PSP 101.0

The PSP model is a joint development of The Pennsylvania State University and Philips Research

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Abstract: The PSP model is a compact MOSFET model intended for digital, analogue, and RF-design, which has been jointly developed by Philips Research and The Pennsylvania State University. The roots of PSP lie in both MOS Model 11 (Philips Research) and SP (Penn State University). PSP is a surface-potential based MOS Model, containing all relevant physical effects (mobility reduction, velocity saturation, DIBL, gate current, lateral doping gradient effects, STI stress, etc.) to model present-day and upcoming deep-submicron bulk CMOS technologies. A source/drain junction model, c.q. the JUNCAP2 model, is an integrated part of PSP. This report contains a full description of the PSP model, including parameter sets, scaling rules, model equations, and a description of the parameter extraction procedure.
In December 2005, the Compact Model Council (CMC) has elected PSP as the new industrial standard model for compact MOSFET modeling.

History of model and documentation

History of the model

April 2005 Release of PSP 100.0 (which includes JUNCAP2 200.0) as part of SiMKit 2.1. A Verilog-A implementation of the PSP-model is made available as well. The PSP-NQS model is released as Verilog-A code only.

August 2005 Release of PSP 100.1 (which includes JUNCAP2 200.1) as part of SiMKit 2.2. Similar to the previous version, a Verilog-A implementation of the PSP-model is made available as well and the PSP-NQS model is released as Verilog-A code only. Focus of this release was mainly on the optimization of the evaluation speed of PSP. Moreover, the PSP implementation has been extended with operating point output (SiMKit-version only).

March 2006 Release of PSP 101.0 (which includes JUNCAP2 200.1) as part of SiMKit 2.3. PSP 101.0 is *not* backward compatible with PSP 100.1. Similar to the previous version, a Verilog-A implementation of the PSP-model is made available as well and the PSP-NQS model is released as Verilog-A code only. Focus of this release was on the implementation of requirements for CMC standardization, especially those which could not preserve backward compatibility. The most important changes comprise:

General

- A complete set of binning scaling rules has been added as a phenomenological alternative to the physics-based geometrical scaling rules.
- BSIM-like instance parameters **AS**, **AD**, **PS**, and **PD** were added for the junction model.
- To avoid confusion between zeros and “O”s, zeros no longer occur in parameter names. They have all been replaced by “O”s.
- Some global parameter names have an additional “O” in their names in order to avoid duplicate names in the global and local model.

Modification of the local model

- The parameters **AF**, **BF**, **F0**, and **NSUB** have been removed. They have been replaced by **DPHIB** and **NEFF**. These modifications improve both the short-channel fits and the reciprocity of capacitances at $V_{\mathrm{DS}} = 0$.
- The CLM-model has been modified to improve the Gummel-symmetry properties of the model.
- The drain-induced barrier lowering model has been modified.
- The new parameter **FETA** has been introduced as an alternative for **XCOR**.
- The range of the parameters **THESATG**, **THESATB**, **RSG**, and **RSB** has been extended to included negative values.
- Inner-fringe capacitances have been removed, in order to ensure the reciprocity of capacitances at $V_{\mathrm{DS}} = 0$.
- Model behavior at large (> 1 V) forward V_{B} has been improved.
- Gummel-symmetry properties at forward V_{B} have been improved.
- The parameter **SO** has been removed. Its value was fixed to the default (**SO** $= 0.98$).

Modifications of the global model

- Length-scaling for **CS** has been added; this greatly improves short-channel I_{D} and g_{m} vs. V_{G} fits.
- Scaling rules for the new parameters **NEFF** and **DPHIB** have been added.
- An $L \cdot W$-scaling term has been added for **THESAT** and **CT**.
- **ALP2** scaling has been modified.
- L-scaling for **A4** has been added.
- Parameters **DLQ** and **DWQ** have been added to allow for an offset in ΔL between IV and CV.

Maintenance

- Gate current now exactly vanishes at zero bias.
- Some numerical issues have been solved.
- Some minor bugs in the JUNCAP2-implementation within PSP have been solved.
- Junctions are no longer swapped when $V_{\mathrm{DS}} < 0$.

History of the documentation

April 2005 First release of PSP (PSP 100.0) documentation.

August 2005 Documentation updated for PSP 100.1, errors corrected and new items added.

March 2006 Documentation adapted to PSP 101.0. Added more details on noise-model implementation and a full description of the NQS-model.

Contents

Section 1

Introduction

1.1 Origin and purpose

The PSP model is a compact MOSFET model intended for digital, analogue, and RF-design, which has been jointly developed by Philips Research and The Pennsylvania State University. The roots of PSP lie in both *MOS Model 11* (Philips) and *SP* (PennState). PSP is a surface-potential based MOS Model, containing all relevant physical effects (mobility reduction, velocity saturation, DIBL, gate current, lateral doping gradient effects, STI stress, etc.) to model present-day and upcoming deep-submicron bulk CMOS technologies. The source/drain junction model, c.q. the JUNCAP2 model, is fully integrated in PSP.

PSP not only gives an accurate description of currents, charges, and their first order derivatives (i.e. transconductance, conductance and capacitances), but also of the higher order derivatives, resulting in an accurate description of electrical distortion behavior. The latter is especially important for analog and RF circuit design. The model furthermore gives an accurate description of the noise behavior of MOSFETs. Finally, PSP has an option for simulation of non-quasi-static (NQS) effects.

The source code of PSP and the most recent version of this documentation are available on the Philips Semiconductors web site: `www.semiconductors.philips.com/philips_models`.

1.2 Structure of PSP

The PSP model has a hierarchical structure, similar to that of MOS Model 11 and SP. This means that there is a strict separation of the geometry scaling in the global model and the model equations in the local model.

As a consequence, PSP can be used at either one of two levels.

- **Global level** One uses a global parameter set, which describes a whole geometry range. Combined with instance parameters (such as L and W), a local parameter set is internally generated and further processed at the local level in exactly the same way as a custom-made local parameter set.
- **Local level** One uses a custom-made local parameter set to simulate a transistor with a specific geometry. Temperature scaling is included at this level.

The set of parameters which occur in the equations for the various electrical quantities is called the *local* parameter set. In PSP, temperature scaling parameters are included in the local parameter set. An overview of the local parameters in PSP is given in Section 2.5.6. Each of these parameters can be determined by purely electrical measurements. As a consequence, a local parameter set gives a complete description of the electrical properties of a device of *one* particular geometry.

Since most of these (local) parameters scale with geometry, all transistors of a particular process can be described by a (larger) set of parameters, called the *global* parameter set. An overview of the global parameters in PSP is given in Section 2.5.3. Roughly speaking, this set contains all local parameters for a long/wide device

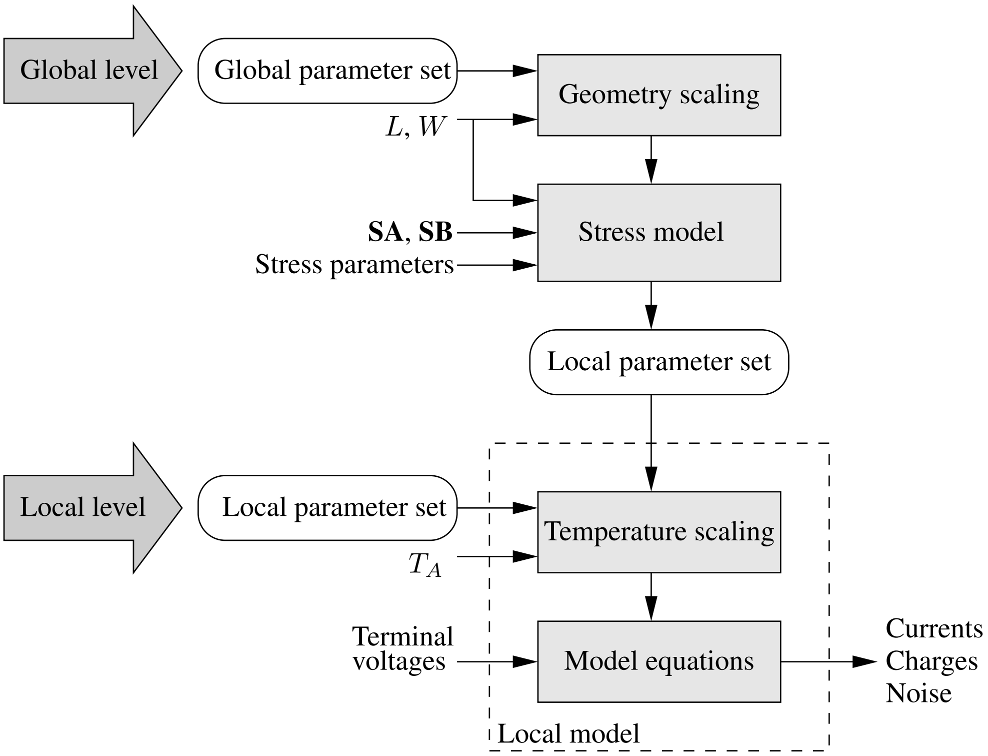

Figure 1.1: Simplified schematic overview of PSP's hierarchical structure.

plus a number of sensitivity coefficients. From the global parameter set, one can obtain a local parameter set for a specific device by applying a set of scaling rules (see Section 3.3). The geometric properties of that specific device (such as its length and width) enter these scaling rules as *instance parameters*.

From PSP 101.0 onwards it is possible to use a set of binning rules (see Section 3.4) as an alternative to the geometrical (physics based) scaling rules. These binning rules come with their own set of parameters (see Section 2.5.4). Similar to the geometrical scaling rules, the binning rules yield a local parameter set which is used as input for the local model.

PSP is preferably used at global level when designing a circuit in a specific technology for which a global parameter set is available. On the other hand, using PSP at local level can be advantageous during parameter extraction.

As an option, it is possible to deal with the modification of transistor properties due to stress. In PSP, this is implemented by an additional set of transformation rules, which are optionally applied to the intermediate local parameter set generated at the global level. The parameters associated with the stress model are consequently part of the global parameter set (both geometrical and binning).

The model structure described above is schematically depicted in Fig. 1.1.

The JUNCAP2 model is implemented in such a way that the same set of JUNCAP2 parameters can be used at both the global and the local level. This is further explained in Section 6.3.

1.3 Availability

The PSP model developers (The Pennsylvania State University and Philips Research) distribute the PSP code in two formats:

1. Verilog-A code
2. C-code (as part of SiMKit)

The C-version is automatically generated from the Verilog-A version by a software package called ADMS [1]. This procedure guarantees the two implementations to contain identical equations. Nevertheless—due to some specific limitations/capabilities of the two formats—there are a few minor differences, which are described in Section 6.4.

1.3.1 SiMKit

SiMKit is a simulator-independent compact transistor model library. Simulator-specific connections are handled through so-called adapters that provide the correct interfacing to the circuit simulator of choice. Currently, adapters to the following circuit simulators are provided:

1. Spectre (Cadence)
2. Pstar (Philips)
3. ADS (Agilent)

Section 2

Constants and Parameters

2.1 Nomenclature

The nomenclature of the quantities listed in the following sections has been chosen to express their purpose and their relation to other quantities and to preclude ambiguity and inconsistency. Throughout this document, all PSP parameter names are printed in boldface capitals. Parameters which refer to the long transistor limit and/or the reference temperature have a name containing an '**O**', while the names of scaling parameters end with the letter '**L**' and/or '**W**' for length or width scaling, respectively. Parameters for temperature scaling start with '**ST**', followed by the name of the parameter to which the temperature scaling applies. Parameters used for the binning model start with '**PO**', '**PL**', '**PW**', or '**PLW**', followed by the name of the local parameter they refer to.

2.2 Parameter clipping

For most parameters, a maximum and/or minimum value is given in the tables below. In PSP, all parameters are limited (clipped) to this pre-specified range in order to prevent difficulties in the numerical evaluation of the model, such as division by zero.

N.B. After computation of the scaling rules (either physical or binning) and stress equations, the resulting local parameters are subjected to the clipping values as given in Section 2.5.6.

2.3 Circuit simulator variables

External electrical variables

The definitions of the external electrical variables are illustrated in Fig. 2.1. The relationship between these external variables and the internal variables used in Chapter 4 is given in Fig. 6.1.

Symbol	Unit	Description
V_{D}^{e}	V	Potential applied to drain node
V_{G}^{e}	V	Potential applied to gate node
V_{S}^{e}	V	Potential applied to source node
V_{B}^{e}	V	Potential applied to bulk node
I_{D}^{e}	A	DC current into drain node
I_{G}^{e}	A	DC current into gate node

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Symbol	Unit	Description
I^e_S	A	DC current into source node
I^e_B	A	DC current into bulk node
S^e_fl	$\mathrm{A^2s}$	Spectral density of flicker noise current in the channel
S^e_id	$\mathrm{A^2s}$	Spectral density of thermal noise current in the channel
$S^e_\mathrm{ig,S}$	$\mathrm{A^2s}$	Spectral density of induced gate noise at source side
$S^e_\mathrm{ig,D}$	$\mathrm{A^2s}$	Spectral density of induced gate noise at drain side
S^e_igs	$\mathrm{A^2s}$	Spectral density of gate current shot noise at source side
S^e_igd	$\mathrm{A^2s}$	Spectral density of gate current shot noise at drain side
$S^e_\mathrm{j,S}$	$\mathrm{A^2s}$	Spectral density of source junction shot noise
$S^e_\mathrm{j,D}$	$\mathrm{A^2s}$	Spectral density of drain junction shot noise
S^e_igid	$\mathrm{A^2s}$	Cross spectral density between S^e_id and (S^e_igS or S^e_igD)

Other circuit simulator variables

Next to the electrical variables described above, the quantities in the table below are also provided to the model by the circuit simulator.

Symbol	Unit	Description
T_A	°C	Ambient circuit temperature
f_op	Hz	Operation frequency

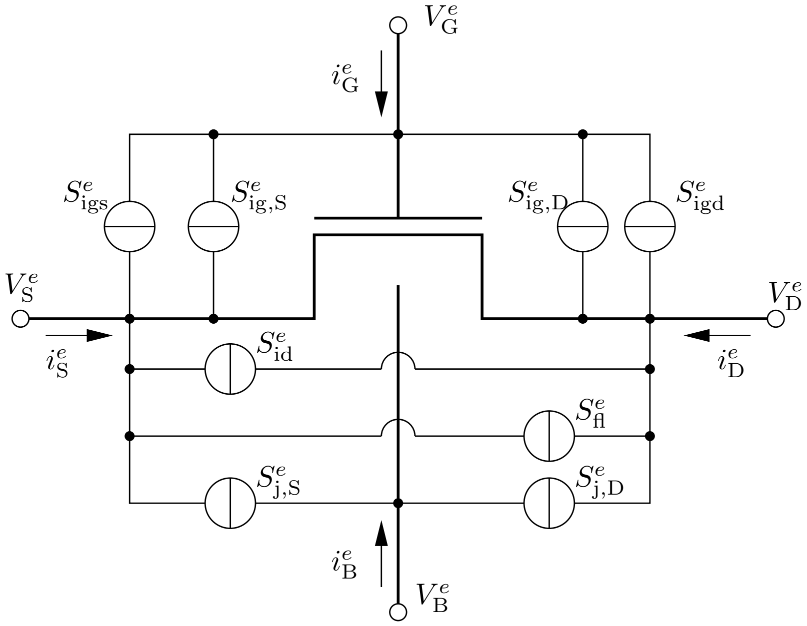
2.4 Model constants

In the following table the symbolic representation, the value and the description of the various physical constants used in the PSP model are given.

