4.8}$$

$$V_{\mathrm{DiSsat_0}} = \frac{V_{\mathrm{inv0}}}{\xi} \tag{4.9}$$

$$V_{\mathrm{DiSsat}} = \frac{2 \cdot V_{\mathrm{DiSsat_0}}}{1 + \sqrt{1 + 2 \cdot \theta_{3T} \cdot V_{\mathrm{DiSsat_0}}}} \tag{4.10}$$

$$V_{\mathrm{SB_{t0}}} = \text{hyp}\left[0.9 \cdot \phi_{\mathrm{B}T}; \epsilon_2\right] + 0.1 \cdot \phi_{\mathrm{B}T} \tag{4.11}$$

$$V_{\mathrm{dep0}} = k_0 \cdot \sqrt{V_{\mathrm{SB_t}}} \tag{4.12}$$

$$V_{\mathrm{dep0_0}} = k_0 \cdot \sqrt{V_{\mathrm{SB_{t0}}}} \tag{4.13}$$

$$F_{\mathrm{mob}} = 1 + \theta_1 \cdot V_{\mathrm{inv0}} + \theta_2 \cdot \frac{V_{\mathrm{dep0}} - V_{\mathrm{dep0_0}}}{k_0} \tag{4.14}$$

Drift-region quantities:

$$f_{\mathrm{lin}} = \text{hyp}\left[1 - \lambda_{\mathrm{D}} \cdot \frac{\sqrt{\phi_0 + \text{hyp}\left[V_{\mathrm{SB}}; \epsilon_1\right]} - \sqrt{\phi_0}}{\sqrt{\phi_0}}; \epsilon_2\right] \tag{4.15}$$

$$V_{\mathrm{oxp}} = \frac{f_{\mathrm{lin}}}{\beta_{\mathrm{acc}T} \cdot R_{\mathrm{D}T}} \tag{4.16}$$

$$F_{\mathrm{mobacc}} = 1 + \tfrac{1}{2} \cdot \theta_{\mathrm{1acc}} \cdot \left(\text{hyp}\left[V_{\mathrm{GS_t}}; \epsilon_2\right] + \text{hyp}\left[V_{\mathrm{GD_t}}; \epsilon_2\right]\right) \tag{4.17}$$

Numerical iteration procedure for the internal drain voltage:

$$V_{\mathrm{DiS}_{\mathrm{eff}}} = \text{hypm}\left[V_{\mathrm{DiS}}, V_{\mathrm{DiSsat}}; m\right] \tag{4.18}$$

$$\mathcal{I}_{\mathrm{ch}}\left[V_{\mathrm{DiS}}, V_{\mathrm{DiSsat}}, V_{\mathrm{inv0}}, \xi, F_{\mathrm{mob}}\right] = \begin{cases} \beta_T \cdot \dfrac{\left(V_{\mathrm{inv0}} - \frac{1}{2} \cdot \xi \cdot V_{\mathrm{DiS}}\right) \cdot V_{\mathrm{DiS}}}{F_{\mathrm{mob}} \cdot \left(1 - \theta_3 \cdot V_{\mathrm{DiS}}\right)} & \\ \quad + G_{\mathrm{min}} \cdot k_0^2 \cdot V_{\mathrm{DiS}}, & V_{\mathrm{DiS}} < 0 \\ \beta_T \cdot \dfrac{\left(V_{\mathrm{inv0}} - \frac{1}{2} \cdot \xi \cdot V_{\mathrm{DiS}_{\mathrm{eff}}}\right) \cdot V_{\mathrm{DiS}_{\mathrm{eff}}}}{F_{\mathrm{mob}} \cdot \left(1 + \theta_3 \cdot V_{\mathrm{DiS}_{\mathrm{eff}}}\right)} & \\ \quad + G_{\mathrm{min}} \cdot k_0^2 \cdot V_{\mathrm{DiS}}, & V_{\mathrm{DiS}} \geq 0 \end{cases} \tag{4.19}$$

$$V_{\mathrm{DiB}_{\mathrm{t}}} = \text{hyp}\left[V_{\mathrm{SB}} + V_{\mathrm{DiS}} + 0.9 \cdot \phi_{\mathrm{BD}T}; \epsilon_2\right] + 0.1 \cdot \phi_{\mathrm{BD}T} \tag{4.20}$$

$$V_{\mathrm{GDi}_{\mathrm{t}}\,\mathrm{eff}} = \begin{cases} V_{\mathrm{GDi}_{\mathrm{t}}}, & V_{\mathrm{GDi}_{\mathrm{t}}} \geq 0 \\ \text{hypm}\left[V_{\mathrm{GDi}_{\mathrm{t}}}, V_{\mathrm{DiB}_{\mathrm{t}}} + k_{0\mathrm{D}} \cdot \sqrt{V_{\mathrm{DiB}_{\mathrm{t}}}}; 8\right], & V_{\mathrm{GDi}_{\mathrm{t}}} < 0 \end{cases} \tag{4.21}$$

$$\mathcal{V}_q^{\mathrm{dr}}\left[V_{\mathrm{GDi}_{\mathrm{t}}}\right] = V_{\mathrm{oxp}} + \begin{cases} V_{\mathrm{GDi}_{\mathrm{t}}}, & V_{\mathrm{GDi}_{\mathrm{t}}} \geq 0 \\ -k_{0\mathrm{D}} \cdot \left(-\dfrac{k_{0\mathrm{D}}}{2} + \sqrt{\left(\dfrac{k_{0\mathrm{D}}}{2}\right)^2 - V_{\mathrm{GDi}_{\mathrm{t}}}}\right), & V_{\mathrm{GDi}_{\mathrm{t}}} < 0 \end{cases} \tag{4.22}$$

$$V_{q\ \mathrm{eff}}^{\mathrm{dr}} = \text{hyp}\left[\mathcal{V}_q^{\mathrm{dr}}\left[V_{\mathrm{GDi}_{\mathrm{t}}\,\mathrm{eff}}\right]; \epsilon_2\right] \tag{4.23}$$

$$V_{\mathrm{DDisat}} = \frac{2 \cdot V_{q\ \mathrm{eff}}^{\mathrm{dr}}}{1 + \sqrt{1 + 2 \cdot \theta_{3\mathrm{D}T} \cdot V_{q\ \mathrm{eff}}^{\mathrm{dr}}}} \tag{4.24}$$

$$V_{\mathrm{DDi}} = V_{\mathrm{DS1}} - V_{\mathrm{DiS}} \tag{4.25}$$

$$V_{\mathrm{DDi}_{\mathrm{eff}}} = \text{hypm}\left[V_{\mathrm{DDi}}, V_{\mathrm{DDisat}}; m_{\mathrm{D}}\right] \tag{4.26}$$

$$\mathcal{I}_{\mathrm{dr}}\left[V_{\mathrm{DiS}}, V_{\mathrm{GS}_{\mathrm{t}}}, V_{\mathrm{DS1}}, V_{\mathrm{SB}}, F_{\mathrm{mobacc}}\right] = \begin{cases} \beta_{\mathrm{acc}T} \cdot \dfrac{\left(V_{q\ \mathrm{eff}}^{\mathrm{dr}} - \frac{1}{2} \cdot V_{\mathrm{DDi}_{\mathrm{eff}}}\right) \cdot V_{\mathrm{DDi}_{\mathrm{eff}}}}{F_{\mathrm{mobacc}} \cdot \left(1 + \theta_{3\mathrm{DT}} \cdot V_{\mathrm{DDi}_{\mathrm{eff}}}\right)} & \\ \quad + G_{\mathrm{min}} \cdot k_{0\mathrm{D}}^2 \cdot V_{\mathrm{DDi}}, & V_{\mathrm{DDi}} \geq 0 \\ \beta_{\mathrm{acc}T} \cdot \dfrac{\left(V_{q\ \mathrm{eff}}^{\mathrm{dr}} - \frac{1}{2} \cdot V_{\mathrm{DDi}}\right) \cdot V_{\mathrm{DDi}}}{F_{\mathrm{mobacc}} \cdot \left(1 - \theta_{3\mathrm{DT}} \cdot V_{\mathrm{DDi}}\right)} & \\ \quad + G_{\mathrm{min}} \cdot k_{0\mathrm{D}}^2 \cdot V_{\mathrm{DDi}}, & V_{\mathrm{DDi}} < 0 \end{cases} \tag{4.27}$$