No.	Symbol	Unit	Value	Description
1	T_0	K	273.15	Offset between Celsius and Kelvin temperature scale
2	k_B	J/K	$1.3806505 \cdot 10^{-23}$	Boltzmann constant
3	$\hbar$	J s	$1.05457168 \cdot 10^{-34}$	Reduced Planck constant
4	q	C	$1.6021918 \cdot 10^{-19}$	Elementary unit charge
5	m_0	kg	$9.1093826 \cdot 10^{-31}$	Electron rest mass
6	ϵ_ox	F/m	$3.453 \cdot 10^{-11}$	Absolute permittivity of oxide
7	ϵ_Si	F/m	$1.045 \cdot 10^{-10}$	Absolute permittivity of silicon
8	QM_N	$\mathrm{V\,m^{\frac{4}{3}}C^{-\frac{2}{3}}}$	5.951993	Constant of quantum-mechanical behavior of electrons
9	QM_P	$\mathrm{V\,m^{\frac{4}{3}}C^{-\frac{2}{3}}}$	7.448711	Constant of quantum-mechanical behavior of holes

2.5 Model parameters

In this section all parameters of the PSP-model are described. The parameters for the intrinsic MOS model, the stress model and the junction model are given in separate tables. The complete parameter list for each of the



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

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

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

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

Figure 2.1: Definition of external electrical quantities.

model entry levels is composed of several parts, as indicated in the table below.

Entry level	**Sections**
Global (geometrical)	2.5.1 (instance parameters) 2.5.3 (intrinsic MOS) 2.5.5 (stress) 2.5.7 (junctions)
Global (binning)	2.5.1 (instance parameters) 2.5.4 (intrinsic MOS) 2.5.5 (stress) 2.5.7 (junctions)
Local	2.5.2 (instance parameters) 2.5.6 (intrinsic MOS) 2.5.7 (junctions)

2.5.1 Instance parameters at global level

No.	**Name**	**Unit**	**Default**	**Min.**	**Max.**	**Description**
0	L	m	$1 \cdot 10^{-6}$	$1 \cdot 10^{-9}$	–	Drawn channel length
1	W	m	$1 \cdot 10^{-6}$	$1 \cdot 10^{-9}$	–	Drawn channel width
2	**SA**	m	0	–	–	Distance between OD-edge and poly at source side
3	**SB**	m	0	–	–	Distance between OD-edge and poly at drain side
4	**ABSOURCE**	m^2	$1 \cdot 10^{-12}$	0	–	Source junction area

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No.	Name	Unit	Default	Min.	Max.	Description
5	**LSSOURCE**	m	$1 \cdot 10^{-6}$	0	–	STI-edge part of source junction perimeter
6	**LGSOURCE**	m	$1 \cdot 10^{-6}$	0	–	Gate-edge part of source junction perimeter
7	**ABDRAIN**	m^2	$1 \cdot 10^{-12}$	0	–	Drain junction area
8	**LSDRAIN**	m	$1 \cdot 10^{-6}$	0	–	STI-edge part of drain junction perimeter
9	**LGDRAIN**	m	$1 \cdot 10^{-6}$	0	–	Gate-edge part of drain junction perimeter
10	**AS**	m^2	$1 \cdot 10^{-12}$	0	–	Source junction area (alternative spec.)
11	**PS**	m	$1 \cdot 10^{-6}$	0	–	Source STI-edge perimeter (alternative spec.)
12	**AD**	m^2	$1 \cdot 10^{-12}$	0	–	Drain junction area (alternative spec.)
13	**PD**	m	$1 \cdot 10^{-6}$	0	–	Drain STI-edge perimeter (alternative spec.)
14	**MULT**	–	1	0	–	Number of devices in parallel

Note that if both **SA** and **SB** are set to 0, the stress-equations are not computed.

The switching parameter **SWJUNCAP** is used to determine the meaning and usage of the junction instance parameters, where **AB** (junction area), **LS** (STI-edge part of junction perimeter), and **LG** (gate-edge part of junction perimeter) are the instance parameters of a single instance (source or drain) of the JUNCAP2 model.

	source			drain		
SWJUNCAP	**AB**	**LS**	**LG**	**AB**	**LS**	**LG**
0	0	0	0	0	0	0
1	**ABSOURCE**	**LSSOURCE**	**LGSOURCE**	**ABDRAIN**	**LSDRAIN**	**LGDRAIN**
2	**AS**	**PS**	0	**AD**	**PD**	0
3	**AS**	**PS** $- W_\mathrm{E}$	W_E	**AD**	**PD** $- W_\mathrm{E}$	W_E

2.5.2 Instance parameters at local level

As explained in Section 6.3, the instance parameters for the JUNCAP2 model are used at the local level as well.

No.	Name	Unit	Default	Min.	Max.	Description
0	**ABSOURCE**	m^2	$1 \cdot 10^{-12}$	0	–	Source junction area
1	**LSSOURCE**	m	$1 \cdot 10^{-6}$	0	–	STI-edge part of source junction perimeter
2	**LGSOURCE**	m	$1 \cdot 10^{-6}$	0	–	Gate-edge part of source junction perimeter
3	**ABDRAIN**	m^2	$1 \cdot 10^{-12}$	0	–	Drain junction area
4	**LSDRAIN**	m	$1 \cdot 10^{-6}$	0	–	STI-edge part of drain junction perimeter
5	**LGDRAIN**	m	$1 \cdot 10^{-6}$	0	–	Gate-edge part of drain junction perimeter
6	**AS**	m^2	$1 \cdot 10^{-12}$	0	–	Source junction area (alternative spec.)
7	**PS**	m	$1 \cdot 10^{-6}$	0	–	Source STI-edge perimeter (alternative spec.)

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No.	Name	Unit	Default	Min.	Max.	Description
8	**AD**	m^2	$1 \cdot 10^{-12}$	0	–	Drain junction area (alternative spec.)
9	**PD**	m	$1 \cdot 10^{-6}$	0	–	Drain STI-edge perimeter (alternative spec.)
10	**JW**	m	$1 \cdot 10^{-6}$	0	–	Junction width
11	**MULT**	–	1	0	–	Number of devices in parallel

Also at the local level, the switching parameter **SWJUNCAP** is used to determine the meaning and usage of the junction instance parameters, where **AB** (junction area), **LS** (STI-edge part of junction perimeter), and **LG** (gate-edge part of junction perimeter) are the instance parameters of a single instance (source or drain) of the JUNCAP2 model. Because the transistor width W is not available at the local level, an additional instance parameter **JW** (junction width) is required when **SWJUNCAP** $= 3$ or 4.

	source			drain		
SWJUNCAP	**AB**	**LS**	**LG**	**AB**	**LS**	**LG**
0	0	0	0	0	0	0
1	**ABSOURCE**	**LSSOURCE**	**LGSOURCE**	**ABDRAIN**	**LSDRAIN**	**LGDRAIN**
2	**AS**	**PS**	0	**AD**	**PD**	0
3	**AS**	**PS** – **JW**	**JW**	**AD**	**PD** – **JW**	**JW**

2.5.3 Parameters for physical geometrical scaling rules (global model)

The physical geometry scaling rules of PSP (see Section 3.3) have been developed to give a good description over the whole geometry range of CMOS technologies.

No.	Name	Unit	Default	Min.	Max.	Description
0	**LEVEL**	–	1010	–	–	Model selection parameter; see Sec. 6.1
1	**TYPE**	–	1	-1	1	Channel type parameter; 1 ↔ NMOS, -1 ↔ PMOS
2	**TR**	°C	21	-273	–	Reference temperature
			Switch Parameters			
3	**SWIGATE**	–	0	0	1	Flag for gate current (0 ↔ “off”)
4	**SWIMPACT**	–	0	0	1	Flag for impact ionization current (0 ↔ “off”)
5	**SWGIDL**	–	0	0	1	Flag for GIDL/GISL current (0 ↔ “off”)
6	**SWJUNCAP**	–	0	0	3	Flag for JUNCAP (0 ↔ “off”); see Sec. 2.5.1
7	**QMC**	–	1	0	–	Quantum-mechanical correction factor
			Process Parameters			
8	**LVARO**	m	0	–	–	Geometry independent difference between actual and programmed poly-silicon gate length
9	**LVARL**	–	0	–	–	Length dependence of ΔL_{PS}
10	**LVARW**	–	0	–	–	Width dependence of ΔL_{PS}
11	**LAP**	m	0	–	–	Effective channel length reduction per side due to lateral diffusion of source/drain dopant ions
12	**WVARO**	m	0	–	–	Geometry independent difference between actual and programmed field-oxide opening
13	**WVARL**	–	0	–	–	Length dependence of ΔW_{OD}
14	**WVARW**	–	0	–	–	Width dependence of ΔW_{OD}
15	**WOT**	m	0	–	–	Effective reduction of channel width per side due to lateral diffusion of channel-stop dopant ions
16	**DLQ**	m	0	–	–	Effective channel length offset for CV
17	**DWQ**	m	0	–	–	Effective channel width offset for CV
18	**VFBO**	V	-1	–	–	Geometry-independent flat-band voltage at **TR**
19	**VFBL**	–	0	–	–	Length dependence **VFB**
20	**VFBW**	–	0	–	–	Width dependence of **VFB**
21	**VFBLW**	–	0	–	–	Area dependence of **VFB**
22	**STVFBO**	V/K	$5 \cdot 10^{-4}$	–	–	Geometry-independent temperature dependence of **VFB**
23	**STVFBL**	–	0	–	–	Length dependence of **STVFB**

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No.	Name	Unit	Default	Min.	Max.	Description
24	**STVFBW**	–	0	–	–	Width dependence of **STVFB**
25	**STVFBLW**	–	0	–	–	Area dependence of **STVFB**
26	**TOXO**	m	$2 \cdot 10^{-9}$	10^{-10}	–	Gate oxide thickness
27	**NSUBO**	m^{-3}	$3 \cdot 10^{23}$	10^{20}	–	Geometry independent substrate doping
28	**NSUBW**	–	0	–	–	Width dependence of substrate doping due to segregation
29	**WSEG**	m	10^{-8}	10^{-10}	–	Characteristic length for segregation of substrate doping
30	**NPCK**	m^{-3}	10^{24}	0	–	Pocket doping level
31	**NPCKW**	–	0	–	–	Width dependence of **NPCK** due to segregation
32	**WSEGP**	m	10^{-8}	10^{-10}	–	Characteristic length for segregation of pocket doping
33	**LPCK**	m	10^{-8}	10^{-10}	–	Characteristic length for lateral doping profile
34	**LPCKW**	–	0	–	–	Width dependence of **LPCK** due to segregation
35	**FOL1**	–	0	–	–	First order length dependence of short channel body-effect
36	**FOL2**	–	0	–	–	Second order length dependence of short channel body-effect
37	**VNSUBO**	V	0	–	–	Effective doping bias-dependence parameter
38	**NSLPO**	V	0.05	–	–	Effective doping bias-dependence parameter
39	**DNSUBO**	V^{-1}	0	–	–	Effective doping bias-dependence parameter
40	**DPHIBO**	V	0	–	–	Geometry independent offset of φ_{B}
41	**DPHIBL**	–	0	–	–	Length dependence of **DPHIB**
42	**DPHIBLEXP**	–	1	–	–	Exponent for length dependence of **DPHIB**
43	**DPHIBW**	–	0	–	–	Width dependence of **DPHIB**
44	**DPHIBLW**	–	0	–	–	Area dependence of **DPHIB**
45	**NPO**	m^{-3}	10^{26}	–	–	Geometry-independent gate poly-silicon doping
46	**NPL**	–	0	–	–	Length dependence of **NP**
47	**CTO**	–	0	–	–	Geometry-independent part of interface states factor **CT**
48	**CTL**	–	0	–	–	Length dependence of **CT**
49	**CTLEXP**	–	1	–	–	Exponent describing length dependence of **CT**
50	**CTW**	–	0	–	–	Width dependence of **CT**
51	**CTLW**	–	0	–	–	Area dependence of **CT**

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No.	Name	Unit	Default	Min.	Max.	Description
52	**TOXOVO**	m	$2 \cdot 10^{-9}$	10^{-10}	–	Overlap oxide thickness
53	**LOV**	m	0	0	–	Overlap length for gate/drain and gate/source overlap capacitance
54	**NOVO**	m^{-3}	$5 \cdot 10^{25}$	–	–	Effective doping of overlap region
			DIBL-Parameters			
55	**CFL**	V^{-1}	0	–	–	Length dependence of DIBL-parameter
56	**CFLEXP**	–	2	–	–	Exponent for length dependence of **CF**
57	**CFW**	–	0	–	–	Width dependence of **CF**
58	**CFBO**	V^{-1}	0	0	1	Back-bias dependence of **CF**
			Mobility Parameters			
59	**UO**	$\mathrm{m}^2/\mathrm{V/s}$	$5 \cdot 10^{-2}$	–	–	Zero-field mobility at **TR**
60	**FBET1**	–	0	–	–	Relative mobility decrease due to first lateral profile
61	**FBET1W**	–	0	–	–	Width dependence of **FBET1**
62	**LP1**	m	10^{-8}	10^{-10}	–	Mobility-related characteristic length of first lateral profile
63	**LP1W**	–	0	–	–	Width dependence of **LP1**
64	**FBET2**	–	0	–	–	Relative mobility decrease due to second lateral profile
65	**LP2**	m	10^{-8}	10^{-10}	–	Mobility-related characteristic length of second lateral profile
66	**BETW1**	–	0	–	–	First higher-order width scaling coefficient of **BETN**
67	**BETW2**	–	0	–	–	Second higher-order width scaling coefficient of **BETN**
68	**WBET**	m	10^{-9}	10^{-10}	–	Characteristic width for width scaling of **BETN**
69	**STBETO**	–	1	–	–	Geometry independent temperature dependence of **BETN**
70	**STBETL**	–	0	–	–	Length dependence of **STBET**
71	**STBETW**	–	0	–	–	Width dependence of **STBET**
72	**STBETLW**	–	0	–	–	Area dependence of **STBET**
73	**MUEO**	m/V	0.5	–	–	Geometry independent mobility reduction coefficient at **TR**
74	**MUEW**	–	0	–	–	Width dependence of **MUE**
75	**STMUEO**	–	0	–	–	Temperature dependence of **MUE**
76	**THEMUO**	–	1.5	0	–	Mobility reduction exponent at **TR**
77	**STTHEMUO**	–	1.5	–	–	Temperature dependence of **THEMU**
78	**CSO**	–	0	–	–	Geometry independent Coulomb scattering parameter at **TR**
79	**CSL**	–	0	–	–	Length dependence of **CS**
80	**CSLEXP**	–	1	–	–	Exponent for length dependence of **CS**

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No.	Name	Unit	Default	Min.	Max.	Description
81	**CSW**	–	0	–	–	Width dependence of **CS**
82	**CSLW**	–	0	–	–	Area dependence of **CS**
83	**STCSO**	–	0	–	–	Temperature dependence of **CS**
84	**XCORO**	V^{-1}	0	–	–	Geometry independent non-universality parameter
85	**XCORL**	–	0	–	–	Length dependence of **XCOR**
86	**XCORW**	–	0	–	–	Width dependence of **XCOR**
87	**XCORLW**	–	0	–	–	Area dependence of **XCOR**
88	**STXCORO**	–	0	–	–	Temperature dependence of **XCOR**
89	**FETAO**	–	1	–	–	Effective field parameter
Series Resistance Parameters						
90	**RSW1**	Ω	2500	–	–	Source/drain series resistance for channel width $W_{\rm EN}$ at **TR**
91	**RSW2**	–	0	–	–	Higher-order width scaling of source/drain series resistance
92	**STRSO**	–	1	–	–	Temperature dependence of **RS**
93	**RSBO**	V^{-1}	0	–	–	Back-bias dependence of **RS**
94	**RSGO**	V^{-1}	0	–	–	Gate-bias dependence of **RS**
Velocity Saturation Parameters						
95	**THESATO**	V^{-1}	0	–	–	Geometry independent velocity saturation parameter at **TR**
96	**THESATL**	V^{-1}	0.05	–	–	Length dependence of **THESAT**
97	**THESATLEXP**	–	1	–	–	Exponent for length dependence of **THESAT**
98	**THESATW**	–	0	–	–	Width dependence of **THESAT**
99	**THESATLW**	–	0	–	–	Area dependence **THESAT**
100	**STTHESATO**	–	1	–	–	Geometry independent temperature dependence of **THESAT**
101	**STTHESATL**	–	0	–	–	Length dependence of **STTHESAT**
102	**STTHESATW**	–	0	–	–	Width dependence of **STTHESAT**
103	**STTHESATLW**	–	0	–	–	Area dependence of **STTHESAT**
104	**THESATBO**	V^{-1}	0	–	–	Back-bias dependence of **THESAT**
105	**THESATGO**	V^{-1}	0	–	–	Gate-bias dependence of **THESAT**
Saturation Voltage Parameters						
106	**AXO**	–	18	–	–	Geometry independent linear/saturation transition factor
107	**AXL**	–	0.4	0	–	Length dependence of **AX**
Channel Length Modulation (CLM) Parameters						
108	**ALPL**	–	$5 \cdot 10^{-4}$	–	–	Length dependence of CLM pre-factor **ALP**
109	**ALPLEXP**	–	1	–	–	Exponent for length dependence of **ALP**

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No.	Name	Unit	Default	Min.	Max.	Description
110	**ALPW**	–	0	–	–	Width dependence of **ALP**
111	**ALP1L1**	V	0	–	–	Length dependence of CLM enhancement factor above threshold
112	**ALP1LEXP**	–	0.5	–	–	Exponent describing the length dependence of **ALP1**
113	**ALP1L2**	–	0	0	–	Second order length dependence of **ALP1**
114	**ALP1W**	–	0	–	–	Width dependence of **ALP1**
115	**ALP2L1**	V	0	–	–	Length dependence of CLM enhancement factor below threshold
116	**ALP2LEXP**	–	0.5	–	–	Exponent describing the length dependence **ALP2**
117	**ALP2L2**	–	0	0	–	Second order length dependence of **ALP2**
118	**ALP2W**	–	0	–	–	Width dependence of **ALP2**
119	**VPO**	V	0.05	10^{-10}	–	CLM logarithmic dependence parameter
Impact Ionization (II) Parameters						
120	**A1O**	–	1	–	–	Geometry independent part of impact-ionization pre-factor **A1**
121	**A1L**	–	0	–	–	Length dependence of **A1**
122	**A1W**	–	0	–	–	Width dependence of **A1**
123	**A2O**	V	10	–	–	Impact-ionization exponent at **TR**
124	**STA2O**	V	0	–	–	Temperature dependence of **A2**
125	**A3O**	–	1.0	–	–	Geometry independent saturation-voltage dependence of II
126	**A3L**	–	0	–	–	Length dependence of **A3**
127	**A3W**	–	0	–	–	Width dependence of **A3**
128	**A4O**	$\mathrm{V}^{-\frac{1}{2}}$	0	–	–	Geometry independent back-bias dependence of II
129	**A4L**	-	0	–	–	Length dependence of **A4**
130	**A4W**	-	0	–	–	Width dependence of **A4**
Gate Current Parameters						
131	**GCOO**	–	0	–	–	Gate tunneling energy adjustment
132	**IGINVLW**	A	0	–	–	Gate channel current pre-factor for a channel area of $W_{\mathrm{EN}} \cdot L_{\mathrm{EN}}$
133	**IGOVW**	A	0	–	–	Gate overlap current pre-factor for a channel width of $W_{\mathrm{EN}} \cdot L_{\mathrm{EN}}$
134	**STIGO**	–	2	–	–	Temperature dependence of gate current
135	**GC2O**	–	0.375	–	–	Gate current slope factor
136	**GC3O**	–	0.063	–	–	Gate current curvature factor
137	**CHIBO**	V	3.1	1	–	Tunneling barrier height
Gate-Induced Drain Leakage (GIDL) Parameters						
138	**AGIDLW**	$\mathrm{A/V}^3$	0	–	–	Width dependence of GIDL pre-factor

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No.	Name	Unit	Default	Min.	Max.	Description
139	**BGIDLO**	V	41	–	–	GIDL probability factor at **TR**
140	**STBGIDLO**	V/K	0	–	–	Temperature dependence of **BGIDL**
141	**CGIDLO**	–	0	–	–	Back-bias dependence of GIDL
			Charge Model Parameters			
142	**CGBOVL**	F	0	–	–	Oxide capacitance for gate–bulk overlap for an area of $W_{\mathrm{EN}} \cdot L_{\mathrm{EN}}$
143	**CFRW**	F	0	–	–	Outer fringe capacitance for a channel width of W_{EN}
			Noise Model Parameters			
144	**FNTO**	–	1.0	–	–	Thermal noise coefficient
145	**NFALW**	$\mathrm{V}^{-1}/\mathrm{m}^4$	$8 \cdot 10^{22}$	–	–	First coefficient of flicker noise for a channel area of $W_{\mathrm{EN}} \cdot L_{\mathrm{EN}}$
146	**NFBLW**	$\mathrm{V}^{-1}/\mathrm{m}^2$	$3 \cdot 10^{7}$	–	–	Second coefficient of flicker noise for a channel area of $W_{\mathrm{EN}} \cdot L_{\mathrm{EN}}$
147	**NFCLW**	V^{-1}	0	–	–	Third coefficient of flicker noise for a channel area of $W_{\mathrm{EN}} \cdot L_{\mathrm{EN}}$
			Other Parameters			
148	**DTA**	K	0	–	–	Temperature offset w.r.t. ambient circuit temperature

2.5.4 Parameters for binning model

The binning scaling rules of PSP (see Section 3.4) have been developed as a flexible but phenomenological alternative to the geometrical scaling rules.

No.	Name	Unit	Default	Min.	Max.	Description
0	**LEVEL**		1011	–	–	Model selection parameter; see Sec. 6.1
1	**TYPE**		1	-1	1	Channel type parameter; 1 ↔ NMOS, -1 ↔ PMOS
2	**TR**	°C	21	-273	–	reference temperature
			Switch Parameters			
3	**SWIGATE**		0	0	1	Flag for gate current (0 ↔ "off")
4	**SWIMPACT**		0	0	1	Flag for impact ionization current (0 ↔ "off")
5	**SWGIDL**		0	0	1	Flag for GIDL/GISL current (0 ↔ "off")
6	**SWJUNCAP**		0	0	3	Flag for JUNCAP (0 ↔ "off"); see Sec. 2.5.2
7	**QMC**		1	0	–	Quantum-mechanical correction factor
			Process Parameters			
8	**LVARO**	m	0	–	–	Geometry independent difference between actual and programmed poly-silicon gate length
9	**LVARL**	-	0	–	–	Length dependence of difference between actual and programmed poly-silicon gate length
10	**LVARW**	-	0	–	–	Width dependence of difference between actual and programmed poly-silicon gate length
11	**LAP**	m	0	–	–	Effective channel length reduction per side due to lateral diffusion of source/drain dopant ions
12	**WVARO**	m	0	–	–	Geometry independent difference between actual and programmed field-oxide opening
13	**WVARL**	-	0	–	–	Length dependence of difference between actual and programmed field-oxide opening
14	**WVARW**	-	0	–	–	Width dependence of difference between actual and programmed field-oxide opening
15	**WOT**	m	0	–	–	Effective reduction of channel width per side due to lateral diffusion of channel-stop dopant ions
16	**DLQ**	m	0	–	–	Effective channel length reduction for CV
17	**DWQ**	m	0	–	–	Effective channel width reduction for CV
18	**POVFB**	V	-1	–	–	Coefficient for the geometry independent part of flat-band voltage at **TR**

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No.	Name	Unit	Default	Min.	Max.	Description
19	**PLVFB**	V	0	–	–	Coefficient for the length dependence of flat-band voltage at **TR**
20	**PWVFB**	V	0	–	–	Coefficient for the width dependence of flat-band voltage at **TR**
21	**PLWVFB**	V	0	–	–	Coefficient for the length times width dependence of flat-band voltage at **TR**
22	**POSTVFB**	V/K	$5 \cdot 10^{-4}$	–	–	Coefficient for the geometry independent part of temperature dependence of **VFB**
23	**PLSTVFB**	V/K	0	–	–	Coefficient for the length dependence of temperature dependence of **VFB**
24	**PWSTVFB**	V/K	0	–	–	Coefficient for the width dependence of temperature dependence of **VFB**
25	**PLWSTVFB**	V/K	0	–	–	Coefficient for the length times width dependence of temperature dependence of **VFB**
26	**POTOX**	m	$2 \cdot 10^{-9}$	–	–	Coefficient for the geometry independent part of gate oxide thickness
27	**PONEFF**	m^{-3}	$5 \cdot 10^{23}$	–	–	Coefficient for the geometry independent part of substrate doping
28	**PLNEFF**	m^{-3}	0	–	–	Coefficient for the length dependence of substrate doping
29	**PWNEFF**	m^{-3}	0	–	–	Coefficient for the width dependence of substrate doping
30	**PLWNEFF**	m^{-3}	0	–	–	Coefficient for the length times width dependence of substrate doping
31	**POVNSUB**	V	0	–	–	Coefficient for the geometry independent part of effective doping bias-dependence parameter
32	**PONSLP**	V	$5 \cdot 10^{-2}$	–	–	Coefficient for the geometry independent part of effective doping bias-dependence parameter
33	**PODNSUB**	V^{-1}	0	–	–	Coefficient for the geometry independent part of effective doping bias-dependence parameter
34	**PODPHIB**	V	0	–	–	Coefficient for the geometry independent part of offset of ϕ_B
35	**PLDPHIB**	V	0	–	–	Coefficient for the length dependence of offset of ϕ_B
36	**PWDPHIB**	V	0	–	–	Coefficient for the width dependence of offset of ϕ_B
37	**PLWDPHIB**	V	0	–	–	Coefficient for the length times width dependence of offset of ϕ_B
38	**PONP**	m^{-3}	$10 \cdot 10^{25}$	–	–	Coefficient for the geometry independent part of gate poly-silicon doping

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No.	Name	Unit	Default	Min.	Max.	Description
39	**PLNP**	m^{-3}	0	–	–	Coefficient for the length dependence of gate poly-silicon doping
40	**PWNP**	m^{-3}	0	–	–	Coefficient for the width dependence of gate poly-silicon doping
41	**PLWNP**	m^{-3}	0	–	–	Coefficient for the length times width dependence of gate poly-silicon doping
42	**POCT**		0	–	–	Coefficient for the geometry independent part of interface states factor
43	**PLCT**		0	–	–	Coefficient for the length dependence of interface states factor
44	**PWCT**		0	–	–	Coefficient for the width dependence of interface states factor
45	**PLWCT**		0	–	–	Coefficient for the length times width dependence of interface states factor
46	**POTOXOV**	m	$2 \cdot 10^{-9}$	–	–	Coefficient for the geometry independent part of overlap oxide thickness
47	**PONOV**	m^{-3}	$5 \cdot 10^{25}$	–	–	Coefficient for the geometry independent part of effective doping of overlap region
48	**PLNOV**	m^{-3}	0	–	–	Coefficient for the length dependence of effective doping of overlap region
49	**PWNOV**	m^{-3}	0	–	–	Coefficient for the width dependence of effective doping of overlap region
50	**PLWNOV**	m^{-3}	0	–	–	Coefficient for the length times width dependence of effective doping of overlap region
			DIBL Parameters			
51	**POCF**	V^{-1}	0	–	–	Coefficient for the geometry independent part of DIBL parameter
52	**PLCF**	V^{-1}	0	–	–	Coefficient for the length dependence of DIBL parameter
53	**PWCF**	V^{-1}	0	–	–	Coefficient for the width dependence of DIBL parameter
54	**PLWCF**	V^{-1}	0	–	–	Coefficient for the length times width dependence of DIBL parameter
55	**POCFB**	V^{-1}	0	–	–	Coefficient for the geometry independent part of back-bias dependence of **CF**
			Mobility Parameters			
56	**POBETN**	m^2/V/s	$7 \cdot 10^{-2}$	–	–	Coefficient for the geometry independent part of product of channel aspect ratio and zero-field mobility at **TR**
57	**PLBETN**	m^2/V/s	0	–	–	Coefficient for the length dependence of product of channel aspect ratio and zero-field mobility at **TR**

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No.	Name	Unit	Default	Min.	Max.	Description
58	**PWBETN**	m^2/V/s	0	–	–	Coefficient for the width dependence of product of channel aspect ratio and zero-field mobility at **TR**
59	**PLWBETN**	m^2/V/s	0	–	–	Coefficient for the length times width dependence of product of channel aspect ratio and zero-field mobility at **TR**
60	**POSTBET**		1	–	–	Coefficient for the geometry independent part of temperature dependence of **BETN**
61	**PLSTBET**		0	–	–	Coefficient for the length dependence of temperature dependence of **BETN**
62	**PWSTBET**		0	–	–	Coefficient for the width dependence of temperature dependence of **BETN**
63	**PLWSTBET**		0	–	–	Coefficient for the length times width dependence of temperature dependence of **BETN**
64	**POMUE**	m/V	$5 \cdot 10^{-1}$	–	–	Coefficient for the geometry independent part of mobility reduction coefficient at **TR**
65	**PLMUE**	m/V	0	–	–	Coefficient for the length dependence of mobility reduction coefficient at **TR**
66	**PWMUE**	m/V	0	–	–	Coefficient for the width dependence of mobility reduction coefficient at **TR**
67	**PLWMUE**	m/V	0	–	–	Coefficient for the length times width dependence of mobility reduction coefficient at **TR**
68	**POSTMUE**		0	–	–	Coefficient for the geometry independent part of temperature dependence of **MUE**
69	**POTHEMU**		1.5	–	–	Coefficient for the geometry independent part of mobility reduction exponent at **TR**
70	**POSTTHEMU**		1.5	–	–	Coefficient for the geometry independent part of temperature dependence of **THEMU**
71	**POCS**		0	–	–	Coefficient for the geometry independent part of Coulomb scattering parameter at **TR**
72	**PLCS**		0	–	–	Coefficient for the length dependence of Coulomb scattering parameter at **TR**
73	**PWCS**		0	–	–	Coefficient for the width dependence of Coulomb scattering parameter at **TR**
74	**PLWCS**		0	–	–	Coefficient for the length times width dependence of Coulomb scattering parameter at **TR**
75	**POSTCS**		0	–	–	Coefficient for the geometry independent part of temperature dependence of **CS**
76	**POXCOR**	V^{-1}	0	–	–	Coefficient for the geometry independent part of non-universality parameter

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No.	Name	Unit	Default	Min.	Max.	Description
77	**PLXCOR**	V^{-1}	0	–	–	Coefficient for the length dependence of non-universality parameter
78	**PWXCOR**	V^{-1}	0	–	–	Coefficient for the width dependence of non-universality parameter
79	**PLWXCOR**	V^{-1}	0	–	–	Coefficient for the length times width dependence of non-universality parameter
80	**POSTXCOR**		0	–	–	Coefficient for the geometry independent part of temperature dependence of **XCOR**
81	**POFETA**		1	–	–	Coefficient for the geometry independent part of effective field parameter
			Series Resistance Parameters			
82	**PORS**	Ω	30	–	–	Coefficient for the geometry independent part of source/drain series resistance at **TR**
83	**PLRS**	Ω	0	–	–	Coefficient for the length dependence of source/drain series resistance at **TR**
84	**PWRS**	Ω	0	–	–	Coefficient for the width dependence of source/drain series resistance at **TR**
85	**PLWRS**	Ω	0	–	–	Coefficient for the length times width dependence of source/drain series resistance at **TR**
86	**POSTRS**		1	–	–	Coefficient for the geometry independent part of temperature dependence of **RS**
87	**PORSB**	V^{-1}	0	–	–	Coefficient for the geometry independent part of back-bias dependence of **RS**
88	**PORSG**	V^{-1}	0	–	–	Coefficient for the geometry independent part of gate-bias dependence of **RS**
			Velocity Saturation Parameters			
89	**POTHESAT**	V^{-1}	1	–	–	Coefficient for the geometry independent part of velocity saturation parameter at **TR**
90	**PLTHESAT**	V^{-1}	0	–	–	Coefficient for the length dependence of velocity saturation parameter at **TR**
91	**PWTHESAT**	V^{-1}	0	–	–	Coefficient for the width dependence of velocity saturation parameter at **TR**
92	**PLWTHESAT**	V^{-1}	0	–	–	Coefficient for the length times width dependence of velocity saturation parameter at **TR**
93	**POSTTHESAT**		1	–	–	Coefficient for the geometry independent part of temperature dependence of **THESAT**
94	**PLSTTHESAT**		0	–	–	Coefficient for the length dependence of temperature dependence of **THESAT**
95	**PWSTTHESAT**		0	–	–	Coefficient for the width dependence of temperature dependence of **THESAT**