Newton-Raphson/bisection iteration procedure:

```
$H_0 = \mathcal{I}_{\mathrm{ch}}\left[0, V_{\mathrm{DiSsat}}, V_{\mathrm{inv0}}, \xi, F_{\mathrm{mob}}\right] - \mathcal{I}_{\mathrm{dr}}\left[0, V_{\mathrm{GS_t}}, V_{\mathrm{DS1}}, V_{\mathrm{SB}}, F_{\mathrm{mobacc}}\right]$
$H_1 = \mathcal{I}_{\mathrm{ch}}\left[V_{\mathrm{DS1}}, V_{\mathrm{DiSsat}}, V_{\mathrm{inv0}}, \xi, F_{\mathrm{mob}}\right] - \mathcal{I}_{\mathrm{dr}}\left[V_{\mathrm{DS1}}, V_{\mathrm{GS_t}}, V_{\mathrm{DS1}}, V_{\mathrm{SB}}, F_{\mathrm{mobacc}}\right]$
if $H_0 = 0$ then $V_{\mathrm{DiS}} = 0$
if $H_1 = 0$ then $V_{\mathrm{DiS}} = V_{\mathrm{DS1}}$
if $H_0 < 0$ then $\{V_{\mathrm{DiSL}} = 0; V_{\mathrm{DiSH}} = V_{\mathrm{DS1}}\}$
          else $\{V_{\mathrm{DiSL}} = V_{\mathrm{DS1}}; V_{\mathrm{DiSH}} = 0\}$
$V_{\mathrm{DiS}} = \frac{1}{2} \cdot (V_{\mathrm{DiSL}} + V_{\mathrm{DiSH}})$
$H = \mathcal{I}_{\mathrm{ch}}\left[V_{\mathrm{DiS}}, V_{\mathrm{DiSsat}}, V_{\mathrm{inv0}}, \xi, F_{\mathrm{mob}}\right] - \mathcal{I}_{\mathrm{dr}}\left[V_{\mathrm{DiS}}, V_{\mathrm{GS_t}}, V_{\mathrm{DS1}}, V_{\mathrm{SB}}, F_{\mathrm{mobacc}}\right]$
$\Delta H = \frac{\partial \mathcal{I}_{\mathrm{ch}}}{\partial V_{\mathrm{DiS}}} - \frac{\partial \mathcal{I}_{\mathrm{dr}}}{\partial V_{\mathrm{DiS}}}$
$\Delta V_{\mathrm{DiS0}} = |V_{\mathrm{DiSH}} - V_{\mathrm{DiSL}}|$
$\Delta V_{\mathrm{DiS}} = \Delta V_{\mathrm{DiS0}}$
error $= |\Delta V_{\mathrm{DiS}}|$
for $\left(i = 0; i < 100 \text{ and } \text{error} > 1 \times 10^{-12}; i = i + 1\right)$
do begin
      if{ $((V_{\mathrm{DiS}} - V_{\mathrm{DiSH}}) \cdot \Delta H - H) \cdot ((V_{\mathrm{DiS}} - V_{\mathrm{DiSL}}) \cdot \Delta H - H) > 0$
          or $|2 \cdot H| > |\Delta V_{\mathrm{DiS0}} \cdot \Delta H|$}
      then
      {
            $\Delta V_{\mathrm{DiS0}} = \Delta V_{\mathrm{DiS}}$
            $\Delta V_{\mathrm{DiS}} = \frac{1}{2} \cdot (V_{\mathrm{DiSH}} - V_{\mathrm{DiSL}})$
            $V_{\mathrm{DiS}} = V_{\mathrm{DiSL}} + \Delta V_{\mathrm{DiS}}$
      }
      else
      {
            $\Delta V_{\mathrm{DiS0}} = \Delta V_{\mathrm{DiS}}$
            $\Delta V_{\mathrm{DiS}} = \frac{H}{\Delta H}$
            $V_{\mathrm{DiS}} = V_{\mathrm{DiS}} - \Delta V_{\mathrm{DiS}}$
      }
      error $= |\Delta V_{\mathrm{DiS}}|$
      $H = \mathcal{I}_{\mathrm{ch}}\left[V_{\mathrm{DiS}}, V_{\mathrm{DiSsat}}, V_{\mathrm{inv0}}, \xi, F_{\mathrm{mob}}\right] - \mathcal{I}_{\mathrm{dr}}\left[V_{\mathrm{DiS}}, V_{\mathrm{GS_t}}, V_{\mathrm{DS1}}, V_{\mathrm{SB}}, F_{\mathrm{mobacc}}\right]$
      $\Delta H = \frac{\partial \mathcal{I}_{\mathrm{ch}}}{\partial V_{\mathrm{DiS}}} - \frac{\partial \mathcal{I}_{\mathrm{dr}}}{\partial V_{\mathrm{DiS}}}$
      if $H < 0$ then $V_{\mathrm{DiSL}} = V_{\mathrm{DiS}}$
                else $V_{\mathrm{DiSH}} = V_{\mathrm{DiS}}$
end
```

(4.28)

$$V_{\mathrm{DDi}} = V_{\mathrm{DS1}} - V_{\mathrm{DiS}} \tag{4.29}$$

Drain-induced barrier lowering and static feedback:

$$V_{\mathrm{GB_{eff0}}} = \text{hyp}\left[V_{\mathrm{GB_{t0}}}; \epsilon_1\right] \tag{4.30}$$

$$\psi_{\mathrm{sat_0}} = \left(\frac{V_{\mathrm{GB_{eff0}}}}{k_0/2 + \sqrt{V_{\mathrm{GB_{eff0}}} + (k_0/2)^2}}\right)^2 \tag{4.31}$$

$$D_{\mathrm{dibl}} = \sigma_{\mathrm{dibl}} \cdot \sqrt{\phi_{\mathrm{B}T}} \cdot \left(\frac{\sqrt{V_{\mathrm{SB_t}}}}{\sqrt{\phi_{\mathrm{B}T}}}\right)^{m_{\sigma_{\mathrm{dibl}}}} \tag{4.32}$$

$$D_{\mathrm{sf}} = \sigma_{\mathrm{sf}} \cdot \sqrt{\text{hyp}\left[\psi_{\mathrm{sat_0}} - V_{\mathrm{SB_t}}; \epsilon_3\right]} \tag{4.33}$$

$$D = D_{\mathrm{dibl}} + \text{hyp}\left[D_{\mathrm{sf}} - D_{\mathrm{dibl}}; \epsilon_4 \cdot \sigma_{\mathrm{sf}}\right] \tag{4.34}$$

$$V_{\mathrm{DS_{eff}}} = \frac{{V_{\mathrm{DS1}}}^4}{\left({V_{\mathrm{limit}}}^2 + {V_{\mathrm{DS1}}}^2\right)^{3/2}} \tag{4.35}$$

$$\Delta V_{\mathrm{G}} = D \cdot V_{\mathrm{DS_{eff}}} \tag{4.36}$$

Surface potential at the source:

$$V_{\mathrm{GB_t}} = V_{\mathrm{GB_{t0}}} + \Delta V_{\mathrm{G}} \tag{4.37}$$

$$V_{\mathrm{GB_{eff}}} = \text{hyp}\left[V_{\mathrm{GB_t}}; \epsilon_1\right] \tag{4.38}$$

$$\Delta_{\mathrm{acc}} = \phi_T \cdot \left(\exp\left[-\frac{Acc \cdot (V_{\mathrm{GB_{eff}}} - \epsilon_1)}{\phi_T}\right] - 1\right) \tag{4.39}$$

$$\Psi_{\mathrm{sat}}\left[V_{\mathrm{GB_{eff}}}, \Delta_{\mathrm{acc}}; k\right] = \left(\frac{V_{\mathrm{GB_{eff}}} + \Delta_{\mathrm{acc}}}{k/2 + \sqrt{V_{\mathrm{GB_{eff}}} + \Delta_{\mathrm{acc}} + (k/2)^2}}\right)^2 - \Delta_{\mathrm{acc}} \tag{4.40}$$

$$\psi_{\mathrm{sat}} = \Psi_{\mathrm{sat}}\left[V_{\mathrm{GB_{eff}}}, \Delta_{\mathrm{acc}}; k_0\right] \tag{4.41}$$

$$f_1\left[\psi_{\mathrm{sat}}, V_{\mathrm{CB_t}}\right] = \psi_{\mathrm{sat}} - \text{hyp}\left[\psi_{\mathrm{sat}} - V_{\mathrm{CB_t}}; \epsilon_1\right] \tag{4.42}$$

$$f_2\left[\psi_{\mathrm{sat}}, V_{\mathrm{CB_t}}\right] = f_1\left[\psi_{\mathrm{sat}}, V_{\mathrm{CB_t}}\right] + \frac{\psi_{\mathrm{sat}} - f_1\left[\psi_{\mathrm{sat}}, V_{\mathrm{CB_t}}\right]}{\sqrt{1 + \frac{\left(\psi_{\mathrm{sat}} - f_1\left[\psi_{\mathrm{sat}}, V_{\mathrm{CB_t}}\right]\right)^2}{16 \cdot {\phi_T}^2}}} \tag{4.43}$$

$$f_3\left[\psi_{\mathrm{sat}}, V_{\mathrm{CB_t}}, V_{\mathrm{GB_{eff}}}\right] = V_{\mathrm{GB_{eff}}} - f_2\left[\psi_{\mathrm{sat}}, V_{\mathrm{CB_t}}\right] \tag{4.44}$$

$$\begin{aligned}\Psi_{\mathrm{s}}\left[V_{\mathrm{GB}_{\mathrm{eff}}},\psi_{\mathrm{sat}},\Delta_{\mathrm{acc}},V_{\mathrm{CB}_{\mathrm{t}}};k,m_0\right] &= f_1\left[\psi_{\mathrm{sat}},V_{\mathrm{CB}_{\mathrm{t}}}\right] \\ &+ \phi_T\cdot(1+m_0)\cdot\ln\left[1+\frac{\left(\dfrac{f_3\left[\psi_{\mathrm{sat}},V_{\mathrm{CB}_{\mathrm{t}}},V_{\mathrm{GB}_{\mathrm{eff}}}\right]}{k}\right)^2-f_1\left[\psi_{\mathrm{sat}},V_{\mathrm{CB}_{\mathrm{t}}}\right]-\Delta_{\mathrm{acc}}}{\phi_T}\right]\end{aligned} \tag{4.45}$$

$$\psi_{\mathrm{s0}} = \Psi_{\mathrm{s}}\left[V_{\mathrm{GB}_{\mathrm{eff}}},\psi_{\mathrm{sat}},\Delta_{\mathrm{acc}},V_{\mathrm{SB}_{\mathrm{t}}};k_0,m_0\right] \tag{4.46}$$

Recalculation of channel-region quantities:

$$\mathcal{V}_{\mathrm{inv}}\left[V_{\mathrm{GB}_{\mathrm{eff}}},\psi_{\mathrm{s}},\Delta_{\mathrm{acc}};k\right] = \mathrm{hyp}\left[V_{\mathrm{GB}_{\mathrm{eff}}}-\psi_{\mathrm{s}}-k\cdot\sqrt{\mathrm{hyp}\left[\psi_{\mathrm{s}}+\Delta_{\mathrm{acc}};\epsilon_2\right]};\epsilon_5\right] \tag{4.47}$$

$$V_{\mathrm{inv0}} = \mathcal{V}_{\mathrm{inv}}\left[V_{\mathrm{GB}_{\mathrm{eff}}},\psi_{\mathrm{s0}},\Delta_{\mathrm{acc}};k_0\right] \tag{4.48}$$

$$\mathcal{V}_{\mathrm{dep}}\left[\psi_{\mathrm{s}},\Delta_{\mathrm{acc}};k,\epsilon\right] = k\cdot\sqrt{\mathrm{hyp}\left[\psi_{\mathrm{s}}+\Delta_{\mathrm{acc}};\epsilon\right]} \tag{4.49}$$

$$V_{\mathrm{dep0}} = \mathcal{V}_{\mathrm{dep}}\left[\psi_{\mathrm{s0}},\Delta_{\mathrm{acc}};k_0,\epsilon_2\right] \tag{4.50}$$