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No.	Name	Unit	Default	Min.	Max.	Description
96	**PLWSTTHESAT**		0	–	–	Coefficient for the length times width dependence of temperature dependence of **THESAT**
97	**POTHESATB**	V^{-1}	0	–	–	Coefficient for the geometry independent part of back-bias dependence of velocity saturation
98	**PLTHESATB**	V^{-1}	0	–	–	Coefficient for the length dependence of back-bias dependence of velocity saturation
99	**PWTHESATB**	V^{-1}	0	–	–	Coefficient for the width dependence of back-bias dependence of velocity saturation
100	**PLWTHESATB**	V^{-1}	0	–	–	Coefficient for the length times width dependence of back-bias dependence of velocity saturation
101	**POTHESATG**	V^{-1}	0	–	–	Coefficient for the geometry independent part of gate-bias dependence of velocity saturation
102	**PLTHESATG**	V^{-1}	0	–	–	Coefficient for the length dependence of gate-bias dependence of velocity saturation
103	**PWTHESATG**	V^{-1}	0	–	–	Coefficient for the width dependence of gate-bias dependence of velocity saturation
104	**PLWTHESATG**	V^{-1}	0	–	–	Coefficient for the length times width dependence of gate-bias dependence of velocity saturation
Saturation Voltage Parameters						
105	**POAX**		3	–	–	Coefficient for the geometry independent part of linear/saturation transition factor
106	**PLAX**		0	–	–	Coefficient for the length dependence of linear/saturation transition factor
107	**PWAX**		0	–	–	Coefficient for the width dependence of linear/saturation transition factor
108	**PLWAX**		0	–	–	Coefficient for the length times width dependence of linear/saturation transition factor
Channel Length Modulation (CLM) Parameters						
109	**POALP**		$1 \cdot 10^{-2}$	–	–	Coefficient for the geometry independent part of CLM pre-factor
110	**PLALP**		0	–	–	Coefficient for the length dependence of CLM pre-factor
111	**PWALP**		0	–	–	Coefficient for the width dependence of CLM pre-factor
112	**PLWALP**		0	–	–	Coefficient for the length times width dependence of CLM pre-factor

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No.	Name	Unit	Default	Min.	Max.	Description
113	**POALP1**	V	0	–	–	Coefficient for the geometry independent part of CLM enhancement factor above threshold
114	**PLALP1**	V	0	–	–	Coefficient for the length dependence of CLM enhancement factor above threshold
115	**PWALP1**	V	0	–	–	Coefficient for the width dependence of CLM enhancement factor above threshold
116	**PLWALP1**	V	0	–	–	Coefficient for the length times width dependence of CLM enhancement factor above threshold
117	**POALP2**	V^{-1}	0	–	–	Coefficient for the geometry independent part of CLM enhancement factor below threshold
118	**PLALP2**	V^{-1}	0	–	–	Coefficient for the length dependence of CLM enhancement factor below threshold
119	**PWALP2**	V^{-1}	0	–	–	Coefficient for the width dependence of CLM enhancement factor below threshold
120	**PLWALP2**	V^{-1}	0	–	–	Coefficient for the length times width dependence of CLM enhancement factor below threshold
121	**POVP**	V	$5 \cdot 10^{-2}$	–	–	Coefficient for the geometry independent part of CLM logarithmic dependence parameter
			Impact Ionization (II) Parameters			
122	**POA1**		1	–	–	Coefficient for the geometry independent part of impact-ionization pre-factor
123	**PLA1**		0	–	–	Coefficient for the length dependence of impact-ionization pre-factor
124	**PWA1**		0	–	–	Coefficient for the width dependence of impact-ionization pre-factor
125	**PLWA1**		0	–	–	Coefficient for the length times width dependence of impact-ionization pre-factor
126	**POA2**	V	10	–	–	Coefficient for the geometry independent part of impact-ionization exponent at **TR**
127	**POSTA2**	V	0	–	–	Coefficient for the geometry independent part of temperature dependence of **A2**
128	**POA3**		1	–	–	Coefficient for the geometry independent part of saturation-voltage dependence of II
129	**PLA3**		0	–	–	Coefficient for the length dependence of saturation-voltage dependence of II
130	**PWA3**		0	–	–	Coefficient for the width dependence of saturation-voltage dependence of II

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No.	Name	Unit	Default	Min.	Max.	Description
131	**PLWA3**		0	–	–	Coefficient for the length times width dependence of saturation-voltage dependence of II
132	**POA4**	$\mathrm{V}^{-0.5}$	0	–	–	Coefficient for the geometry independent part of back-bias dependence of II
133	**PLA4**	$\mathrm{V}^{-0.5}$	0	–	–	Coefficient for the length dependence of back-bias dependence of II
134	**PWA4**	$\mathrm{V}^{-0.5}$	0	–	–	Coefficient for the width dependence of back-bias dependence of II
135	**PLWA4**	$\mathrm{V}^{-0.5}$	0	–	–	Coefficient for the length times width dependence of back-bias dependence of II
Gate Current Parameters						
136	**POGCO**		0	–	–	Coefficient for the geometry independent part of gate tunneling energy adjustment
137	**POIGINV**	A	0	–	–	Coefficient for the geometry independent part of gate channel current pre-factor
138	**PLIGINV**	A	0	–	–	Coefficient for the length dependence of gate channel current pre-factor
139	**PWIGINV**	A	0	–	–	Coefficient for the width dependence of gate channel current pre-factor
140	**PLWIGINV**	A	0	–	–	Coefficient for the length times width dependence of gate channel current pre-factor
141	**POIGOV**	A	0	–	–	Coefficient for the geometry independent part of gate overlap current pre-factor
142	**PLIGOV**	A	0	–	–	Coefficient for the length dependence of gate overlap current pre-factor
143	**PWIGOV**	A	0	–	–	Coefficient for the width dependence of gate overlap current pre-factor
144	**PLWIGOV**	A	0	–	–	Coefficient for the length times width dependence of gate overlap current pre-factor
145	**POSTIG**		2	–	–	Coefficient for the geometry independent part of temperature dependence of gate current
146	**POGC2**		$3.75 \cdot 10^{-1}$	–	–	Coefficient for the geometry independent part of gate current slope factor
147	**POGC3**		$6.3 \cdot 10^{-2}$	–	–	Coefficient for the geometry independent part of gate current curvature factor
148	**POCHIB**	V	3.1	–	–	Coefficient for the geometry independent part of tunneling barrier height
Gate-Induced Drain Leakage (GIDL) Parameters						
149	**POAGIDL**	$\mathrm{A/V}^3$	0	–	–	Coefficient for the geometry independent part of GIDL pre-factor

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No.	Name	Unit	Default	Min.	Max.	Description
150	**PLAGIDL**	A/V^3	0	–	–	Coefficient for the length dependence of GIDL pre-factor
151	**PWAGIDL**	A/V^3	0	–	–	Coefficient for the width dependence of GIDL pre-factor
152	**PLWAGIDL**	A/V^3	0	–	–	Coefficient for the length times width dependence of GIDL pre-factor
153	**POBGIDL**	V	41	–	–	Coefficient for the geometry independent part of GIDL probability factor at **TR**
154	**POSTBGIDL**	V/K	0	–	–	Coefficient for the geometry independent part of temperature dependence of **BGIDL**
155	**POCGIDL**		0	–	–	Coefficient for the geometry independent part of back-bias dependence of GIDL
Charge Model Parameters						
156	**POCOX**	F	$1 \cdot 10^{-14}$	–	–	Coefficient for the geometry independent part of oxide capacitance for intrinsic channel
157	**PLCOX**	F	0	–	–	Coefficient for the length dependence of oxide capacitance for intrinsic channel
158	**PWCOX**	F	0	–	–	Coefficient for the width dependence of oxide capacitance for intrinsic channel
159	**PLWCOX**	F	0	–	–	Coefficient for the length times width dependence of oxide capacitance for intrinsic channel
160	**POCGOV**	F	$1 \cdot 10^{-15}$	–	–	Coefficient for the geometry independent part of oxide capacitance for gate-drain/source overlap
161	**PLCGOV**	F	0	–	–	Coefficient for the length dependence of oxide capacitance for gate-drain/source overlap
162	**PWCGOV**	F	0	–	–	Coefficient for the width dependence of oxide capacitance for gate-drain/source overlap
163	**PLWCGOV**	F	0	–	–	Coefficient for the length times width dependence of oxide capacitance for gate-drain/source overlap
164	**POCGBOV**	F	0	–	–	Coefficient for the geometry independent part of oxide capacitance for gate-bulk overlap
165	**PLCGBOV**	F	0	–	–	Coefficient for the length dependence of oxide capacitance for gate-bulk overlap
166	**PWCGBOV**	F	0	–	–	Coefficient for the width dependence of oxide capacitance for gate-bulk overlap
167	**PLWCGBOV**	F	0	–	–	Coefficient for the length times width dependence of oxide capacitance for gate-bulk overlap

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No.	Name	Unit	Default	Min.	Max.	Description
168	**POCFR**	F	0	–	–	Coefficient for the geometry independent part of outer fringe capacitance
169	**PLCFR**	F	0	–	–	Coefficient for the length dependence of outer fringe capacitance
170	**PWCFR**	F	0	–	–	Coefficient for the width dependence of outer fringe capacitance
171	**PLWCFR**	F	0	–	–	Coefficient for the length times width dependence of outer fringe capacitance
			Noise Model Parameters			
172	**POFNT**		1	–	–	Coefficient for the geometry independent part of thermal noise coefficient
173	**PONFA**	$\mathrm{V}^{-1}/\mathrm{m}^4$	$8 \cdot 10^{22}$	–	–	Coefficient for the geometry independent part of first coefficient of flicker noise
174	**PLNFA**	$\mathrm{V}^{-1}/\mathrm{m}^4$	0	–	–	Coefficient for the length dependence of first coefficient of flicker noise
175	**PWNFA**	$\mathrm{V}^{-1}/\mathrm{m}^4$	0	–	–	Coefficient for the width dependence of first coefficient of flicker noise
176	**PLWNFA**	$\mathrm{V}^{-1}/\mathrm{m}^4$	0	–	–	Coefficient for the length times width dependence of first coefficient of flicker noise
177	**PONFB**	$\mathrm{V}^{-1}/\mathrm{m}^2$	$3 \cdot 10^{7}$	–	–	Coefficient for the geometry independent part of second coefficient of flicker noise
178	**PLNFB**	$\mathrm{V}^{-1}/\mathrm{m}^2$	0	–	–	Coefficient for the length dependence of second coefficient of flicker noise
179	**PWNFB**	$\mathrm{V}^{-1}/\mathrm{m}^2$	0	–	–	Coefficient for the width dependence of second coefficient of flicker noise
180	**PLWNFB**	$\mathrm{V}^{-1}/\mathrm{m}^2$	0	–	–	Coefficient for the length times width dependence of second coefficient of flicker noise
181	**PONFC**	V^{-1}	0	–	–	Coefficient for the geometry independent part of third coefficient of flicker noise
182	**PLNFC**	V^{-1}	0	–	–	Coefficient for the length dependence of third coefficient of flicker noise
183	**PWNFC**	V^{-1}	0	–	–	Coefficient for the width dependence of third coefficient of flicker noise
184	**PLWNFC**	V^{-1}	0	–	–	Coefficient for the length times width dependence of third coefficient of flicker noise
			Other Parameters			
185	**DTA**	K	0	–	–	temperature offset w.r.t. ambient circuit temperature

2.5.5 Parameters for stress model

The stress model of BSIM4.4.0 has been adopted in PSP with as little modifications as possible. Parameter names have been copied, but they have been subjected to PSP conventions by replacing every zero by an '**O**'. Moreover, the parameters **STK2** and **LODK2** are not available in PSP. Except for these changes, stress parameters determined for BSIM can be directly applied in PSP.

The parameters in this section are part of PSP's global parameter set (both geometrical and binning).

No.	Name	Unit	Default	Min.	Max.	Description
0	**SAREF**	m	10^{-6}	10^{-9}	–	Reference distance between OD edge to Poly from one side
1	**SBREF**	m	10^{-6}	10^{-9}	–	Reference distance between OD edge to Poly from other side
2	**WLOD**	m	0	–	–	Width parameter
3	**KUO**	m	0	–	–	Mobility degradation/enhancement coefficient
4	**KVSAT**	m	0	-1	$+1$	Saturation velocity degradation/enhancement parameter
5	**TKUO**	–	0	–	–	Temperature coefficient of **KUO**
6	**LKUO**	$\mathrm{m}^{\mathbf{LLODKUO}}$	0	–	–	Length dependence of **KUO**
7	**WKUO**	$\mathrm{m}^{\mathbf{WLODKUO}}$	0	–	–	Width dependence of **KUO**
8	**PKUO**	$\mathrm{m}^{\mathbf{LLODKUO}+\mathbf{WLODKUO}}$	0	–	–	Cross-term dependence of **KUO**
9	**LLODKUO**	–	0	0	–	Length parameter for mobility stress effect
10	**WLODKUO**	–	0	0	–	Width parameter for mobility stress effect
11	**KVTHO**	Vm	0	–	–	Threshold shift parameter
12	**LKVTHO**	$\mathrm{m}^{\mathbf{LLODVTH}}$	0	–	–	Length dependence of **KVTHO**
13	**WKVTHO**	$\mathrm{m}^{\mathbf{WLODVTH}}$	0	–	–	Width dependence of **KVTHO**
14	**PKVTHO**	$\mathrm{m}^{\mathbf{LLODVTH}+\mathbf{WLODVTH}}$	0	–	–	Cross-term dependence of **KVTHO**
15	**LLODVTH**	–	0	0	–	Length parameter for threshold voltage stress effect
16	**WLODVTH**	–	0	0	–	Width parameter for threshold voltage stress effect
17	**STETAO**	m	0	–	–	ETAO shift factor related to threshold voltage change

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No.	Name	Unit	Default	Min.	Max.	Description
18	**LODETAO**	–	1	0	–	ETAO shift modification factor

2.5.6 Parameters for local model

The set of local parameters valid for an individual transistor with a specific channel width and length are given in the table below. Since the local parameter set is valid for one device with a specific geometry, it does not contain the channel length and width as instance parameters.

No.	Name	Unit	Default	Min.	Max.	Description
0	**LEVEL**	–	101	–	–	Model selection parameter; see Sec. 6.1
1	**TYPE**	–	1	-1	1	Channel type parameter; 1 ↔ NMOS, -1 ↔ PMOS
2	**TR**	°C	21	-273	–	Reference temperature
			Switch Parameters			
3	**SWIGATE**	–	0	0	1	Flag for gate current (0 ↔ "off")
4	**SWIMPACT**	–	0	0	1	Flag for impact ionization current (0 ↔ "off")
5	**SWGIDL**	–	0	0	1	Flag for GIDL/GISL current (0 ↔ "off")
6	**SWJUNCAP**	–	0	0	3	Flag for JUNCAP (0 ↔ "off"); see Sec. 2.5.2
7	**QMC**	–	1	0	–	Quantum-mechanical correction factor
			Process Parameters			
8	**VFB**	V	-1	–	–	Flat-band voltage at **TR**
9	**STVFB**	V/K	$5 \cdot 10^{-4}$	–	–	Temperature dependence of **VFB**
10	**TOX**	m	$2 \cdot 10^{-9}$	10^{-10}	–	Gate oxide thickness
11	**NEFF**	m^{-3}	$5 \cdot 10^{23}$	10^{20}	10^{26}	Substrate doping
12	**VNSUB**	V	0	–	–	Effective doping bias-dependence parameter
13	**NSLP**	V	0.05	10^{-3}	–	Effective doping bias-dependence parameter
14	**DNSUB**	V^{-1}	0	0	1	Effective doping bias-dependence parameter
15	**DPHIB**	V	0	–	–	Offset of φ_{B}
16	**NP**	m^{-3}	10^{26}	0	–	Gate poly-silicon doping
17	**CT**	–	0	0	–	Interface states factor
18	**TOXOV**	m	$2 \cdot 10^{-9}$	10^{-10}	–	Overlap oxide thickness
19	**NOV**	m^{-3}	$5 \cdot 10^{25}$	10^{20}	10^{27}	Effective doping of overlap region
			DIBL Parameters			
20	**CF**	V^{-1}	0	0	–	DIBL parameter
21	**CFB**	V^{-1}	0	0	–	Back-bias dependence of **CF**
			Mobility Parameters			
22	**BETN**	m^2/V/s	$7 \cdot 10^{-2}$	0	–	Product of channel aspect ratio and zero-field mobility at **TR**
23	**STBET**	–	1	–	–	Temperature dependence of **BETN**
24	**MUE**	m/V	0.5	0	–	Mobility reduction coefficient at **TR**
25	**STMUE**	–	0	–	–	Temperature dependence of **MUE**
26	**THEMU**	–	1.5	0	–	Mobility reduction exponent at **TR**

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No.	Name	Unit	Default	Min.	Max.	Description
27	**STTHEMU**	–	1.5	–	–	Temperature dependence of **THEMU**
28	**CS**	–	0	0	–	Coulomb scattering parameter at **TR**
29	**STCS**	–	0	–	–	Temperature dependence of **CS**
30	**XCOR**	V^{-1}	0	0	–	Non-universality parameter
31	**STXCOR**	–	0	–	–	Temperature dependence of **XCOR**
32	**FETA**	–	1	0	–	Effective field parameter
Series Resistance Parameters						
33	**RS**	Ω	30	0	–	Source/drain series resistance at **TR**
34	**STRS**	–	1	–	–	Temperature dependence of **RS**
35	**RSB**	V^{-1}	0	-0.5	1	Back-bias dependence of **RS**
36	**RSG**	V^{-1}	0	-0.5	–	Gate-bias dependence of **RS**
Velocity Saturation Parameters						
37	**THESAT**	V^{-1}	1	0	–	Velocity saturation parameter at **TR**
38	**STTHESAT**	–	1	–	–	Temperature dependence of **THESAT**
39	**THESATB**	V^{-1}	0	-0.5	1	Back-bias dependence of velocity saturation
40	**THESATG**	V^{-1}	0	-0.5	–	Gate-bias dependence of velocity saturation
Saturation Voltage Parameter						
41	**AX**	-	3	2	–	Linear/saturation transition factor
Channel Length Modulation (CLM) Parameters						
42	**ALP**	–	0.01	0	–	CLM pre-factor
43	**ALP1**	V	0	0	–	CLM enhancement factor above threshold
44	**ALP2**	V^{-1}	0	0	–	CLM enhancement factor below threshold
45	**VP**	V	0.05	10^{-10}	–	CLM logarithmic dependence parameter
Impact Ionization (II) Parameters						
46	**A1**	–	1	0	–	Impact-ionization pre-factor
47	**A2**	V	10	0	–	Impact-ionization exponent at **TR**
48	**STA2**	V	0	–	–	Temperature dependence of **A2**
49	**A3**	–	1	0	–	Saturation-voltage dependence of II
50	**A4**	$\mathrm{V}^{-\frac{1}{2}}$	0	0	–	Back-bias dependence of II
Gate Current Parameters						
51	**GCO**	–	0	-10	10	Gate tunnelling energy adjustment
52	**IGINV**	A	0	0	–	Gate channel current pre-factor
53	**IGOV**	A	0	0	–	Gate overlap current pre-factor
54	**STIG**	–	2	–	–	Temperature dependence of gate current
55	**GC2**	–	0.375	0	10	Gate current slope factor
56	**GC3**	–	0.063	-2	2	Gate current curvature factor
57	**CHIB**	V	3.1	1	–	Tunnelling barrier height
Gate-Induced Drain Leakage (GIDL) Parameters						

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No.	Name	Unit	Default	Min.	Max.	Description
58	**AGIDL**	A/V^3	0	0	–	GIDL pre-factor
59	**BGIDL**	V	41	0	–	GIDL probability factor at **TR**
60	**STBGIDL**	V/K	0	–	–	Temperature dependence of **BGIDL**
61	**CGIDL**	-	0	–	–	Back-bias dependence of GIDL
Charge Model Parameters						
62	**COX**	F	10^{-14}	0	–	Oxide capacitance for intrinsic channel
63	**CGOV**	F	10^{-15}	0	–	Oxide capacitance for gate–drain/source overlap
64	**CGBOV**	F	0	0	–	Oxide capacitance for gate–bulk overlap
65	**CFR**	F	0	0	–	Outer fringe capacitance
Noise Model Parameters						
66	**FNT**	–	1.0	0	–	Thermal noise coefficient
67	**NFA**	V^{-1}/m^4	$8 \cdot 10^{22}$	0	–	First coefficient of flicker noise
68	**NFB**	V^{-1}/m^2	$3 \cdot 10^{7}$	0	–	Second coefficient of flicker noise
69	**NFC**	V^{-1}	0	0	–	Third coefficient of flicker noise
Other Parameters						
70	**DTA**	K	0	–	–	Temperature offset w.r.t. ambient circuit temperature

2.5.7 Parameters for source-bulk and drain-bulk junction model

The JUNCAP2 parameters are part of both the global and the local parameter sets.

No.	Name	Unit	Default	Min.	Max.	Description
0	**TRJ**	°C	21	$T_{\min}$	–	Reference temperature
1	**IMAX**	A	1000	10^{-12}	–	Maximum current up to which forward current behaves exponentially
						Capacitance Parameters
2	**CJORBOT**	F/m^2	10^{-3}	10^{-12}	–	Zero-bias capacitance per unit-of-area of bottom component
3	**CJORSTI**	F/m	10^{-9}	10^{-18}	–	Zero-bias capacitance per unit-of-length of STI-edge component
4	**CJORGAT**	F/m	10^{-9}	10^{-18}	–	Zero-bias capacitance per unit-of-length of gate-edge component
5	**VBIRBOT**	V	1	$V_{\rm bi,low}$	–	Built-in voltage at the reference temperature of bottom component
6	**VBIRSTI**	V	1	$V_{\rm bi,low}$	–	Built-in voltage at the reference temperature of STI-edge component
7	**VBIRGAT**	V	1	$V_{\rm bi,low}$	–	Built-in voltage at the reference temperature of gate-edge component
8	**PBOT**	-	0.5	0.05	0.95	Grading coefficient of bottom component
9	**PSTI**	-	0.5	0.05	0.95	Grading coefficient of STI-edge component
10	**PGAT**	-	0.5	0.05	0.95	Grading coefficient of gate-edge component
						Ideal-current Parameters
11	**PHIGBOT**	V	1.16	–	–	Zero-temperature bandgap voltage of bottom component
12	**PHIGSTI**	V	1.16	–	–	Zero-temperature bandgap voltage of STI-edge component
13	**PHIGGAT**	V	1.16	–	–	Zero-temperature bandgap voltage of gate-edge component
14	**IDSATRBOT**	A/m^2	10^{-12}	0	–	Saturation current density at the reference temperature of bottom component
15	**IDSATRSTI**	A/m	10^{-18}	0	–	Saturation current density at the reference temperature of STI-edge component
16	**IDSATRGAT**	A/m	10^{-18}	0	–	Saturation current density at the reference temperature of gate-edge component
17	**CSRHBOT**	A/m^3	10^{2}	0	–	Shockley-Read-Hall prefactor of bottom component
18	**CSRHSTI**	A/m^2	10^{-4}	0	–	Shockley-Read-Hall prefactor of STI-edge component
19	**CSRHGAT**	A/m^2	10^{-4}	0	–	Shockley-Read-Hall prefactor of gate-edge component
20	**XJUNSTI**	m	10^{-7}	10^{-9}	–	Junction depth of STI-edge component
21	**XJUNGAT**	m	10^{-7}	10^{-9}	–	Junction depth of gate-edge component

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No.	Name	Unit	Default	Min.	Max.	Description
			Trap-assisted Tunneling Parameters			
22	**CTATBOT**	A/m^3	10^2	0	–	Trap-assisted tunneling prefactor of bottom component
23	**CTATSTI**	A/m^2	10^{-4}	0	–	Trap-assisted tunneling prefactor of STI-edge component
24	**CTATGAT**	A/m^2	10^{-4}	0	–	Trap-assisted tunneling prefactor of gate-edge component
25	**MEFFTATBOT**	-	0.25	.01	–	Effective mass (in units of m_0) for trap-assisted tunneling of bottom component
26	**MEFFTATSTI**	-	0.25	.01	–	Effective mass (in units of m_0) for trap-assisted tunneling of STI-edge component
27	**MEFFTATGAT**	-	0.25	.01	–	Effective mass (in units of m_0) for trap-assisted tunneling of gate-edge component
			Band-to-band Tunneling Parameters			
28	**CBBTBOT**	AV^{-3}	10^{-12}	0	–	Band-to-band tunneling prefactor of bottom component
29	**CBBTSTI**	AV^{-3}m	10^{-18}	0	–	Band-to-band tunneling prefactor of STI-edge component
30	**CBBTGAT**	AV^{-3}m	10^{-18}	0	–	Band-to-band tunneling prefactor of gate-edge component
31	**FBBTRBOT**	Vm^{-1}	10^9	–	–	Normalization field at the reference temperature for band-to-band tunneling of bottom component
32	**FBBTRSTI**	Vm^{-1}	10^9	–	–	Normalization field at the reference temperature for band-to-band tunneling of STI-edge component
33	**FBBTRGAT**	Vm^{-1}	10^9	–	–	Normalization field at the reference temperature for band-to-band tunneling of gate-edge component
34	**STFBBTBOT**	K^{-1}	-10^{-3}	–	–	Temperature scaling parameter for band-to-band tunneling of bottom component
35	**STFBBTSTI**	K^{-1}	-10^{-3}	–	–	Temperature scaling parameter for band-to-band tunneling of STI-edge component
36	**STFBBTGAT**	K^{-1}	-10^{-3}	–	–	Temperature scaling parameter for band-to-band tunneling of gate-edge component
			Avalanche and Breakdown Parameters			
37	**VBRBOT**	V	10	0.1	–	Breakdown voltage of bottom component
38	**VBRSTI**	V	10	0.1	–	Breakdown voltage of STI-edge component
39	**VBRGAT**	V	10	0.1	–	Breakdown voltage of gate-edge component

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No.	Name	Unit	Default	Min.	Max.	Description
40	**PBRBOT**	V	4	0.1	–	Breakdown onset tuning parameter of bottom component
41	**PBRSTI**	V	4	0.1	–	Breakdown onset tuning parameter of STI-edge component
42	**PBRGAT**	V	4	0.1	–	Breakdown onset tuning parameter of gate-edge component

Section 3

Geometry and Stress dependence

3.1 Introduction

The physical geometry scaling rules of PSP (Section 3.3) have been developed to give a good description over the whole geometry range of CMOS technologies. As an alternative, the binning-rules can be used (Section 3.4) to allow for a more phenomenological geometry dependency. (Note that the user has to choose between the two options; the geometrical scaling rules and the binning scaling rules cannot be used at the same time.) In both cases, the result is a local parameter set (for a transistor of the specified L and W), which is fed into the local model.

Use of the stress model (Section 3.5) leads to a stress-dependent modification of some of the local parameters calculated from the geometrical or binning scaling rules.

3.2 Effective length and width

$$L_{\mathrm{EN}} = 10^{-6} \tag{3.1}$$

$$W_{\mathrm{EN}} = 10^{-6} \tag{3.2}$$

$$\Delta L_{\mathrm{PS}} = \mathbf{LVAR0} \cdot \left(1 + \mathbf{LVARL} \cdot \frac{L_{\mathrm{EN}}}{L}\right) \cdot \left(1 + \mathbf{LVARW} \cdot \frac{W_{\mathrm{EN}}}{W}\right) \tag{3.3}$$

$$\Delta W_{\mathrm{OD}} = \mathbf{WVAR0} \cdot \left(1 + \mathbf{WVARL} \cdot \frac{L_{\mathrm{EN}}}{L}\right) \cdot \left(1 + \mathbf{WVARW} \cdot \frac{W_{\mathrm{EN}}}{W}\right) \tag{3.4}$$

$$L_{\mathrm{E}} = L - \Delta L = L + \Delta L_{\mathrm{PS}} - 2 \cdot \mathbf{LAP} \tag{3.5}$$

$$W_{\mathrm{E}} = W - \Delta W = W + \Delta W_{\mathrm{OD}} - 2 \cdot \mathbf{WOT} \tag{3.6}$$

$$L_{\mathrm{E,CV}} = L + \Delta L_{\mathrm{PS}} - 2 \cdot \mathbf{LAP} + \mathbf{DLQ} \tag{3.7}$$

$$W_{\mathrm{E,CV}} = W + \Delta W_{\mathrm{OD}} - 2 \cdot \mathbf{WOT} + \mathbf{DWQ} \tag{3.8}$$

$$L_{\mathrm{G,CV}} = L + \Delta L_{\mathrm{PS}} + \mathbf{DLQ} \tag{3.9}$$

$$W_{\mathrm{G,CV}} = W + \Delta W_{\mathrm{OD}} + \mathbf{DWQ} \tag{3.10}$$

Note: If the calculated L_{E}, W_{E}, $L_{\mathrm{E,CV}}$, $W_{\mathrm{E,CV}}$, $L_{\mathrm{G,CV}}$, or $W_{\mathrm{G,CV}}$ is smaller than 1 nm (10^{-9} m), the value

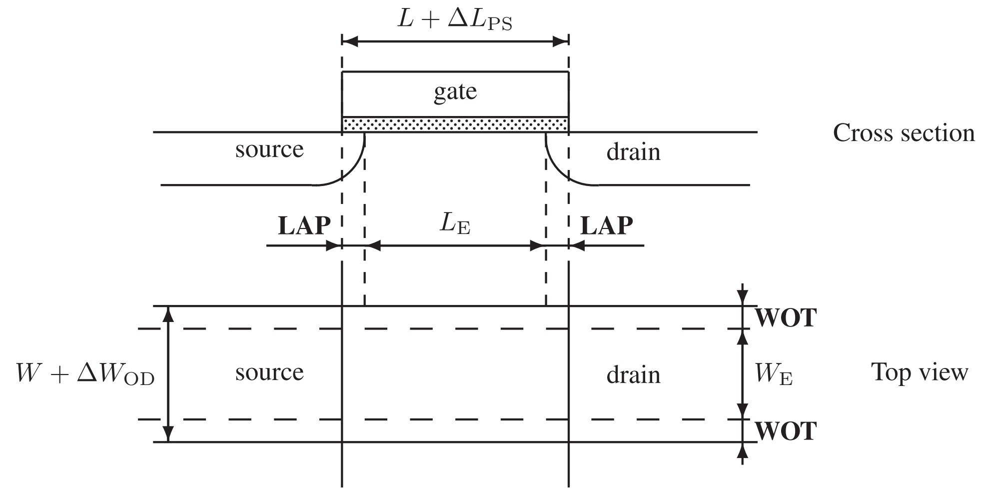


Figure 3.1: Specification of the dimensions of a MOS transistor

is clipped to this lower bound of 1 nm.