$$\psi_{\mathrm{s0}_0} = \Psi_{\mathrm{s}}\left[V_{\mathrm{GB}_{\mathrm{eff}}},\psi_{\mathrm{sat}},\Delta_{\mathrm{acc}},V_{\mathrm{SB}_{\mathrm{t0}}};k_0,m_0\right] \tag{4.51}$$

$$V_{\mathrm{dep0}_0} = \mathcal{V}_{\mathrm{dep}}\left[\psi_{\mathrm{s0}_0},\Delta_{\mathrm{acc}};k_0,\epsilon_2\right] \tag{4.52}$$

$$F_{\mathrm{mob}} = 1+\theta_1\cdot V_{\mathrm{inv0}}+\theta_2\cdot\frac{\mathrm{hyp}\left[V_{\mathrm{dep0}}-V_{\mathrm{dep0}_0};\epsilon_5\right]}{k_0} \tag{4.53}$$

$$\delta = \frac{k_0}{2\cdot\sqrt{V_1+\mathrm{hyp}\left[\psi_{\mathrm{s0}}+\Delta_{\mathrm{acc}};\epsilon_5\right]}} \tag{4.54}$$

$$\xi = 1+\delta \tag{4.55}$$

$$V_{\mathrm{DiSsat}_0} = \frac{V_{\mathrm{inv0}}}{\xi} \tag{4.56}$$

$$V_{\mathrm{DiSsat}} = \frac{2\cdot V_{\mathrm{DiSsat}_0}}{1+\sqrt{1+2\cdot\theta_{3T}\cdot V_{\mathrm{DiSsat}_0}}} \tag{4.57}$$

$$V_{\mathrm{DiSsat}_{\mathrm{eff}}} = V_{\mathrm{limit}}+\mathrm{hyp}\left[V_{\mathrm{DiSsat}}-V_{\mathrm{limit}};\epsilon_3\right] \tag{4.58}$$

Surface potential at the internal drain:

$$V_{\mathrm{DiS}_{\mathrm{eff}}} = \mathrm{hypm}\left[V_{\mathrm{DiS}},V_{\mathrm{DiSsat}_{\mathrm{eff}}};m\right] \tag{4.59}$$

$$V_{\mathrm{DiB}_{\mathrm{t,eff}}} = \mathrm{hyp}\left[V_{\mathrm{SB}}+V_{\mathrm{DiS}_{\mathrm{eff}}}+0.9\cdot\phi_{\mathrm{B}T};\epsilon_2\right]+0.1\cdot\phi_{\mathrm{B}T} \tag{4.60}$$

$$\psi_{\mathrm{sL}} = \Psi_{\mathrm{s}}\left[V_{\mathrm{GB}_{\mathrm{eff}}},\psi_{\mathrm{sat}},\Delta_{\mathrm{acc}},V_{\mathrm{DiB}_{\mathrm{t,eff}}};k_0,m_0\right] \tag{4.61}$$

Drain-source current:

$$\begin{aligned}\mathcal{V}_{\mathrm{inv_{ex}}}&\left[\psi_{\mathrm{s}},\Delta_{\mathrm{acc}},V_{\mathrm{CB_t}};k,m_0\right]\\ &= k\cdot\frac{\phi_T\cdot\exp\left[\dfrac{\psi_{\mathrm{s}}-V_{\mathrm{CB_t}}}{(1+m_0)\cdot\phi_T}\right]}{\sqrt{\mathrm{hyp}\left[\psi_{\mathrm{s}}+\Delta_{\mathrm{acc}};\epsilon_8\right]+\phi_T\cdot\exp\left[\dfrac{\psi_{\mathrm{s}}-V_{\mathrm{CB_t}}}{(1+m_0)\cdot\phi_T}\right]}+\sqrt{\mathrm{hyp}\left[\psi_{\mathrm{s}}+\Delta_{\mathrm{acc}};\epsilon_8\right]}}\end{aligned} \tag{4.62}$$

$$V_{\mathrm{inv_{ex0}}}=\mathcal{V}_{\mathrm{inv_{ex}}}\left[\psi_{\mathrm{s0}},\Delta_{\mathrm{acc}},V_{\mathrm{SB_t}};k_0,m_0\right] \tag{4.63}$$

$$V_{\mathrm{inv_{exL}}}=\mathcal{V}_{\mathrm{inv_{ex}}}\left[\psi_{\mathrm{sL}},\Delta_{\mathrm{acc}},V_{\mathrm{DiB_{t,eff}}};k_0,m_0\right] \tag{4.64}$$

$$\Delta\psi_{\mathrm{s}}=\psi_{\mathrm{sL}}-\psi_{\mathrm{s0}} \tag{4.65}$$

$$\overline{V_{\mathrm{inv}}}=V_{\mathrm{inv0}}-\tfrac{1}{2}\cdot\xi\cdot\Delta\psi_{\mathrm{s}} \tag{4.66}$$

$$F_{\mathrm{mobsat}}=1+\theta_{3T}\cdot\Delta\psi_{\mathrm{s}} \tag{4.67}$$

$$G_{\mathrm{mob}}=F_{\mathrm{mob}}\cdot F_{\mathrm{mobsat}} \tag{4.68}$$

$$G_{\Delta L}=\mathrm{hyp}\left[1-\alpha\cdot\ln\left[\frac{V_{\mathrm{DS1}}-V_{\mathrm{DiS_{eff}}}+\sqrt{(V_{\mathrm{DS1}}-V_{\mathrm{DiS_{eff}}})^2+V_P^2}}{V_P}\right];\epsilon_5\right] \tag{4.69}$$

$$x_0=2\cdot\frac{\psi_{\mathrm{sat}}+\phi_T-V_{\mathrm{SB_t}}}{\phi_T} \tag{4.70}$$

$$x_L=2\cdot\frac{\psi_{\mathrm{sat}}+\phi_T-V_{\mathrm{DiB_{t,eff}}}}{\phi_T} \tag{4.71}$$

$$G=\begin{cases}\dfrac{\exp[x_0]+\exp[x_L]}{1+\exp[x_0]+\exp[x_L]}, & x_0\le 80\wedge x_L\le 80,\\ 1, & x_0>80\vee x_L>80\end{cases} \tag{4.72}$$

$$I_{\mathrm{drift}}=\beta_T\cdot G\cdot\frac{\overline{V_{\mathrm{inv}}}\cdot\Delta\psi_{\mathrm{s}}}{G_{\mathrm{mob}}\cdot G_{\Delta L}} \tag{4.73}$$

$$I_{\mathrm{diff}}=\beta_T\cdot\phi_T\cdot\frac{V_{\mathrm{inv_{ex0}}}-V_{\mathrm{inv_{exL}}}}{G_{\mathrm{mob}}\cdot G_{\Delta L}} \tag{4.74}$$

$$I_{\mathrm{DS}}=I_{\mathrm{drift}}+I_{\mathrm{diff}} \tag{4.75}$$

Avalanche current:

$$I_{\mathrm{AVL_{ch}}} = \begin{cases} a_{1chT} \cdot |I_{\mathrm{DS}}| \cdot \exp\left[-\dfrac{a_{2ch}}{|V_{\mathrm{DiS}}| - a_{3ch} \cdot V_{\mathrm{DiSsat_{eff}}}}\right], & |V_{\mathrm{DiS}}| - a_{3ch} \cdot V_{\mathrm{DiSsat_{eff}}} > -\dfrac{a_{2ch}}{A}, \\ 0, & |V_{\mathrm{DiS}}| - a_{3ch} \cdot V_{\mathrm{DiSsat_{eff}}} \leq -\dfrac{a_{2ch}}{A} \end{cases} \tag{4.76}$$

$$F_{\mathrm{mobsat_{sat}}} = 1 + \theta_{3_T} \cdot V_{\mathrm{DiSsat_{eff}}} \tag{4.77}$$

$$G_{\mathrm{mob_{sat}}} = F_{\mathrm{mob}} \cdot F_{\mathrm{mobsat_{sat}}} \tag{4.78}$$

$$\overline{V_{\mathrm{inv_{sat}}}} = \text{hyp}\left[V_{\mathrm{inv0}} - \tfrac{1}{2} \cdot \xi \cdot V_{\mathrm{DiSsat_{eff}}}; \epsilon_2\right] \tag{4.79}$$

$$I_{\mathrm{sat}} = \beta_T \cdot G \cdot \frac{\overline{V_{\mathrm{inv_{sat}}}} \cdot V_{\mathrm{DiSsat_{eff}}}}{G_{\mathrm{mob_{sat}}}} \tag{4.80}$$

$$V_{\mathrm{ch_{sat}}} = R_{\mathrm{D}_T} \cdot I_{\mathrm{sat}} \tag{4.81}$$

$$f_{\mathrm{acc}} = \frac{\beta_{\mathrm{acc}_T} \cdot R_{\mathrm{D}_T}}{F_{\mathrm{mobacc}}} \tag{4.82}$$

$$V_{\mathrm{oxp_{avl}}} = \frac{f_{\mathrm{lin}}}{f_{\mathrm{acc}}} \tag{4.83}$$

$$V_{\mathrm{DSsat}} = V_{\mathrm{oxp_{avl}}} + V_{\mathrm{GS_t}} - \sqrt{\text{hyp}\left[\left(V_{\mathrm{oxp_{avl}}} + V_{\mathrm{GS_t}} - V_{\mathrm{DiSsat_{eff}}}\right)^2 - \frac{2 \cdot V_{\mathrm{ch_{sat}}}}{f_{\mathrm{acc}}}; \epsilon_5\right]} \tag{4.84}$$

$$V_{\mathrm{DSsat_{eff}}} = V_{\mathrm{limit}} + \text{hyp}\left[V_{\mathrm{DSsat}} - V_{\mathrm{limit}}; \epsilon_3\right] \tag{4.85}$$

$$I_{\mathrm{AVL_{dr}}} = \begin{cases} a_{1drT} \cdot |I_{\mathrm{DS}}| \cdot \exp\left[-\dfrac{a_{2dr}}{|V_{\mathrm{DS_1}}| - a_{3dr} \cdot V_{\mathrm{DSsat_{eff}}}}\right], & |V_{\mathrm{DS_1}}| - a_{3dr} \cdot V_{\mathrm{DSsat_{eff}}} > -\dfrac{a_{2dr}}{A}, \\ 0, & |V_{\mathrm{DS_1}}| - a_{3dr} \cdot V_{\mathrm{DSsat_{eff}}} \leq -\dfrac{a_{2dr}}{A} \end{cases} \tag{4.86}$$