3.3 Geometrical scaling rules

The physical scaling rules to calculate the local parameters from a global parameter set are given in this section.

Note: After calculation of the local parameters (and possible application of the stress equations in Section 3.5), clipping is applied according to Section 2.5.6.

Process Parameters

$$\mathbf{VFB} = \mathbf{VFBO} \cdot \left(1 + \mathbf{VFBL} \cdot \frac{L_{\mathrm{EN}}}{L_{\mathrm{E}}}\right) \cdot \left(1 + \mathbf{VFBW} \cdot \frac{W_{\mathrm{EN}}}{W_{\mathrm{E}}}\right) \cdot \left(1 + \mathbf{VFBLW} \cdot \frac{W_{\mathrm{EN}} \cdot L_{\mathrm{EN}}}{W_{\mathrm{E}} \cdot L_{\mathrm{E}}}\right) \quad (3.11)$$

$$\mathbf{STVFB} = \mathbf{STVFBO} \cdot \left(1 + \mathbf{STVFBL} \cdot \frac{L_{\mathrm{EN}}}{L_{\mathrm{E}}}\right) \cdot \left(1 + \mathbf{STVFBW} \cdot \frac{W_{\mathrm{EN}}}{W_{\mathrm{E}}}\right) \cdot \left(1 + \mathbf{STVFBLW} \cdot \frac{W_{\mathrm{EN}} \cdot L_{\mathrm{EN}}}{W_{\mathrm{E}} \cdot L_{\mathrm{E}}}\right) \quad (3.12)$$

$$\mathbf{TOX} = \mathbf{TOXO} \quad (3.13)$$

$$N_{\mathrm{sub0,eff}} = \mathbf{NSUBO} \cdot \mathrm{MAX}\left(\left[1 + \mathbf{NSUBW} \cdot \frac{W_{\mathrm{EN}}}{W_{\mathrm{E}}} \cdot \ln\left(1 + \frac{W_{\mathrm{E}}}{\mathbf{WSEG}}\right)\right], 10^{-3}\right) \tag{3.14}$$

$$N_{\mathrm{pck,eff}} = \mathbf{NPCK} \cdot \mathrm{MAX}\left(\left[1 + \mathbf{NPCKW} \cdot \frac{W_{\mathrm{EN}}}{W_{\mathrm{E}}} \cdot \ln\left(1 + \frac{W_{\mathrm{E}}}{\mathbf{WSEGP}}\right)\right], 10^{-3}\right) \tag{3.15}$$

$$L_{\mathrm{pck,eff}} = \mathbf{LPCK} \cdot \mathrm{MAX}\left(\left[1 + \mathbf{LPCKW} \cdot \frac{W_{\mathrm{EN}}}{W_{\mathrm{E}}} \cdot \ln\left(1 + \frac{W_{\mathrm{E}}}{\mathbf{WSEGP}}\right)\right], 10^{-3}\right) \tag{3.16}$$

$$a = 7.5 \cdot 10^{10} \tag{3.17}$$

$$b = \sqrt{N_{\mathrm{sub0,eff}} + 0.5 \cdot N_{\mathrm{pck,eff}}} - \sqrt{N_{\mathrm{sub0,eff}}} \tag{3.18}$$

$$N_{\mathrm{sub}} = \begin{cases} N_{\mathrm{sub0,eff}} + N_{\mathrm{pck,eff}} \cdot \left[2 - \dfrac{L_{\mathrm{E}}}{L_{\mathrm{pck,eff}}}\right] & \text{for } L_{\mathrm{E}} < L_{\mathrm{pck,eff}} \\ N_{\mathrm{sub0,eff}} + N_{\mathrm{pck,eff}} \cdot \dfrac{L_{\mathrm{pck,eff}}}{L_{\mathrm{E}}} & \text{for } L_{\mathrm{pck,eff}} \le L_{\mathrm{E}} \le 2 \cdot L_{\mathrm{pck,eff}} \\ \Bigg[\sqrt{N_{\mathrm{sub0,eff}}} + \\ \quad a \cdot \ln\left(1 + 2 \cdot \dfrac{L_{\mathrm{pck,eff}}}{L_{\mathrm{E}}} \cdot \left[\exp\left(\dfrac{b}{a}\right) - 1\right]\right)\Bigg]^2 & \text{for } L_{\mathrm{E}} > 2 \cdot L_{\mathrm{pck,eff}} \end{cases} \tag{3.19}$$

$$\mathbf{NEFF} = N_{\mathrm{sub}} \cdot \left(1 - \mathbf{FOL1} \cdot \frac{L_{\mathrm{EN}}}{L_{\mathrm{E}}} - \mathbf{FOL2} \cdot \left[\frac{L_{\mathrm{EN}}}{L_{\mathrm{E}}}\right]^2\right) \tag{3.20}$$

$$\mathbf{VNSUB} = \mathbf{VNSUBO} \tag{3.21}$$

$$\mathbf{NSLP} = \mathbf{NSLPO} \tag{3.22}$$

$$\mathbf{DNSUB} = \mathbf{DNSUBO} \tag{3.23}$$

$$\mathbf{DPHIB} = \left(\mathbf{DPHIBO} + \mathbf{DPHIBL} \cdot \left[\frac{L_{\mathrm{EN}}}{L_{\mathrm{E}}}\right]^{\mathbf{DPHIBLEXP}}\right) \cdot \left(1 + \mathbf{DPHIBW} \cdot \frac{W_{\mathrm{EN}}}{W_{\mathrm{E}}}\right) \cdot \left(1 + \mathbf{DPHIBLW} \cdot \frac{W_{\mathrm{EN}} \cdot L_{\mathrm{EN}}}{W_{\mathrm{E}} \cdot L_{\mathrm{E}}}\right) \tag{3.24}$$

$$\mathbf{NP} = \mathbf{NPO} \cdot \left(1 + \mathbf{NPL} \cdot \frac{L_{\mathrm{EN}}}{L_{\mathrm{E}}}\right) \tag{3.25}$$

$$\mathbf{CT} = \left(\mathbf{CTO} + \mathbf{CTL} \cdot \left[\frac{L_{\mathrm{EN}}}{L_{\mathrm{E}}}\right]^{\mathbf{CTLEXP}}\right) \cdot \left(1 + \mathbf{CTW} \cdot \frac{W_{\mathrm{EN}}}{W_{\mathrm{E}}}\right) \cdot \left(1 + \mathbf{CTLW} \cdot \frac{W_{\mathrm{EN}} \cdot L_{\mathrm{EN}}}{W_{\mathrm{E}} \cdot L_{\mathrm{E}}}\right) \tag{3.26}$$

$$\mathbf{TOXOV} = \mathbf{TOXOVO} \tag{3.27}$$

$$\mathbf{NOV} = \mathbf{NOVO} \tag{3.28}$$

DIBL Parameters

$$\mathbf{CF} = \mathbf{CFL} \cdot \left[\frac{L_{\mathrm{EN}}}{L_{\mathrm{E}}}\right]^{\mathbf{CFLEXP}} \cdot \left(1 + \mathbf{CFW} \cdot \frac{W_{\mathrm{EN}}}{W_{\mathrm{E}}}\right) \tag{3.29}$$

$$\mathbf{CFB} = \mathbf{CFBO} \tag{3.30}$$

Mobility Parameters

$$F_{\beta 1,\mathrm{eff}} = \mathbf{FBET1} \cdot \left(1 + \mathbf{FBET1W} \cdot \frac{W_{\mathrm{EN}}}{W_{\mathrm{E}}}\right) \tag{3.31}$$

$$L_{\mathrm{P1,eff}} = \mathbf{LP1} \cdot \mathrm{MAX}\left(\left[1 + \mathbf{LP1W} \cdot \frac{W_{\mathrm{EN}}}{W_{\mathrm{E}}}\right], 10^{-3}\right) \tag{3.32}$$

$$\begin{aligned} G_{\mathrm{P,E}} = 1 + F_{\beta 1,\mathrm{eff}} \cdot \frac{L_{\mathrm{P1,eff}}}{L_{\mathrm{E}}} \cdot \left[1 - \exp\left(-\frac{L_{\mathrm{E}}}{L_{\mathrm{P1,eff}}}\right)\right] \\ + \mathbf{FBET2} \cdot \frac{\mathbf{LP2}}{L_{\mathrm{E}}} \cdot \left[1 - \exp\left(-\frac{L_{\mathrm{E}}}{\mathbf{LP2}}\right)\right] \end{aligned} \tag{3.33}$$

$$G_{\mathrm{W,E}} = 1 + \mathbf{BETW1} \cdot \frac{W_{\mathrm{EN}}}{W_{\mathrm{E}}} + \mathbf{BETW2} \cdot \frac{W_{\mathrm{EN}}}{W_{\mathrm{E}}} \cdot \ln\left(1 + \frac{W_{\mathrm{E}}}{\mathbf{WBET}}\right) \tag{3.34}$$

$$\mathbf{BETN} = \frac{\mathbf{UO}}{G_{\mathrm{P,E}}} \cdot \frac{W_{\mathrm{E}}}{L_{\mathrm{E}}} \cdot G_{\mathrm{W,E}} \tag{3.35}$$

$$\begin{aligned} \mathbf{STBET} = \mathbf{STBETO} \cdot \left(1 + \mathbf{STBETL} \cdot \frac{L_{\mathrm{EN}}}{L_{\mathrm{E}}}\right) \cdot \left(1 + \mathbf{STBETW} \cdot \frac{W_{\mathrm{EN}}}{W_{\mathrm{E}}}\right) \\ \cdot \left(1 + \mathbf{STBETLW} \cdot \frac{W_{\mathrm{EN}} \cdot L_{\mathrm{EN}}}{W_{\mathrm{E}} \cdot L_{\mathrm{E}}}\right) \end{aligned}$$

$$\mathbf{MUE} = \mathbf{MUEO} \cdot \left[1 + \mathbf{MUEW} \cdot \frac{W_{\mathrm{EN}}}{W_{\mathrm{E}}}\right] \tag{3.36}$$

$$\mathbf{STMUE} = \mathbf{STMUEO} \tag{3.37}$$

$$\mathbf{THEMU} = \mathbf{THEMUO} \tag{3.38}$$

$$\mathbf{STTHEMU} = \mathbf{STTHEMUO} \tag{3.39}$$

$$\begin{aligned} \mathbf{CS} = \left(\mathbf{CSO} + \mathbf{CSL} \cdot \left[\frac{L_{\mathrm{EN}}}{L_{\mathrm{E}}}\right]^{\mathbf{CSLEXP}}\right) \cdot \left(1 + \mathbf{CSW} \cdot \frac{W_{\mathrm{EN}}}{W_{\mathrm{E}}}\right) \\ \cdot \left(1 + \mathbf{CSLW} \cdot \frac{W_{\mathrm{EN}} \cdot L_{\mathrm{EN}}}{W_{\mathrm{E}} \cdot L_{\mathrm{E}}}\right) \end{aligned} \tag{3.40}$$

$$\mathbf{STCS} = \mathbf{STCSO} \tag{3.41}$$

$$\mathbf{XCOR} = \mathbf{XCORO} \cdot \left(1 + \mathbf{XCORL} \cdot \frac{L_\mathrm{EN}}{L_\mathrm{E}}\right) \cdot \left(1 + \mathbf{XCORW} \cdot \frac{W_\mathrm{EN}}{W_\mathrm{E}}\right) \cdot \left(1 + \mathbf{XCORLW} \cdot \frac{W_\mathrm{EN} \cdot L_\mathrm{EN}}{W_\mathrm{E} \cdot L_\mathrm{E}}\right) \tag{3.42}$$

$$\mathbf{STXCOR} = \mathbf{STXCORO} \tag{3.43}$$

$$\mathbf{FETA} = \mathbf{FETAO} \tag{3.44}$$

Series Resistance Parameters

$$\mathbf{RS} = \mathbf{RSW1} \cdot \frac{W_\mathrm{EN}}{W_\mathrm{E}} \cdot \left[1 + \mathbf{RSW2} \cdot \frac{W_\mathrm{EN}}{W_\mathrm{E}}\right] \tag{3.45}$$

$$\mathbf{STRS} = \mathbf{STRSO} \tag{3.46}$$

$$\mathbf{RSB} = \mathbf{RSBO} \tag{3.47}$$

$$\mathbf{RSG} = \mathbf{RSGO} \tag{3.48}$$

Velocity Saturation Parameters

$$\mathbf{THESAT} = \left(\mathbf{THESATO} + \mathbf{THESATL} \cdot \frac{G_\mathrm{W,E}}{G_\mathrm{P,E}} \cdot \left[\frac{L_\mathrm{EN}}{L_\mathrm{E}}\right]^{\mathbf{THESATLEXP}}\right) \cdot \left(1 + \mathbf{THESATW} \cdot \frac{W_\mathrm{EN}}{W_\mathrm{E}}\right) \cdot \left(1 + \mathbf{THESATLW} \cdot \frac{W_\mathrm{EN} \cdot L_\mathrm{EN}}{W_\mathrm{E} \cdot L_\mathrm{E}}\right) \tag{3.49}$$

$$\mathbf{STTHESAT} = \mathbf{STTHESATO} \cdot \left(1 + \mathbf{STTHESATL} \cdot \frac{L_\mathrm{EN}}{L_\mathrm{E}}\right) \cdot \left(1 + \mathbf{STTHESATW} \cdot \frac{W_\mathrm{EN}}{W_\mathrm{E}}\right) \cdot \left(1 + \mathbf{STTHESATLW} \cdot \frac{W_\mathrm{EN} \cdot L_\mathrm{EN}}{W_\mathrm{E} \cdot L_\mathrm{E}}\right) \tag{3.50}$$

$$\mathbf{THESATB} = \mathbf{THESATBO} \tag{3.51}$$

$$\mathbf{THESATG} = \mathbf{THESATGO} \tag{3.52}$$

Saturation Voltage Parameter

$$\mathbf{AX} = \frac{\mathbf{AX0}}{1 + \mathbf{AXL} \cdot \dfrac{L_\mathrm{EN}}{L_\mathrm{E}}} \tag{3.53}$$