$$I_{\mathrm{AVL}} = I_{\mathrm{AVL_{ch}}} + I_{\mathrm{AVL_{dr}}} \tag{4.87}$$

4.3 Charge Equations

Surface potential for accumulation in the channel region:

$$f_{1\mathrm{acc}}\left[V_{\mathrm{GB_t}}, V_{\mathrm{GB_{eff}}}; Acc\right] = Acc \cdot \left(V_{\mathrm{GB_t}} - V_{\mathrm{GB_{eff}}}\right) \tag{4.88}$$

$$f_{2\mathrm{acc}}\left[V_{\mathrm{GB_t}}, V_{\mathrm{GB_{eff}}}; Acc\right] = \frac{f_{1\mathrm{acc}}\left[V_{\mathrm{GB_t}}, V_{\mathrm{GB_{eff}}}; Acc\right]}{\sqrt{1 + \dfrac{f_{1\mathrm{acc}}^2\left[V_{\mathrm{GB_t}}, V_{\mathrm{GB_{eff}}}; Acc\right]}{16 \cdot {\phi_T}^2}}} \tag{4.89}$$

$$f_{3\mathrm{acc}}\left[V_{\mathrm{GB_t}}, V_{\mathrm{GB_{eff}}}; Acc\right] = V_{\mathrm{GB_t}} - V_{\mathrm{GB_{eff}}} - f_{2\mathrm{acc}}\left[V_{\mathrm{GB_t}}, V_{\mathrm{GB_{eff}}}; Acc\right] \tag{4.90}$$

$$\begin{aligned}&\Psi_{\mathrm{sacc}}\left[V_{\mathrm{GB_t}}, V_{\mathrm{GB_{eff}}}; k, Acc\right]\\ &\quad = -\phi_T \cdot \ln\left[1 + \frac{\left(\dfrac{f_{3\mathrm{acc}}\left[V_{\mathrm{GB_t}}, V_{\mathrm{GB_{eff}}}; Acc\right]}{k}\right)^2 - f_{2\mathrm{acc}}\left[V_{\mathrm{GB_t}}, V_{\mathrm{GB_{eff}}}; Acc\right]}{\phi_T}\right]\end{aligned} \tag{4.91}$$

$$\psi_{\mathrm{sacc}} = \Psi_{\mathrm{sacc}}\left[V_{\mathrm{GB_t}}, V_{\mathrm{GB_{eff}}}; k_0, Acc\right] \tag{4.92}$$

Charges in the channel region:

$$V_{\mathrm{ox}} = V_{\mathrm{GB_t}} - \tfrac{1}{2} \cdot \left(\psi_{\mathrm{s0}} + \psi_{\mathrm{sL}}\right) - \psi_{\mathrm{sacc}} \tag{4.93}$$

$$V_{\mathrm{GT0}} = \mathcal{V}_{\mathrm{inv}}\left[V_{\mathrm{GB_{eff}}}, \psi_{\mathrm{s0}}, \Delta_{\mathrm{acc}}; k_0\right] \tag{4.94}$$

$$V_{\mathrm{GTL}} = \mathcal{V}_{\mathrm{inv}}\left[V_{\mathrm{GB_{eff}}}, \psi_{\mathrm{sL}}, \Delta_{\mathrm{acc}}; k_0\right] \tag{4.95}$$

$$\Delta V_{\mathrm{GT}} = V_{\mathrm{GT0}} - V_{\mathrm{GTL}} \tag{4.96}$$

$$\overline{V_{\mathrm{GT}}} = \tfrac{1}{2} \cdot \left(V_{\mathrm{GT0}} + V_{\mathrm{GTL}}\right) \tag{4.97}$$

$$F_j = \frac{\Delta V_{\mathrm{GT}}}{\overline{V_{\mathrm{GT}}} + \xi \cdot \phi_T} \tag{4.98}$$

$$Q_{\mathrm{G_{mos}}} = C_{\mathrm{ox}} \cdot \left(V_{\mathrm{ox}} + \frac{F_j}{12 \cdot \xi} \cdot \Delta V_{\mathrm{GT}}\right) \tag{4.99}$$

$$Q_{\mathrm{D_{mos}}} = -\frac{C_{\mathrm{ox}}}{2} \cdot \left(\overline{V_{\mathrm{GT}}} - \frac{\Delta V_{\mathrm{GT}}}{6} \cdot \left\{1 - \frac{F_j}{2} - \frac{F_j^2}{20}\right\}\right) \tag{4.100}$$

$$Q_{\mathrm{S_{mos}}} = -\frac{C_{\mathrm{ox}}}{2} \cdot \left(\overline{V_{\mathrm{GT}}} + \frac{\Delta V_{\mathrm{GT}}}{6} \cdot \left\{1 + \frac{F_j}{2} - \frac{F_j^2}{20}\right\}\right) \tag{4.101}$$

$$Q_{\mathrm{B_{mos}}} = -\left(Q_{\mathrm{G_{mos}}} + Q_{\mathrm{D_{mos}}} + Q_{\mathrm{S_{mos}}}\right) \tag{4.102}$$

$$Q_{\mathrm{G}}^{\mathrm{ch}} = Q_{\mathrm{G_{mos}}} \tag{4.103}$$

$$Q_{\mathrm{D}}^{\mathrm{ch}} = F_L \cdot Q_{\mathrm{D_{mos}}} \tag{4.104}$$

$$Q_{\mathrm{S}}^{\mathrm{ch}} = Q_{\mathrm{S_{mos}}} + \left(1 - F_L\right) \cdot Q_{\mathrm{D_{mos}}} \tag{4.105}$$

$$Q_{\mathrm{B}}^{\mathrm{ch}} = -\left(Q_{\mathrm{G}}^{\mathrm{ch}} + Q_{\mathrm{D}}^{\mathrm{ch}} + Q_{\mathrm{S}}^{\mathrm{ch}}\right) \tag{4.106}$$

Surface potential at the internal drain in the drift region:

$$V_{\mathrm{DiS_{dr,eff}}} = V_{\mathrm{DiS}} \tag{4.107}$$

$$V_{\mathrm{GDi_{t,eff}}} = V_{\mathrm{GS_t}} - V_{\mathrm{DiS_{dr,eff}}} \tag{4.108}$$

$$V_{\mathrm{DiG_{eff}}} = \text{hyp}\left[-V_{\mathrm{GDi_{t,eff}}}; \epsilon_7\right] \tag{4.109}$$

$$\Delta_{\mathrm{acc_{Di}}} = \phi_T \cdot \left(\exp\left[-\frac{Acc_{\mathrm{D}}\left(V_{\mathrm{DiG_{eff}}} - \epsilon_7\right)}{\phi_T}\right] - 1\right) \tag{4.110}$$

$$\psi_{\mathrm{sat_{Di}}} = \Psi_{\mathrm{sat}}\left[V_{\mathrm{DiG_{eff}}}, \Delta_{\mathrm{acc_{Di}}}; k_{0\mathrm{D}}\right] \tag{4.111}$$

$$V_{\mathrm{DiB_t}} = \text{hyp}\left[V_{\mathrm{SB}} + V_{\mathrm{DiS_{dr,eff}}} + 0.9 \cdot \phi_{\mathrm{BD}T}; \epsilon_2\right] + 0.1 \cdot \phi_{\mathrm{BD}T} \tag{4.112}$$

$$\psi_{\mathrm{sDi}} = \Psi_{\mathrm{s}}\left[V_{\mathrm{DiG_{eff}}}, \psi_{\mathrm{sat_{Di}}}, \Delta_{\mathrm{acc_{Di}}}, V_{\mathrm{DiB_t}}; k_{0\mathrm{D}}, m_0\right] \tag{4.113}$$

$$\psi_{\mathrm{sacc_{Di}}} = \Psi_{\mathrm{sacc}}\left[-V_{\mathrm{GDi_{t,eff}}}, V_{\mathrm{DiG_{eff}}}; k_{0\mathrm{D}}, Acc_{\mathrm{D}}\right] \tag{4.114}$$

Drift-region charges at the internal drain:

$$V^{\mathrm{dr}}_{\mathrm{ox\,Di}} = V_{\mathrm{GDi_{t,eff}}} + \psi_{\mathrm{sDi}} + \psi_{\mathrm{sacc_{Di}}} \tag{4.115}$$

$$V_{\mathrm{dep_{Di}}} = \mathcal{V}_{\mathrm{dep}}\left[\psi_{\mathrm{sDi}}, \Delta_{\mathrm{acc_{Di}}}; k_{0\mathrm{D}}, \epsilon_2\right] \tag{4.116}$$

$$V_{\mathrm{inv_{Di}}} = \mathcal{V}_{\mathrm{inv}}\left[V_{\mathrm{DiG_{eff}}}, \psi_{\mathrm{sDi}}, \Delta_{\mathrm{acc_{Di}}}; k_{0\mathrm{D}}\right] \tag{4.117}$$

$$V^{\mathrm{accdep}}_{q\,\mathrm{Di}} = V^{\mathrm{dr}}_{\mathrm{ox\,Di}} + V_{\mathrm{inv_{Di}}} \tag{4.118}$$

$$V^{\mathrm{dr}}_{q_{\mathrm{Di}}} = V_{\mathrm{oxp}} + V^{\mathrm{accdep}}_{q\,\mathrm{Di}} \tag{4.119}$$

$$V^{\mathrm{dr}}_{q_{\mathrm{Di}}\mathrm{eff}} = V_{\mathrm{limit}} + \text{hyp}\left[V^{\mathrm{dr}}_{q_{\mathrm{Di}}} - V_{\mathrm{limit}}; \epsilon_7\right] \tag{4.120}$$

$$V_{\mathrm{DDisat}} = \frac{2 \cdot V^{\mathrm{dr}}_{q_{\mathrm{Di}}\mathrm{eff}}}{1 + \sqrt{1 + 2 \cdot \theta_{3\mathrm{D}T} \cdot V^{\mathrm{dr}}_{q_{\mathrm{Di}}\mathrm{eff}}}} \tag{4.121}$$

$$V_{\mathrm{DDi_{eff}}} = \text{hypm}\left[V_{\mathrm{DDi}}, V_{\mathrm{DDisat}}; m_{\mathrm{D}}\right] \tag{4.122}$$

Surface potential at the drain in the drift region:

$$V_{\mathrm{DS}_{\mathrm{dr,eff}}} = V_{\mathrm{DiS}_{\mathrm{dr,eff}}} + V_{\mathrm{DDi}_{\mathrm{eff}}} \tag{4.123}$$

$$V_{\mathrm{GD}_{\mathrm{t,eff}}} = V_{\mathrm{GS}_{\mathrm{t}}} - V_{\mathrm{DS}_{\mathrm{dr,eff}}} \tag{4.124}$$

$$V_{\mathrm{DG}_{\mathrm{eff}}} = \text{hyp}\left[-V_{\mathrm{GD}_{\mathrm{t,eff}}}; \epsilon_7\right] \tag{4.125}$$

$$\Delta_{\mathrm{acc}_{\mathrm{D}}} = \phi_T \cdot \left(\exp\left[-\frac{Acc_{\mathrm{D}}\left(V_{\mathrm{DG}_{\mathrm{eff}}} - \epsilon_7\right)}{\phi_T}\right] - 1\right) \tag{4.126}$$

$$\psi_{\mathrm{sat}_{\mathrm{D}}} = \Psi_{\mathrm{sat}}\left[V_{\mathrm{DG}_{\mathrm{eff}}}, \Delta_{\mathrm{acc}_{\mathrm{D}}}; k_{0\mathrm{D}}\right] \tag{4.127}$$

$$V_{\mathrm{DB}_{\mathrm{t}}} = \text{hyp}\left[V_{\mathrm{SB}} + V_{\mathrm{DS}_{\mathrm{dr,eff}}} + 0.9 \cdot \phi_{\mathrm{BD}T}; \epsilon_2\right] + 0.1 \cdot \phi_{\mathrm{BD}T} \tag{4.128}$$

$$\psi_{\mathrm{sD}} = \Psi_{\mathrm{s}}\left[V_{\mathrm{DG}_{\mathrm{eff}}}, \psi_{\mathrm{sat}_{\mathrm{D}}}, \Delta_{\mathrm{acc}_{\mathrm{D}}}, V_{\mathrm{DB}_{\mathrm{t}}}; k_{0\mathrm{D}}, m_0\right] \tag{4.129}$$

$$\psi_{\mathrm{sacc}_{\mathrm{D}}} = \Psi_{\mathrm{sacc}}\left[-V_{\mathrm{GD}_{\mathrm{t,eff}}}, V_{\mathrm{DG}_{\mathrm{eff}}}; k_{0\mathrm{D}}, Acc_{\mathrm{D}}\right] \tag{4.130}$$

Drift-region charges at the drain:

$$V_{\mathrm{ox\,D}}^{\mathrm{dr}} = V_{\mathrm{GD}_{\mathrm{t,eff}}} + \psi_{\mathrm{sD}} + \psi_{\mathrm{sacc}_{\mathrm{D}}} \tag{4.131}$$

$$V_{\mathrm{dep}_{\mathrm{D}}} = \mathcal{V}_{\mathrm{dep}}\left[\psi_{\mathrm{sD}}, \Delta_{\mathrm{acc}_{\mathrm{D}}}; k_{0\mathrm{D}}, \epsilon_2\right] \tag{4.132}$$

$$V_{\mathrm{inv}_{\mathrm{D}}} = \mathcal{V}_{\mathrm{inv}}\left[V_{\mathrm{DG}_{\mathrm{eff}}}, \psi_{\mathrm{sD}}, \Delta_{\mathrm{acc}_{\mathrm{D}}}; k_{0\mathrm{D}}\right] \tag{4.133}$$

$$V_{q\,\mathrm{D}}^{\mathrm{accdep}} = V_{\mathrm{ox\,D}}^{\mathrm{dr}} + V_{\mathrm{inv}_{\mathrm{D}}} \tag{4.134}$$

$$V_{q_{\mathrm{D}}}^{\mathrm{dr}} = V_{\mathrm{oxp}} + V_{q\,\mathrm{D}}^{\mathrm{accdep}} \tag{4.135}$$

$$V_{q_{\mathrm{D}}\,\mathrm{eff}}^{\mathrm{dr}} = V_{\mathrm{limit}} + \text{hyp}\left[V_{q_{\mathrm{D}}}^{\mathrm{dr}} - V_{\mathrm{limit}}; \epsilon_7\right] \tag{4.136}$$

Total charges in the drift region:

$$\overline{V_q^{\mathrm{dr}}}_{\mathrm{eff}} = \tfrac{1}{2} \cdot \left(V_{q_{\mathrm{Di}}\,\mathrm{eff}}^{\mathrm{dr}} + V_{q_{\mathrm{D}}\,\mathrm{eff}}^{\mathrm{dr}}\right) \tag{4.137}$$

$$\Delta V_q^{\mathrm{accdep}} = V_{q\,\mathrm{Di}}^{\mathrm{accdep}} - V_{q\,\mathrm{D}}^{\mathrm{accdep}} \tag{4.138}$$

$$F_{j_{\mathrm{dr}}} = \frac{\Delta V_q^{\mathrm{accdep}}}{\overline{V_q^{\mathrm{dr}}}_{\mathrm{eff}}} \tag{4.139}$$

$$Q_{\mathrm{D}}^{\mathrm{accdep}} = -\frac{C_{\mathrm{oxD}}}{2} \cdot \left(\overline{V_q^{\mathrm{dr}}}_{\mathrm{eff}} - \frac{\Delta V_q^{\mathrm{accdep}}}{6} \cdot \left\{1 - \frac{F_{j_{\mathrm{dr}}}}{2} - \frac{F_{j_{\mathrm{dr}}}^2}{20}\right\}\right) \tag{4.140}$$

$$Q_{\mathrm{S}}^{\mathrm{accdep}} = -\frac{C_{\mathrm{oxD}}}{2} \cdot \left(\overline{V_q^{\mathrm{dr}}}_{\mathrm{eff}} + \frac{\Delta V_q^{\mathrm{accdep}}}{6} \cdot \left\{1 + \frac{F_{j_{\mathrm{dr}}}}{2} - \frac{F_{j_{\mathrm{dr}}}^2}{20}\right\}\right) \tag{4.141}$$

Inclusion of asymmetry:

$$V_{\mathrm{T_t}} = V_{\mathrm{FB}T} + \phi_{\mathrm{B}T} - V_{\mathrm{FBD}T} + k_0 \cdot \sqrt{V_{\mathrm{DiB_{t,eff}}}} \tag{4.142}$$

$$V_{\mathrm{GDi_{lim}}} = V_{\mathrm{GDi_{t,eff}}} - \mathrm{hyp}\left[V_{\mathrm{GDi_{t,eff}}} - V_{\mathrm{T_t}}; \epsilon_7\right] \tag{4.143}$$

$$V_{\mathrm{GD_{lim}}} = V_{\mathrm{GDi_{lim}}} - V_{\mathrm{DDi_{eff}}} \tag{4.144}$$

$$V_{\mathrm{GD_{acc,lim}}} = \mathrm{hyp}\left[V_{\mathrm{GD_{lim}}}; \epsilon_7\right] \tag{4.145}$$

$$V_{\mathrm{GDi_{acc,lim}}} = \mathrm{hyp}\left[V_{\mathrm{GDi_{lim}}}; \epsilon_7\right] \tag{4.146}$$

$$\Delta V_{\mathrm{acc,lim}} = V_{\mathrm{GDi_{acc,lim}}} - V_{\mathrm{GD_{acc,lim}}} \tag{4.147}$$

$$\overline{V_{\mathrm{acc,lim}}} = \frac{1}{2} \cdot \left(V_{\mathrm{GDi_{acc,lim}}} + V_{\mathrm{GD_{acc,lim}}}\right) \tag{4.148}$$

$$F_{j_{\mathrm{acc,lim}}} = \frac{\Delta V_{\mathrm{acc,lim}}}{\overline{V_{\mathrm{acc,lim}}} + V_{\mathrm{oxp}}} \tag{4.149}$$

$$Q_{\mathrm{S_{acc,lim}}} = -\frac{C_{\mathrm{oxD}}}{2} \cdot \left(\overline{V_{\mathrm{acc,lim}}} + \frac{\Delta V_{\mathrm{acc,lim}}}{6} \cdot \left\{1 + \frac{F_{j_{\mathrm{acc,lim}}}}{2} - \frac{F_{j_{\mathrm{acc,lim}}}^2}{20}\right\}\right) \tag{4.150}$$

Total drift-region charges:

$$Q_{\mathrm{D}}^{\mathrm{dr}} = Q_{\mathrm{D}}^{\mathrm{accdep}} + F_L \cdot Q_{\mathrm{S}}^{\mathrm{accdep}} + (1 - F_L) \cdot Q_{\mathrm{S_{acc,lim}}} \tag{4.151}$$

$$Q_{\mathrm{S}}^{\mathrm{dr}} = (1 - F_L) \cdot \left(Q_{\mathrm{S}}^{\mathrm{accdep}} - Q_{\mathrm{S_{acc,lim}}}\right) \tag{4.152}$$

$$Q_{\mathrm{B}}^{\mathrm{dr}} = \frac{C_{\mathrm{oxD}}}{2} \cdot \left(V_{\mathrm{inv_D}} + V_{\mathrm{inv_{Di}}}\right) \tag{4.153}$$

$$Q_{\mathrm{G}}^{\mathrm{dr}} = -\left(Q_{\mathrm{S}}^{\mathrm{dr}} + Q_{\mathrm{D}}^{\mathrm{dr}} + Q_{\mathrm{B}}^{\mathrm{dr}}\right) \tag{4.154}$$

Total charges:

$$Q_{\mathrm{G}} = Q_{\mathrm{G}}^{\mathrm{ch}} + Q_{\mathrm{G}}^{\mathrm{dr}} \tag{4.155}$$

$$Q_{\mathrm{D}} = Q_{\mathrm{D}}^{\mathrm{ch}} + Q_{\mathrm{D}}^{\mathrm{dr}} \tag{4.156}$$

$$Q_{\mathrm{S}} = Q_{\mathrm{S}}^{\mathrm{ch}} + Q_{\mathrm{S}}^{\mathrm{dr}} \tag{4.157}$$

$$Q_{\mathrm{B}} = -\left(Q_{\mathrm{G}} + Q_{\mathrm{D}} + Q_{\mathrm{S}}\right) \tag{4.158}$$