Channel Length Modulation (CLM) Parameters

$$\mathbf{ALP} = \mathbf{ALPL} \cdot \left[\frac{L_{\mathrm{EN}}}{L_{\mathrm{E}}}\right]^{\mathbf{ALPLEXP}} \cdot \left(1 + \mathbf{ALPW} \cdot \frac{W_{\mathrm{EN}}}{W_{\mathrm{E}}}\right) \tag{3.54}$$

$$\mathbf{ALP1} = \frac{\mathbf{ALP1L1} \cdot \left[\frac{L_{\mathrm{EN}}}{L_{\mathrm{E}}}\right]^{\mathbf{ALP1LEXP}}}{1 + \mathbf{ALP1L2} \cdot \left[\frac{L_{\mathrm{EN}}}{L_{\mathrm{E}}}\right]^{\mathbf{ALP1LEXP}+1}} \cdot \left(1 + \mathbf{ALP1W} \cdot \frac{W_{\mathrm{EN}}}{W_{\mathrm{E}}}\right) \tag{3.55}$$

$$\mathbf{ALP2} = \frac{\mathbf{ALP2L1} \cdot \left[\frac{L_{\mathrm{EN}}}{L_{\mathrm{E}}}\right]^{\mathbf{ALP2LEXP}}}{1 + \mathbf{ALP2L2} \cdot \left[\frac{L_{\mathrm{EN}}}{L_{\mathrm{E}}}\right]^{\mathbf{ALP2LEXP}+1}} \cdot \left(1 + \mathbf{ALP2W} \cdot \frac{W_{\mathrm{EN}}}{W_{\mathrm{E}}}\right) \tag{3.56}$$

$$\mathbf{VP} = \mathbf{VPO} \tag{3.57}$$

Impact Ionization (II) Parameters

$$\mathbf{A1} = \mathbf{A1O} \cdot \left(1 + \mathbf{A1L} \cdot \frac{L_{\mathrm{EN}}}{L_{\mathrm{E}}}\right) \cdot \left(1 + \mathbf{A1W} \cdot \frac{W_{\mathrm{EN}}}{W_{\mathrm{E}}}\right) \tag{3.58}$$

$$\mathbf{A2} = \mathbf{A2O} \tag{3.59}$$

$$\mathbf{STA2} = \mathbf{STA2O} \tag{3.60}$$

$$\mathbf{A3} = \mathbf{A3O} \cdot \left(1 + \mathbf{A3L} \cdot \frac{L_{\mathrm{EN}}}{L_{\mathrm{E}}}\right) \cdot \left(1 + \mathbf{A3W} \cdot \frac{W_{\mathrm{EN}}}{W_{\mathrm{E}}}\right) \tag{3.61}$$

$$\mathbf{A4} = \mathbf{A4O} \cdot \left(1 + \mathbf{A4L} \cdot \frac{L_{\mathrm{EN}}}{L_{\mathrm{E}}}\right) \cdot \left(1 + \mathbf{A4W} \cdot \frac{W_{\mathrm{EN}}}{W_{\mathrm{E}}}\right) \tag{3.62}$$

Gate Current Parameters

$$\mathbf{GCO} = \mathbf{GCOO} \tag{3.63}$$

$$\mathbf{IGINV} = \mathbf{IGINVLW} \cdot \frac{W_{\mathrm{E}} \cdot L_{\mathrm{E}}}{W_{\mathrm{EN}} \cdot L_{\mathrm{EN}}} \tag{3.64}$$

$$\mathbf{IGOV} = \mathbf{IGOVW} \cdot \frac{W_{\mathrm{E}} \cdot \mathbf{LOV}}{W_{\mathrm{EN}} \cdot L_{\mathrm{EN}}} \tag{3.65}$$

$$\mathbf{STIG} = \mathbf{STIGO} \tag{3.66}$$

$$\mathbf{GC2} = \mathbf{GC2O} \tag{3.67}$$

$$\mathbf{GC3} = \mathbf{GC3O} \tag{3.68}$$

$$\mathbf{CHIB} = \mathbf{CHIBO} \tag{3.69}$$

Gate-Induced Drain Leakage (GIDL) Parameters

$$\mathbf{AGIDL} = \mathbf{AGIDLW} \cdot \frac{W_{\mathrm{E}} \cdot \mathbf{LOV}}{W_{\mathrm{EN}} \cdot L_{\mathrm{EN}}} \tag{3.70}$$

$$\mathbf{BGIDL} = \mathbf{BGIDLO} \tag{3.71}$$

$$\mathbf{CGIDL} = \mathbf{CGIDLO} \tag{3.72}$$

Charge Model Parameters

$$\mathbf{COX} = \epsilon_{\mathrm{ox}} \cdot \frac{W_{\mathrm{E,CV}} \cdot L_{\mathrm{E,CV}}}{\mathbf{TOX}} \tag{3.73}$$

$$\mathbf{CGOV} = \epsilon_{\mathrm{ox}} \cdot \frac{W_{\mathrm{E,CV}} \cdot \mathbf{LOV}}{\mathbf{TOXOV}} \tag{3.74}$$

$$\mathbf{CGBOV} = \mathbf{CGBOVL} \cdot \frac{L_{\mathrm{G,CV}}}{L_{\mathrm{EN}}} \tag{3.75}$$

$$\mathbf{CFR} = \mathbf{CFRW} \cdot \frac{W_{\mathrm{G,CV}}}{W_{\mathrm{EN}}} \tag{3.76}$$

Noise Model Parameters

$$\mathbf{NFA} = \mathbf{NFALW} \cdot \frac{W_{\mathrm{EN}} \cdot L_{\mathrm{EN}}}{W_{\mathrm{E}} \cdot L_{\mathrm{E}}} \tag{3.77}$$

$$\mathbf{NFB} = \mathbf{NFBLW} \cdot \frac{W_{\mathrm{EN}} \cdot L_{\mathrm{EN}}}{W_{\mathrm{E}} \cdot L_{\mathrm{E}}} \tag{3.78}$$

$$\mathbf{NFC} = \mathbf{NFCLW} \cdot \frac{W_{\mathrm{EN}} \cdot L_{\mathrm{EN}}}{W_{\mathrm{E}} \cdot L_{\mathrm{E}}} \tag{3.79}$$

3.4 Binning equations

The binning equations are provided as a (phenomenological) alternative to the physical scaling equations for computing local parameters. The physical geometrical scaling rules have been developed to give a good description over the whole geometry range of CMOS technologies. For processes under development, however, it is sometimes useful to have more flexible scaling relations. In that case on could opt for a binning strategy, where the accuracy with geometry is mostly determined by the number of bins used. The physical scaling rules of Section 3.3 are generally not suitable for binning strategies, since they may result in discontinuities in local parameter values at the bin boundaries. Consequently, special binning geometrical scaling relations have been developed, which guarantee continuity of the resulting local model parameters at the bin boundaries.

Only four different types of binning scaling rules are used, which are based on first order developments of the geometrical scaling rules in terms of L_E, $1/L_\mathrm{E}$, W_E, and $1/W_\mathrm{E}$ (examples below are for a fictitious parameter **YYY**):

1. Type I

$$\mathbf{YYY} = \mathbf{POYYY} + \mathbf{PLYYY} \cdot \frac{L_\mathrm{EN}}{L_\mathrm{E}} + \mathbf{PWYYY} \cdot \frac{W_\mathrm{EN}}{W_\mathrm{E}} + \mathbf{PLWYYY} \cdot \frac{L_\mathrm{EN} \cdot W_\mathrm{EN}}{L_\mathrm{E} \cdot W_\mathrm{E}} \tag{3.80}$$

2. Type II

$$\mathbf{YYY} = \mathbf{POYYY} + \mathbf{PLYYY} \cdot \frac{L_\mathrm{E}}{L_\mathrm{EN}} + \mathbf{PWYYY} \cdot \frac{W_\mathrm{E}}{W_\mathrm{EN}} + \mathbf{PLWYYY} \cdot \frac{L_\mathrm{E} \cdot W_\mathrm{E}}{L_\mathrm{EN} \cdot W_\mathrm{EN}} \tag{3.81}$$

3. Type III

$$\mathbf{YYY} = \mathbf{POYYY} + \mathbf{PLYYY} \cdot \frac{L_\mathrm{EN}}{L_\mathrm{E}} + \mathbf{PWYYY} \cdot \frac{W_\mathrm{E}}{W_\mathrm{EN}} + \mathbf{PLWYYY} \cdot \frac{W_\mathrm{E} \cdot L_\mathrm{EN}}{W_\mathrm{EN} \cdot L_\mathrm{E}} \tag{3.82}$$

4. Type IV (no binning)

$$\mathbf{YYY} = \mathbf{POYYY} \tag{3.83}$$

In Table 3.1 a survey of the binning type used for each local parameter is given. In some cases where the geometrical scaling rule is constant, the binning rule is chosen to be more flexible.

When using the binning rules above, the binning parameters for one bin can be directly calculated from the local parameter sets of the four corner devices of the bin (see Sec. 7.6). This results in a *separate parameter set for each bin.* The binning scheme ensures that the local parameters are exactly reproduced at the bin corners and that no humps occur in the local parameter values across bin boundaries.

Note: After calculation of the local parameters from the binning rules (and possible application of the stress equations in Section 3.5), clipping is applied according to Section 2.5.6.

Table 3.1: Overview of local parameters and binning type. The third column indicates whether there is a physical geometrical scaling rule for the local parameters.

#	parameter	physical scaling	binning	#	parameter	physical scaling	binning
0	**LEVEL**	no	no	36	**RSG**	no	no
1	**TYPE**	no	no	37	**THESAT**	yes	type I
2	**TR**	no	no	38	**STTHESAT**	yes	type I
3	**SWIGATE**	no	no	39	**THESATB**	no	type I
4	**SWIMPACT**	no	no	40	**THESATG**	no	type I
5	**SWGIDL**	no	no	41	**AX**	yes	type I
6	**SWJUNCAP**	no	no	42	**ALP**	yes	type I
7	**QMC**	no	no	43	**ALP1**	yes	type I
8	**VFB**	yes	type I	44	**ALP2**	yes	type I
9	**STVFB**	yes	type I	45	**VP**	no	no
10	**TOX**	no	no	46	**A1**	yes	type I
11	**NEFF**	yes	type I	47	**A2**	no	no
12	**VNSUB**	no	no	48	**STA2**	no	no
13	**NSLP**	no	no	49	**A3**	yes	type I
14	**DNSUB**	no	no	50	**A4**	yes	type I
15	**DPHIB**	yes	type I	51	**GCO**	no	no
16	**NP**	yes	type I	52	**IGINV**	yes	type II
17	**CT**	yes	type I	53	**IGOV**	yes	type III
18	**TOXOV**	no	no	54	**STIG**	no	no
19	**NOV**	no	type I	55	**GC2**	no	no
20	**CF**	yes	type I	56	**GC3**	no	no
21	**CFB**	no	no	57	**CHIB**	no	no
22	**BETN**	yes	type III	58	**AGIDL**	yes	type III
23	**STBET**	yes	type I	59	**BGIDL**	no	no
24	**MUE**	yes	type I	60	**STBGIDL**	no	no
25	**STMUE**	no	no	61	**CGIDL**	no	no
26	**THEMU**	no	no	62	**COX**	yes	type II
27	**STTHEMU**	no	no	63	**CGOV**	yes	type III
28	**CS**	yes	type I	64	**CGBOV**	yes	type II
29	**STCS**	no	no	65	**CFR**	yes	type III
30	**XCOR**	yes	type I	66	**FNT**	no	no
31	**STXCOR**	no	no	67	**NFA**	yes	type I
32	**FETA**	no	no	68	**NFB**	yes	type I
33	**RS**	yes	type I	69	**NFC**	yes	type I
34	**STRS**	no	no	70	**DTA**	no	no
35	**RSB**	no	no				

Process Parameters

$$\mathbf{VFB} = \mathbf{POVFB} + \mathbf{PLVFB} \cdot \frac{L_{\mathrm{EN}}}{L_{\mathrm{E}}} + \mathbf{PWVFB} \cdot \frac{W_{\mathrm{EN}}}{W_{\mathrm{E}}} + \mathbf{PLWVFB} \cdot \frac{L_{\mathrm{EN}} \cdot W_{\mathrm{EN}}}{L_{\mathrm{E}} \cdot W_{\mathrm{E}}} \tag{3.84}$$

$$\mathbf{STVFB} = \mathbf{POSTVFB} + \mathbf{PLSTVFB} \cdot \frac{L_{\mathrm{EN}}}{L_{\mathrm{E}}} + \mathbf{PWSTVFB} \cdot \frac{W_{\mathrm{EN}}}{W_{\mathrm{E}}} + \mathbf{PLWSTVFB} \cdot \frac{L_{\mathrm{EN}} \cdot W_{\mathrm{EN}}}{L_{\mathrm{E}} \cdot W_{\mathrm{E}}} \tag{3.85}$$

$$\mathbf{TOX} = \mathbf{POTOX} \tag{3.86}$$

$$\mathbf{NEFF} = \mathbf{PONEFF} + \mathbf{PLNEFF} \cdot \frac{L_{\mathrm{EN}}}{L_{\mathrm{E}}} + \mathbf{PWNEFF} \cdot \frac{W_{\mathrm{EN}}}{W_{\mathrm{E}}} + \mathbf{PLWNEFF} \cdot \frac{L_{\mathrm{EN}} \cdot W_{\mathrm{EN}}}{L_{\mathrm{E}} \cdot W_{\mathrm{E}}} \tag{3.87}$$

$$\mathbf{VNSUB} = \mathbf{POVNSUB} \tag{3.88}$$

$$\mathbf{NSLP} = \mathbf{PONSLP} \tag{3.89}$$

$$\mathbf{DNSUB} = \mathbf{PODNSUB} \tag{3.90}$$

$$\mathbf{DPHIB} = \mathbf{PODPHIB} + \mathbf{PLDPHIB} \cdot \frac{L_{\mathrm{EN}}}{L_{\mathrm{E}}} + \mathbf{PWDPHIB} \cdot \frac{W_{\mathrm{EN}}}{W_{\mathrm{E}}} + \mathbf{PLWDPHIB} \cdot \frac{L_{\mathrm{EN}} \cdot W_{\mathrm{EN}}}{L_{\mathrm{E}} \cdot W_{\mathrm{E}}} \tag{3.91}$$

$$\mathbf{NP} = \mathbf{PONP} + \mathbf{PLNP} \cdot \frac{L_{\mathrm{EN}}}{L_{\mathrm{E}}} + \mathbf{PWNP} \cdot \frac{W_{\mathrm{EN}}}{W_{\mathrm{E}}} + \mathbf{PLWNP} \cdot \frac{L_{\mathrm{EN}} \cdot W_{\mathrm{EN}}}{L_{\mathrm{E}} \cdot W_{\mathrm{E}}} \tag{3.92}$$

$$\mathbf{CT} = \mathbf{POCT} + \mathbf{PLCT} \cdot \frac{L_{\mathrm{EN}}}{L_{\mathrm{E}}} + \mathbf{PWCT} \cdot \frac{W_{\mathrm{EN}}}{W_{\mathrm{E}}} + \mathbf{PLWCT} \cdot \frac{L_{\mathrm{EN}} \cdot W_{\mathrm{EN}}}{L_{\mathrm{E}} \cdot W_{\mathrm{E}}} \tag{3.93}$$

$$\mathbf{TOXOV} = \mathbf{POTOXOV} \tag{3.94}$$

$$\mathbf{NOV} = \mathbf{PONOV} + \mathbf{PLNOV} \cdot \frac{L_{\mathrm{EN}}}{L_{\mathrm{E}}} + \mathbf{PWNOV} \cdot \frac{W_{\mathrm{EN}}}{W_{\mathrm{E}}} + \mathbf{PLWNOV} \cdot \frac{L_{\mathrm{EN}} \cdot W_{\mathrm{EN}}}{L_{\mathrm{E}} \cdot W_{\mathrm{E}}} \tag{3.95}$$