4.4 Noise Equations

Noise transfer function:

$$g_{\mathrm{m_{ch}}} = \max\left[\beta_T \cdot \frac{\Delta\psi_{\mathrm{s}}}{G_{\mathrm{mob}}} \cdot \left(1 - \theta_1 \cdot \frac{\overline{V_{\mathrm{inv}}}}{F_{\mathrm{mob}}}\right), 1 \times 10^{-10}\right] \tag{4.159}$$

$$g_{\mathrm{ds_{ch}}} = \max\left[\beta_T \cdot \frac{V_{\mathrm{inv0}} + \xi \cdot V_{\mathrm{limit}} - \xi \cdot \Delta\psi_{\mathrm{s}} - \frac{1}{2} \cdot \theta_{3T} \cdot \xi \cdot (\Delta\psi_{\mathrm{s}})^2}{G_{\mathrm{mob}} \cdot F_{\mathrm{mobsat}}}, 0\right] \tag{4.160}$$

$$V_{\mathrm{DiB_t}} = \text{hyp}\left[V_{\mathrm{SB}} + V_{\mathrm{DiS}} + 0.9 \cdot \phi_{\mathrm{BD}T}; \epsilon_2\right] + 0.1 \cdot \phi_{\mathrm{BD}T} \tag{4.161}$$

$$V_{\mathrm{GDi_t\,eff}} = \begin{cases} V_{\mathrm{GDi_t}}, & V_{\mathrm{GDi_t}} \geq 0 \\ \\ \text{hypm}\left[V_{\mathrm{GDi_t}}, V_{\mathrm{DiB_t}} + k_{\mathrm{0D}} \cdot \sqrt{V_{\mathrm{DiB_t}}}; 8\right], & V_{\mathrm{GDi_t}} < 0 \end{cases} \tag{4.162}$$

$$V_{q\ \mathrm{eff}}^{\mathrm{dr}} = \text{hyp}\left[\mathcal{V}_q^{\mathrm{dr}}\left[V_{\mathrm{GDi_t\,eff}}\right]; \epsilon_2\right] \tag{4.163}$$

$$V_{\mathrm{DDisat}} = \frac{2 \cdot V_{q\ \mathrm{eff}}^{\mathrm{dr}}}{1 + \sqrt{1 + 2 \cdot \theta_{3\mathrm{D}T} \cdot V_{q\ \mathrm{eff}}^{\mathrm{dr}}}} \tag{4.164}$$

$$V_{\mathrm{DDi_{eff}}} = \text{hypm}\left[V_{\mathrm{DDi}}, V_{\mathrm{DDisat}}; m_{\mathrm{D}}\right] \tag{4.165}$$

$$F_{\mathrm{mobsat}}^{\mathrm{dr}} = 1 + \theta_{\mathrm{3DT}} \cdot V_{\mathrm{DDi_{eff}}} \tag{4.166}$$

$$g_{\mathrm{m_{dr}}} = \max\left[\beta_{\mathrm{acc}T} \cdot \frac{\partial V_{q\ \mathrm{eff}}^{\mathrm{dr}}}{\partial V_{\mathrm{GDi_t\,eff}}} \cdot \frac{\partial V_{\mathrm{GDi_t\,eff}}}{\partial V_{\mathrm{GDi_t}}} \cdot \frac{V_{\mathrm{DDi_{eff}}}}{F_{\mathrm{mobacc}} \cdot F_{\mathrm{mobsat}}^{\mathrm{dr}}}, 1 \times 10^{-10}\right] \tag{4.167}$$

$$g_{\mathrm{ds_{dr}}} = \max\left[\beta_{\mathrm{acc}T} \cdot \frac{V_{q\ \mathrm{eff}}^{\mathrm{dr}} - V_{\mathrm{DDi_{eff}}} - \frac{1}{2} \cdot \theta_{\mathrm{3DT}} \cdot \left(V_{\mathrm{DDi_{eff}}}\right)^2}{F_{\mathrm{mobacc}} \cdot \left(F_{\mathrm{mobsat}}^{\mathrm{dr}}\right)^2}, 1 \times 10^{-10}\right] \tag{4.168}$$

$$g_{\mathrm{transfer}} = \frac{g_{\mathrm{ds_{dr}}} + g_{\mathrm{m_{dr}}}}{g_{\mathrm{ds_{ch}}} + g_{\mathrm{ds_{dr}}} + g_{\mathrm{m_{dr}}}} \tag{4.169}$$

Flicker noise:

$$N_0 = \frac{\epsilon_{\mathrm{ox}}}{q \cdot t_{\mathrm{ox}}} \cdot V_{\mathrm{inv_{ex0}}} \tag{4.170}$$

$$N_{\mathrm{L}} = \frac{\epsilon_{\mathrm{ox}}}{q \cdot t_{\mathrm{ox}}} \cdot V_{\mathrm{inv_{exL}}} \tag{4.171}$$

$$N^* = \frac{\epsilon_{\mathrm{ox}}}{q \cdot t_{\mathrm{ox}}} \cdot \xi \cdot \phi_T \tag{4.172}$$

$$
\begin{aligned}
S_{\mathrm{D_{fl0}}} = \frac{q \cdot \phi_T^2 \cdot t_{\mathrm{ox}} \cdot \beta_T \cdot I_{\mathrm{DS}}}{\epsilon_{\mathrm{ox}} \cdot N^* \cdot G_{\mathrm{mob}}} & \left\{ \left(N_{f\mathrm{A}} - N^* \cdot N_{f\mathrm{B}} + N^{*2} \cdot N_{f\mathrm{C}} \right) \cdot \ln \left[\frac{N_0 + N^*}{N_\mathrm{L} + N^*} \right] \right. \\
& \left. + \left(N_{f\mathrm{B}} - N^* \cdot N_{f\mathrm{C}} \right) \cdot \left(N_0 - N_\mathrm{L} \right) + \frac{N_{f\mathrm{C}}}{2} \cdot \left({N_0}^2 - {N_\mathrm{L}}^2 \right) \right\} \\
& + \phi_T \cdot I_{\mathrm{DS}}^2 \cdot \left(1 - G_{\Delta L} \right) \cdot \frac{N_{f\mathrm{A}} + N_{f\mathrm{B}} \cdot N_\mathrm{L} + N_{f\mathrm{C}} \cdot N_\mathrm{L}^2}{\left(N_\mathrm{L} + N^* \right)^2}
\end{aligned}
\tag{4.173}
$$

$$
S_{\mathrm{D_{fl}}} = g_{\mathrm{transfer}}^2 \cdot \frac{\max \left[S_{\mathrm{D_{fl0}}}, 0 \right]}{f} \tag{4.174}
$$

Thermal noise:

$$
\begin{aligned}
S_{\mathrm{D_{th0}}} = \beta_T \cdot & \left\{ \frac{F_{\mathrm{mobsat}} \cdot G_{\Delta L}}{F_{\mathrm{mob}}} \cdot \left(\overline{V_{\mathrm{inv}}} + \frac{\xi^2}{12} \cdot \frac{{\Delta\psi_\mathrm{s}}^2}{\overline{V_{\mathrm{inv}}} + \xi \cdot \phi_T} \right) \right. \\
& \left. - \frac{\theta_{3T} \cdot \overline{V_{\mathrm{inv}}} \cdot \Delta\psi_\mathrm{s}}{F_{\mathrm{mob}}} \cdot \left(2 - \frac{\theta_{3T} \cdot \Delta\psi_\mathrm{s}}{F_{\mathrm{mobsat}} \cdot G_{\Delta L}} \right) \right\}
\end{aligned}
\tag{4.175}
$$

$$
S_{\mathrm{D_{th}}} = g_{\mathrm{transfer}}^2 \cdot N_{T_T} \cdot \max \left[S_{\mathrm{D_{th0}}}, 0 \right] \tag{4.176}
$$

$$
S_{\mathrm{G_{th}}} = N_{T_T} \cdot \frac{\left(2 \cdot \pi \cdot C_{\mathrm{ox}} \right)^2}{3 \cdot g_{\mathrm{m_{ch}}}} \cdot f^2 \tag{4.177}
$$

$$
S_{\mathrm{GD_{th}}} = 0.4 \cdot \mathrm{j} \cdot \sqrt{S_{\mathrm{G_{th}}} \cdot S_{\mathrm{D_{th}}}} \tag{4.178}
$$

4.5 Self-Heating

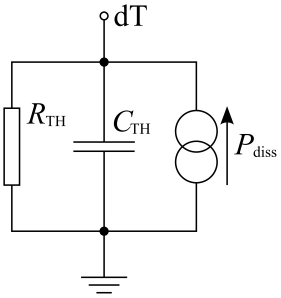
4.5.1 Equivalent Circuit

Self-heating is part of the model. It is defined in the usual way by adding a self-heating network (see Figure 6) containing a current source describing the dissipated power and both a thermal resistance R_{TH} and a thermal capacitance C_{TH}. The resistor and capacitor are both connected between ground and the temperature node dT. The value of the voltage V_{dT} at the temperature node gives the increase in local temperature, which is included in the calculation of the temperature-scaling relations; see Eqns. (3.2) and (3.34). For the value of A_{TH}, we recommend using values from literature that describe the temperature scaling of the thermal conductivity. For the most important materials, the values are given in Figure 6, which is largely based on Ref. [8]; see also [1]. For example, if the value of V_{dT} is 0.5 V, the increase in temperature is 0.5 degrees Celsius.

4.5.2 Model Equations

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

$$
\begin{aligned}
P_{\mathrm{diss}} &= I_\mathrm{D}^e V_\mathrm{D}^e + I_\mathrm{S}^e V_\mathrm{S}^e + I_\mathrm{B}^e V_\mathrm{B}^e && (4.179) \\
&= I''_{\mathrm{DS}} V''_{\mathrm{DS}} + I''_{\mathrm{DB}} \cdot \left(V''_{\mathrm{DS}} - V''_{\mathrm{SB}} \right) + I''_{\mathrm{SB}} V''_{\mathrm{SB}} && (4.180)
\end{aligned}
$$



Material	A_{TH}
Si	1.3
Ge	1.25
GaAs	1.25
AlAs	1.37
InAs	1.1
InP	1.4
GaP	1.4
SiO_2	0.7

Figure 6: On the left, the self-heating network, where the node voltage V_{dT} is used in the temperature-scaling relations. Note that for increased flexibility, the node dT is available to the user. On the right are parameter values that can be used for A_{TH}.

where all variables are given in Figure 5 in section 2.3. Note that only the steady-state currents contribute to the dissipated power. The total dissipation applies for the electrical model (mnet[1], mpet[1], mos2002et[2]) and geometrical model (mnt[1], mpt[1], mos2002t[2]).

4.5.3 Usage

A Pstar example is given below to illustrate how self-heating works.

Example:

```
Title: Example of self-heating in MOS Model 20 (2002.2);

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

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

run;
```

---

[1] *Pstar* model name

[2] *Spectre/ADS* model name

Result:

```
     DC   Analysis.
      Ground node is set to node 0.


VN(DT)               =     1.066E+00
Pdiss.MNET_1         =     3.556E-03
```

The voltage on node dT is 1.066E+00 V, which means that the local temperature is increased by 1.066 °C.

5 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 Ref. [4]. However, in case of a non-negligible temperature rise due to self-heating, one cannot 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 only one single temperature. 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, usually 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.

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

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

- **Measurement II (subvt):** Sub-threshold I_{D} versus V_{GS} characteristics:

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

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

---

[1] The bias conditions to be used for the measurements are dependent on the maximum voltages $V_{\mathrm{DS,\,max}}$ and $V_{\mathrm{GS,\,max}}$. Of course, it is advisable to restrict the range of voltages to these maximum voltages. Otherwise, physical effects atypical 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 : $V_{\mathrm{DS}} = 0, \ldots, V_{\mathrm{DS,\,max}}$
$V_{\mathrm{GS}} = V_{\mathrm{T}} + 0.1$ V, $V_{\mathrm{T}} + 1.1$ V, $V_{\mathrm{T}} + 2.1$ V, $V_{\mathrm{T}} + 3.1$ V
$V_{\mathrm{SB}} = 0$, 2, and 4 V

p-channel : $V_{\mathrm{DS}} = 0, \ldots, -V_{\mathrm{DS,\,max}}$
$V_{\mathrm{GS}} = V_{\mathrm{T}} - 0.1$ V, $V_{\mathrm{T}} - 1.1$ V, $V_{\mathrm{T}} - 2.1$ V, $V_{\mathrm{T}} - 3.1$ V
$V_{\mathrm{BS}} = 0$, -2, and -4 V

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

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

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

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

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

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

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

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

The values of transconductance g_{m} and output conductance g_{DS} are determined from the *I*-*V* curves by numerically calculating the derivative of I_{D} with respect to V_{GS} and V_{DS}, respectively. In measurements II and III, use is made of the threshold voltage V_{T}, which has to be determined for all of the source-bulk bias values V_{SB} used in 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 $T_{\min} = -40$ °C to $T_{\max} = 125$ °C. Finally, to determine the width scaling parameters, the measurements at room temperature need to be performed for a narrow and broad transistor.

5.2 Extraction of Miniset Parameters (including Temperature Scaling)

In case of a non-negligible 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 $\Delta T_{\mathrm{self-heating}}$ 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 $\Delta T_{\mathrm{self-heating}}$ due to self-heating, according to

$$\Delta T_{\mathrm{self-heating}} = R_{\mathrm{th}} \cdot I_{\mathrm{DS}} \cdot V_{\mathrm{DS}}. \tag{5.1}$$

Here, R_{th} denotes the thermal resistance (in kelvins 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

$$R_{\mathrm{th_{SOI}}} = \left(\frac{t_{\mathrm{BOX}}}{k_{\mathrm{ox}}} + \frac{t_{\mathrm{Si}}}{k_{\mathrm{Si}}}\right) \cdot \frac{1}{A}, \qquad \text{or} \qquad R_{\mathrm{th_{bulk}}} = \frac{t_{\mathrm{Si}}}{k_{\mathrm{Si}}} \cdot \frac{1}{A}, \tag{5.2}$$

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 7. The physical constants k_{Si} and k_{ox} are the thermal conductivity of silicon and oxide, respectively. At $T = 27$ °C, these conductivities are given by $k_{\mathrm{ox}} = 1.4$ W/(K·m) and $k_{\mathrm{Si}} = 1.41 \cdot 10^2$ 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. Ref. [7].

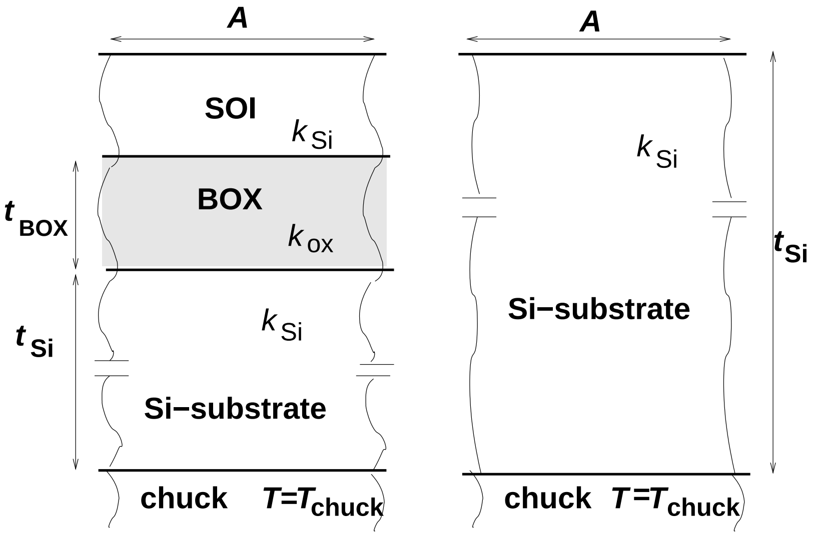


Figure 7: *Geometry for the one-dimensional heat flow in a transistor in an SOI process (left) and a bulk process (right).*

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
$S_{T;\mathrm{V_{FB}}}$	STVFB	$-1.0 \cdot 10^{-3}$	$-1.0 \cdot 10^{-3}$
V_{FBD}	VFBD	0.0	0.0
$S_{T;\mathrm{V_{FB}}}$	STVFB	0.0	0.0
k_0	KO	1.6	1.6
$k_{0\mathrm{D}}$	KOD	1.0	1.0
ϕ_{B}	PHIB	0.9	0.9
$S_{T;\phi_{\mathrm{B}}}$	STPHIB	$-1.0 \cdot 10^{-3}$	$-1.0 \cdot 10^{-3}$
ϕ_{BD}	PHIBD	0.8	0.8
$S_{T;\phi_{\mathrm{BD}}}$	STPHIBD	$-1.0 \cdot 10^{-3}$	$-1.0 \cdot 10^{-3}$
β	BET	$(2.2 \cdot 10^{-12}/t_{\mathrm{ox}}) \cdot (W/L_{\mathrm{ch}})$	$(0.8 \cdot 10^{-12}/t_{\mathrm{ox}}) \cdot (W/L_{\mathrm{ch}})$
η_{β}	ETABET	1.6	1.6
β_{acc}	BETACC	$(2.2 \cdot 10^{-12}/t_{\mathrm{ox}}) \cdot (W/L_{\mathrm{dr}})$	$(0.8 \cdot 10^{-12}/t_{\mathrm{ox}}) \cdot (W/L_{\mathrm{dr}})$
$\eta_{\beta_{\mathrm{acc}}}$	ETABETACC	1.6	1.6
R_{D}	RD	$5.0 \cdot 10^{3} \cdot (L_{\mathrm{dr}}/W)$	$1.5 \cdot 10^{4} \cdot (L_{\mathrm{dr}}/W)$
$\eta_{R_{\mathrm{D}}}$	ETARD	1.5	1.5
λ_{D}	LAMD	0.2	0.2
θ_1	THE1	0.05	0.05
$\theta_{1\mathrm{acc}}$	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
θ_{3D}	THE3D	0.0	0.0
$\eta_{\theta_{3D}}$	ETATHE3D	1.0	1.0
m_{D}	MEXPD	2.0	2.0
α	ALP	$2.0 \cdot 10^{-3}$	$2.0 \cdot 10^{-3}$
V_{P}	VP	$5.0 \cdot 10^{-2}$	$5.0 \cdot 10^{-2}$
σ_{dibl}	SDIBL	$1.0 \cdot 10^{-3}$	$1.0 \cdot 10^{-3}$
$m_{\sigma_{\mathrm{dibl}}}$	MSDIBL	1.0	1.0
m_0	MO	$1.0 \cdot 10^{-3}$	$1.0 \cdot 10^{-3}$
σ_{sf}	SSF	$1.0 \cdot 10^{-6}$	$1.0 \cdot 10^{-6}$
a_{1ch}	A1CH	18	18
$S_{T;a_{1ch}}$	STA1CH	0.0	0.0
a_{2ch}	A2CH	73	73
a_{3ch}	A3CH	1.0	1.0
a_{1dr}	A1DR	18	18
$S_{T;a_{1dr}}$	STA1DR	0.0	0.0
a_{2dr}	A2DR	73	73
a_{3dr}	A3DR	1.0	1.0
C_{ox}	COX	$(3.453 \cdot 10^{-11}/t_{\mathrm{ox}}) \cdot W \cdot L_{\mathrm{ch}}$	$(3.453 \cdot 10^{-11}/t_{\mathrm{ox}}) \cdot W \cdot L_{\mathrm{ch}}$
C_{oxD}	COXD	$(3.453 \cdot 10^{-11}/t_{\mathrm{ox}}) \cdot W \cdot L_{\mathrm{dr}}$	$(3.453 \cdot 10^{-11}/t_{\mathrm{ox}}) \cdot W \cdot L_{\mathrm{dr}}$
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 cannot 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 strategy is described, for 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 the model and measurements.

Step	Optimised Parameters	Measurement	Fitted on	abs/ rel	Specific Conditions
1	$\phi_{\rm B}$, k_0	I (idvg), $T = T_{\rm ref}$	$I_{\rm D}$	abs	$I_{\rm D} < 0.1 \cdot I_{{\rm D},\max_{\rm idvg}}$
2	$\phi_{\rm B}$, m_0, $\sigma_{\rm dibl}$, $m_{\sigma_{\rm dibl}}$	II (subvt), $T = T_{\rm ref}$	$I_{\rm D}$	rel	$I_{\rm D} < 0.1 \cdot I_{{\rm D},\max_{\rm idvg}}$
3	$S_{T;\phi_{\rm B}}$	I (idvg), $T = T_{\rm min}, \ldots, T_{\rm max}$	$I_{\rm D}$	abs	$I_{\rm D} < 0.1 \cdot I_{{\rm D},\max_{\rm idvg}}$
4	θ_1, θ_3, η_{θ_3}	IV (idvdh), $T = T_{\rm min}, \ldots, T_{\rm max}$	$I_{\rm D}$	abs	in saturation
5	θ_{3D}, $\eta_{\theta_{3D}}$	IV (idvdh), $T = T_{\rm min}, \ldots, T_{\rm max}$	$I_{\rm D}$	abs	in saturation
6	β, η_β	IV (idvdh), $T = T_{\rm min}, \ldots, T_{\rm max}$	$I_{\rm D}$	abs	in saturation
7	α, $V_{\rm P}$, $\sigma_{\rm sf}$	III (idvd), $T = T_{\rm ref}$	$g_{\rm DS}$	rel	in saturation, $V_{\rm GS} < V_T + 3.1$ V
8	β, η_β	III (idvd), $T = T_{\rm ref}$	$g_{\rm DS}$	rel	in saturation, $V_{\rm GS} = V_T + 3.1$ V
9	$\beta_{\rm acc}$, $\eta_{\beta_{\rm acc}}$, $R_{\rm D}$	IV (idvdh), $T = T_{\rm min}, \ldots, T_{\rm max}$	$I_{\rm D}$	abs	in linear region, $\eta_{R_{\rm D}} = \eta_{\beta_{\rm acc}}$
10	$\theta_{\rm 1acc}$	I (idvg), $T = T_{\rm ref}$	$I_{\rm D}$	abs	-
11	θ_2	III (idvd), $T = T_{\rm ref}$	$I_{\rm D}$	abs	$V_{\rm SB} > 0$
12	$\lambda_{\rm D}$	I (idvg), $T = T_{\rm ref}$	$I_{\rm D}$	abs	$V_{\rm SB} > 0$
13	a_{1ch}, a_{2ch}, a_{3ch}	V (ibvg), $T = T_{\rm ref}$	$I_{\rm B}$	abs	-
15	$S_{T;a_{1ch}}$	V (ibvg), $T = T_{\rm min}, \ldots, T_{\rm max}$	$I_{\rm B}$	abs	-
16	a_{1dr}, a_{2dr}, a_{3dr}	V (ibvg), $T = T_{\rm ref}$	$I_{\rm B}$	abs	-
17	$S_{T;a_{1dr}}$	V (ibvg), $T = T_{\rm min}, \ldots, T_{\rm max}$	$I_{\rm B}$	abs	-

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

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 the model and measurements.

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

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

5.3 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 $\Delta W_{\rm D}$, since it affects the DC, the AC, and the noise model; see Section 3.2.3. Here, ΔW and $\Delta W_{\rm D}$ can be determined from the extrapolated zero-crossing in the gain factors β and $\beta_{\rm acc}$ (or $1/R_{\rm D}$), respectively, versus mask width W. As an LDMOS transistor may have different mask widths for the source and the drain, different values of ΔW and $\Delta W_{\rm D}$ can also 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 to the width can be found. For the determination of a geometry-scaled parameter set, a three-step procedure is recommended:

1. determine minisets ($\phi_{\rm B}$, k_0, β, $\ldots$) including temperature scaling for all measured devices, as explained in Section 5.2.
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.

6 Pstar-Specific Items

6.1 Syntax

Model without self-heating:

n-channel geometrical model : mn_i (D,G,S,B) <parameters>
p-channel geometrical model : mp_i (D,G,S,B) <parameters>
n-channel electrical model : mne_i (D,G,S,B) <parameters>
p-channel electrical model : mpe_i (D,G,S,B) <parameters>

Model including self-heating:

n-channel geometrical model : mnt_i (D,G,S,B,dT) <parameters>
p-channel geometrical model : mpt_i (D,G,S,B,dT) <parameters>
n-channel electrical model : mnet_i (D,G,S,B,dT) <parameters>
p-channel electrical model : mpet_i (D,G,S,B,dT) <parameters>

where:

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

D, G, S, and B are the drain, gate, source, and bulk terminals respectively. For the model including self-heating, the extra terminal dT is required (see Section 4.5).

6.2 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.

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

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	Threshold voltage of the drift region: $V_{\mathrm{TOD}} = V_{\mathrm{FBD}T} - \phi_{\mathrm{BD}T} - k_{0\mathrm{D}} \cdot \sqrt{\phi_{\mathrm{BD}T}}$
10	$V_{\mathrm{DiS_{eff}}}$	VDISEFF	V	Effective internal drain to source voltage at actual bias
11	$V_{\mathrm{DiSsat_{eff}}}$	VDISSAT	V	Saturation voltage of the channel region at actual bias
12	V_{DDisat}	VDDISAT	V	Saturation voltage of the drift region at actual bias
13	g_{m}	GM	A/V	Transconductance (assuming that $V_{\mathrm{DS}} > 0$): $g_{\mathrm{m}} = \partial I_{\mathrm{DS}} / \partial V_{\mathrm{GS}}$
14	g_{mb}	GMB	A/V	Substrate-transconductance (assuming $V_{\mathrm{DS}} > 0$): $g_{\mathrm{mb}} = \partial I_{\mathrm{DS}} / \partial V_{\mathrm{BS}}$
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	$C_{\mathrm{DD}} = \partial Q_{\mathrm{D}} / \partial V_{\mathrm{DS}}$
17	C_{DG}	CDG	F	$C_{\mathrm{DG}} = -\partial Q_{\mathrm{D}} / \partial V_{\mathrm{GS}}$
18	C_{DS}	CDS	F	$C_{\mathrm{DS}} = C_{\mathrm{DD}} - C_{\mathrm{DG}} - C_{\mathrm{DB}}$
19	C_{DB}	CDB	F	$C_{\mathrm{DB}} = \partial Q_{\mathrm{D}} / \partial V_{\mathrm{SB}}$
20	C_{GD}	CGD	F	$C_{\mathrm{GD}} = -\partial Q_{\mathrm{G}} / \partial V_{\mathrm{DS}}$
21	C_{GG}	CGG	F	$C_{\mathrm{GG}} = \partial Q_{\mathrm{G}} / \partial V_{\mathrm{GS}}$
22	C_{GS}	CGS	F	$C_{\mathrm{GS}} = C_{\mathrm{GG}} - C_{\mathrm{GD}} - C_{\mathrm{GB}}$
23	C_{GB}	CGB	F	$C_{\mathrm{GB}} = \partial Q_{\mathrm{G}} / \partial V_{\mathrm{SB}}$
24	C_{SD}	CSD	F	$C_{\mathrm{SD}} = -\partial Q_{\mathrm{S}} / \partial V_{\mathrm{DS}}$
25	C_{SG}	CSG	F	$C_{\mathrm{SG}} = -\partial Q_{\mathrm{S}} / \partial V_{\mathrm{GS}}$
26	C_{SS}	CSS	F	$C_{\mathrm{SS}} = C_{\mathrm{SG}} + C_{\mathrm{SD}} + C_{\mathrm{SB}}$
27	C_{SB}	CSB	F	$C_{\mathrm{SB}} = \partial Q_{\mathrm{S}} / \partial V_{\mathrm{SB}}$
28	C_{BD}	CBD	F	$C_{\mathrm{BD}} = -\partial Q_{\mathrm{B}} / \partial V_{\mathrm{DS}}$
29	C_{BG}	CBG	F	$C_{\mathrm{BG}} = -\partial Q_{\mathrm{B}} / \partial V_{\mathrm{GS}}$
30	C_{BS}	CBS	F	$C_{\mathrm{BS}} = C_{\mathrm{BB}} - C_{\mathrm{BD}} - C_{\mathrm{BG}}$
31	C_{BB}	CBB	F	$C_{\mathrm{BB}} = -\partial Q_{\mathrm{B}} / \partial V_{\mathrm{SB}}$
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: $u = g_{\mathrm{m}} / g_{\mathrm{ds}}$
35	R_{out}	ROUT	Ω	Small-signal output resistance: $R_{\mathrm{out}} = 1 / g_{\mathrm{ds}}$
36	V_{Early}	VEARLY	V	Equivalent Early voltage: $V_{\mathrm{Early}} = \lvert I_{\mathrm{DS}} \rvert / g_{\mathrm{ds}}$
37	β_{eff}	BEFF	$\mathrm{A/V^2}$	Gain factor: $\beta_{\mathrm{eff}} = 2 \cdot \lvert I_{\mathrm{DS}} \rvert / V_{\mathrm{inv_{ex0}}}^{2}$
38	f_{T}	FUG	Hz	Unity gain frequency at actual bias: $f_{\mathrm{T}} = \dfrac{g_{\mathrm{m}}}{2 \cdot \pi \cdot (C_{\mathrm{GG}} + C_{\mathrm{GSO}} + C_{\mathrm{GDO}})}$
39	$g_{\mathrm{m_{ch}}}$	GMMOS	A/V	Transconductance of the channel region
40	$\sqrt{S_{\mathrm{V_{Gth}}}}$	SQRTSFW	$\mathrm{V}/\sqrt{\mathrm{Hz}}$	Input-referred RMS thermal noise voltage density: $\sqrt{S_{\mathrm{V_{Gth}}}} = \sqrt{S_{\mathrm{D_{th}}}} / g_{\mathrm{m_{ch}}}$
41	$\sqrt{S_{\mathrm{V_{Gfl}}}}$	SQRTSFF	$\mathrm{V}/\sqrt{\mathrm{Hz}}$	Input-referred RMS flicker noise voltage density at 1 kHz: $\sqrt{S_{\mathrm{V_{Gfl}}}} = \sqrt{S_{\mathrm{D_{fl}}}[1\mathrm{kHz}]} / g_{\mathrm{m_{ch}}}$
42	f_{knee}	FKNEE	Hz	Cross-over frequency above which thermal noise is dominant: $f_{\mathrm{knee}} = 1\mathrm{Hz} \cdot S_{\mathrm{D_{fl}}}[1\mathrm{Hz}] / S_{\mathrm{D_{th}}}$

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A Auxiliary Functions

The hyp function:

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

The hypm function:

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