DIBL Parameters

$$\mathbf{CF} = \mathbf{POCF} + \mathbf{PLCF} \cdot \frac{L_{\mathrm{EN}}}{L_{\mathrm{E}}} + \mathbf{PWCF} \cdot \frac{W_{\mathrm{EN}}}{W_{\mathrm{E}}} + \mathbf{PLWCF} \cdot \frac{L_{\mathrm{EN}} \cdot W_{\mathrm{EN}}}{L_{\mathrm{E}} \cdot W_{\mathrm{E}}} \tag{3.96}$$

$$\mathbf{CFB} = \mathbf{POCFB} \tag{3.97}$$

Mobility Parameters

$$\mathbf{BETN} = \mathbf{POBETN} + \mathbf{PLBETN} \cdot \frac{L_{\mathrm{EN}}}{L_{\mathrm{E}}} + \mathbf{PWBETN} \cdot \frac{W_{\mathrm{E}}}{W_{\mathrm{EN}}} + \mathbf{PLWBETN} \cdot \frac{W_{\mathrm{E}} \cdot L_{\mathrm{EN}}}{W_{\mathrm{EN}} \cdot L_{\mathrm{E}}} \tag{3.98}$$

$$\mathbf{STBET} = \mathbf{POSTBET} + \mathbf{PLSTBET} \cdot \frac{L_{\mathrm{EN}}}{L_{\mathrm{E}}} + \mathbf{PWSTBET} \cdot \frac{W_{\mathrm{EN}}}{W_{\mathrm{E}}} + \mathbf{PLWSTBET} \cdot \frac{L_{\mathrm{EN}} \cdot W_{\mathrm{EN}}}{L_{\mathrm{E}} \cdot W_{\mathrm{E}}} \tag{3.99}$$

$$\mathbf{MUE} = \mathbf{POMUE} + \mathbf{PLMUE} \cdot \frac{L_{\mathrm{EN}}}{L_{\mathrm{E}}} + \mathbf{PWMUE} \cdot \frac{W_{\mathrm{EN}}}{W_{\mathrm{E}}} + \mathbf{PLWMUE} \cdot \frac{L_{\mathrm{EN}} \cdot W_{\mathrm{EN}}}{L_{\mathrm{E}} \cdot W_{\mathrm{E}}} \tag{3.100}$$

$$\mathbf{STMUE} = \mathbf{POSTMUE} \tag{3.101}$$

$$\mathbf{THEMU} = \mathbf{POTHEMU} \tag{3.102}$$

$$\mathbf{STTHEMU} = \mathbf{POSTTHEMU} \tag{3.103}$$

$$\mathbf{CS} = \mathbf{POCS} + \mathbf{PLCS} \cdot \frac{L_{\mathrm{EN}}}{L_{\mathrm{E}}} + \mathbf{PWCS} \cdot \frac{W_{\mathrm{EN}}}{W_{\mathrm{E}}} + \mathbf{PLWCS} \cdot \frac{L_{\mathrm{EN}} \cdot W_{\mathrm{EN}}}{L_{\mathrm{E}} \cdot W_{\mathrm{E}}} \tag{3.104}$$

$$\mathbf{STCS} = \mathbf{POSTCS} \tag{3.105}$$

$$\mathbf{XCOR} = \mathbf{POXCOR} + \mathbf{PLXCOR} \cdot \frac{L_{\mathrm{EN}}}{L_{\mathrm{E}}} + \mathbf{PWXCOR} \cdot \frac{W_{\mathrm{EN}}}{W_{\mathrm{E}}} + \mathbf{PLWXCOR} \cdot \frac{L_{\mathrm{EN}} \cdot W_{\mathrm{EN}}}{L_{\mathrm{E}} \cdot W_{\mathrm{E}}} \tag{3.106}$$

$$\mathbf{STXCOR} = \mathbf{POSTXCOR} \tag{3.107}$$

$$\mathbf{FETA} = \mathbf{POFETA} \tag{3.108}$$

Series Resistance Parameters

$$\mathbf{RS} = \mathbf{PORS} + \mathbf{PLRS} \cdot \frac{L_{\mathrm{EN}}}{L_{\mathrm{E}}} + \mathbf{PWRS} \cdot \frac{W_{\mathrm{EN}}}{W_{\mathrm{E}}} + \mathbf{PLWRS} \cdot \frac{L_{\mathrm{EN}} \cdot W_{\mathrm{EN}}}{L_{\mathrm{E}} \cdot W_{\mathrm{E}}} \tag{3.109}$$

$$\mathbf{STRS} = \mathbf{POSTRS} \tag{3.110}$$

$$\mathbf{RSB} = \mathbf{PORSB} \tag{3.111}$$

$$\mathbf{RSG} = \mathbf{PORSG} \tag{3.112}$$

Velocity Saturation Parameters

$$\begin{aligned}\mathbf{THESAT} = \mathbf{POTHESAT} + \mathbf{PLTHESAT} \cdot \frac{L_{\mathrm{EN}}}{L_{\mathrm{E}}} \\ + \mathbf{PWTHESAT} \cdot \frac{W_{\mathrm{EN}}}{W_{\mathrm{E}}} + \mathbf{PLWTHESAT} \cdot \frac{L_{\mathrm{EN}} \cdot W_{\mathrm{EN}}}{L_{\mathrm{E}} \cdot W_{\mathrm{E}}}\end{aligned} \tag{3.113}$$

$$\begin{aligned}\mathbf{STTHESAT} = \mathbf{POSTTHESAT} + \mathbf{PLSTTHESAT} \cdot \frac{L_{\mathrm{EN}}}{L_{\mathrm{E}}} \\ + \mathbf{PWSTTHESAT} \cdot \frac{W_{\mathrm{EN}}}{W_{\mathrm{E}}} + \mathbf{PLWSTTHESAT} \cdot \frac{L_{\mathrm{EN}} \cdot W_{\mathrm{EN}}}{L_{\mathrm{E}} \cdot W_{\mathrm{E}}}\end{aligned} \tag{3.114}$$

$$\begin{aligned}\mathbf{THESATB} = \mathbf{POTHESATB} + \mathbf{PLTHESATB} \cdot \frac{L_{\mathrm{EN}}}{L_{\mathrm{E}}} \\ + \mathbf{PWTHESATB} \cdot \frac{W_{\mathrm{EN}}}{W_{\mathrm{E}}} + \mathbf{PLWTHESATB} \cdot \frac{L_{\mathrm{EN}} \cdot W_{\mathrm{EN}}}{L_{\mathrm{E}} \cdot W_{\mathrm{E}}}\end{aligned} \tag{3.115}$$

$$\begin{aligned}\mathbf{THESATG} = \mathbf{POTHESATG} + \mathbf{PLTHESATG} \cdot \frac{L_{\mathrm{EN}}}{L_{\mathrm{E}}} \\ + \mathbf{PWTHESATG} \cdot \frac{W_{\mathrm{EN}}}{W_{\mathrm{E}}} + \mathbf{PLWTHESATG} \cdot \frac{L_{\mathrm{EN}} \cdot W_{\mathrm{EN}}}{L_{\mathrm{E}} \cdot W_{\mathrm{E}}}\end{aligned} \tag{3.116}$$

Saturation Voltage Parameters

$$\mathbf{AX} = \mathbf{POAX} + \mathbf{PLAX} \cdot \frac{L_{\mathrm{EN}}}{L_{\mathrm{E}}} + \mathbf{PWAX} \cdot \frac{W_{\mathrm{EN}}}{W_{\mathrm{E}}} + \mathbf{PLWAX} \cdot \frac{L_{\mathrm{EN}} \cdot W_{\mathrm{EN}}}{L_{\mathrm{E}} \cdot W_{\mathrm{E}}} \tag{3.117}$$

Channel Length Modulation (CLM) Parameters

$$\mathbf{ALP} = \mathbf{POALP} + \mathbf{PLALP} \cdot \frac{L_{\mathrm{EN}}}{L_{\mathrm{E}}} + \mathbf{PWALP} \cdot \frac{W_{\mathrm{EN}}}{W_{\mathrm{E}}} + \mathbf{PLWALP} \cdot \frac{L_{\mathrm{EN}} \cdot W_{\mathrm{EN}}}{L_{\mathrm{E}} \cdot W_{\mathrm{E}}} \tag{3.118}$$

$$\mathbf{ALP1} = \mathbf{POALP1} + \mathbf{PLALP1} \cdot \frac{L_{\mathrm{EN}}}{L_{\mathrm{E}}} + \mathbf{PWALP1} \cdot \frac{W_{\mathrm{EN}}}{W_{\mathrm{E}}} + \mathbf{PLWALP1} \cdot \frac{L_{\mathrm{EN}} \cdot W_{\mathrm{EN}}}{L_{\mathrm{E}} \cdot W_{\mathrm{E}}} \tag{3.119}$$

$$\mathbf{ALP2} = \mathbf{POALP2} + \mathbf{PLALP2} \cdot \frac{L_{\mathrm{EN}}}{L_{\mathrm{E}}} + \mathbf{PWALP2} \cdot \frac{W_{\mathrm{EN}}}{W_{\mathrm{E}}} + \mathbf{PLWALP2} \cdot \frac{L_{\mathrm{EN}} \cdot W_{\mathrm{EN}}}{L_{\mathrm{E}} \cdot W_{\mathrm{E}}} \tag{3.120}$$

$$\mathbf{VP} = \mathbf{POVP} \tag{3.121}$$

Impact Ionization (II) Parameters

$$\mathbf{A1} = \mathbf{POA1} + \mathbf{PLA1} \cdot \frac{L_{\mathrm{EN}}}{L_{\mathrm{E}}} + \mathbf{PWA1} \cdot \frac{W_{\mathrm{EN}}}{W_{\mathrm{E}}} + \mathbf{PLWA1} \cdot \frac{L_{\mathrm{EN}} \cdot W_{\mathrm{EN}}}{L_{\mathrm{E}} \cdot W_{\mathrm{E}}} \tag{3.122}$$

$$\mathbf{A2} = \mathbf{POA2} \tag{3.123}$$

$$\mathbf{STA2} = \mathbf{POSTA2} \tag{3.124}$$

$$\mathbf{A3} = \mathbf{POA3} + \mathbf{PLA3} \cdot \frac{L_{\mathrm{EN}}}{L_{\mathrm{E}}} + \mathbf{PWA3} \cdot \frac{W_{\mathrm{EN}}}{W_{\mathrm{E}}} + \mathbf{PLWA3} \cdot \frac{L_{\mathrm{EN}} \cdot W_{\mathrm{EN}}}{L_{\mathrm{E}} \cdot W_{\mathrm{E}}} \tag{3.125}$$

$$\mathbf{A4} = \mathbf{POA4} + \mathbf{PLA4} \cdot \frac{L_{\mathrm{EN}}}{L_{\mathrm{E}}} + \mathbf{PWA4} \cdot \frac{W_{\mathrm{EN}}}{W_{\mathrm{E}}} + \mathbf{PLWA4} \cdot \frac{L_{\mathrm{EN}} \cdot W_{\mathrm{EN}}}{L_{\mathrm{E}} \cdot W_{\mathrm{E}}} \tag{3.126}$$

Gate Current Parameters

$$\mathbf{GCO} = \mathbf{POGCO} \tag{3.127}$$

$$\begin{aligned} \mathbf{IGINV} = \mathbf{POIGINV} + \mathbf{PLIGINV} \cdot \frac{L_{\mathrm{E}}}{L_{\mathrm{EN}}} \\ + \mathbf{PWIGINV} \cdot \frac{W_{\mathrm{E}}}{W_{\mathrm{EN}}} + \mathbf{PLWIGINV} \cdot \frac{L_{\mathrm{E}} \cdot W_{\mathrm{E}}}{L_{\mathrm{EN}} \cdot W_{\mathrm{EN}}} \end{aligned} \tag{3.128}$$

$$\mathbf{IGOV} = \mathbf{POIGOV} + \mathbf{PLIGOV} \cdot \frac{L_{\mathrm{EN}}}{L_{\mathrm{E}}} + \mathbf{PWIGOV} \cdot \frac{W_{\mathrm{E}}}{W_{\mathrm{EN}}} + \mathbf{PLWIGOV} \cdot \frac{W_{\mathrm{E}} \cdot L_{\mathrm{EN}}}{W_{\mathrm{EN}} \cdot L_{\mathrm{E}}} \tag{3.129}$$

$$\mathbf{STIG} = \mathbf{POSTIG} \tag{3.130}$$

$$\mathbf{GC2} = \mathbf{POGC2} \tag{3.131}$$

$$\mathbf{GC3} = \mathbf{POGC3} \tag{3.132}$$

$$\mathbf{CHIB} = \mathbf{POCHIB} \tag{3.133}$$

Gate-Induced Drain Leakage (GIDL) Parameters

$$\mathbf{AGIDL} = \mathbf{POAGIDL} + \mathbf{PLAGIDL} \cdot \frac{L_{\rm EN}}{L_{\rm E}} + \mathbf{PWAGIDL} \cdot \frac{W_{\rm E}}{W_{\rm EN}} + \mathbf{PLWAGIDL} \cdot \frac{W_{\rm E} \cdot L_{\rm EN}}{W_{\rm EN} \cdot L_{\rm E}} \tag{3.134}$$

$$\mathbf{BGIDL} = \mathbf{POBGIDL} \tag{3.135}$$

$$\mathbf{STBGIDL} = \mathbf{POSTBGIDL} \tag{3.136}$$

$$\mathbf{CGIDL} = \mathbf{POCGIDL} \tag{3.137}$$

Charge Model Parameters

$$\mathbf{COX} = \mathbf{POCOX} + \mathbf{PLCOX} \cdot \frac{L_{\rm E,CV}}{L_{\rm EN}} + \mathbf{PWCOX} \cdot \frac{W_{\rm E,CV}}{W_{\rm EN}} + \mathbf{PLWCOX} \cdot \frac{L_{\rm E,CV} \cdot W_{\rm E,CV}}{L_{\rm EN} \cdot W_{\rm EN}} \tag{3.138}$$

$$\mathbf{CGOV} = \mathbf{POCGOV} + \mathbf{PLCGOV} \cdot \frac{L_{\rm EN}}{L_{\rm E,CV}} + \mathbf{PWCGOV} \cdot \frac{W_{\rm E,CV}}{W_{\rm EN}} + \mathbf{PLWCGOV} \cdot \frac{W_{\rm E,CV} \cdot L_{\rm EN}}{W_{\rm EN} \cdot L_{\rm E,CV}} \tag{3.139}$$

$$\mathbf{CGBOV} = \mathbf{POCGBOV} + \mathbf{PLCGBOV} \cdot \frac{L_{\rm G,CV}}{L_{\rm EN}} + \mathbf{PWCGBOV} \cdot \frac{W_{\rm G,CV}}{W_{\rm EN}} + \mathbf{PLWCGBOV} \cdot \frac{L_{\rm G,CV} \cdot W_{\rm G,CV}}{L_{\rm EN} \cdot W_{\rm EN}} \tag{3.140}$$

$$\mathbf{CFR} = \mathbf{POCFR} + \mathbf{PLCFR} \cdot \frac{L_{\rm EN}}{L_{\rm G,CV}} + \mathbf{PWCFR} \cdot \frac{W_{\rm G,CV}}{W_{\rm EN}} + \mathbf{PLWCFR} \cdot \frac{W_{\rm G,CV} \cdot L_{\rm EN}}{W_{\rm EN} \cdot L_{\rm G,CV}} \tag{3.141}$$

Noise Model Parameters

$$\mathbf{FNT} = \mathbf{POFNT} \tag{3.142}$$

$$\mathbf{NFA} = \mathbf{PONFA} + \mathbf{PLNFA} \cdot \frac{L_{\rm EN}}{L_{\rm E}} + \mathbf{PWNFA} \cdot \frac{W_{\rm EN}}{W_{\rm E}} + \mathbf{PLWNFA} \cdot \frac{L_{\rm EN} \cdot W_{\rm EN}}{L_{\rm E} \cdot W_{\rm E}} \tag{3.143}$$

$$\mathbf{NFB} = \mathbf{PONFB} + \mathbf{PLNFB} \cdot \frac{L_{\rm EN}}{L_{\rm E}} + \mathbf{PWNFB} \cdot \frac{W_{\rm EN}}{W_{\rm E}} + \mathbf{PLWNFB} \cdot \frac{L_{\rm EN} \cdot W_{\rm EN}}{L_{\rm E} \cdot W_{\rm E}} \tag{3.144}$$

$$\mathbf{NFC} = \mathbf{PONFC} + \mathbf{PLNFC} \cdot \frac{L_{\rm EN}}{L_{\rm E}} + \mathbf{PWNFC} \cdot \frac{W_{\rm EN}}{W_{\rm E}} + \mathbf{PLWNFC} \cdot \frac{L_{\rm EN} \cdot W_{\rm EN}}{L_{\rm E} \cdot W_{\rm E}} \tag{3.145}$$

3.5 Parameter modification due to stress effects

The stress model of BSIM4.4.0 [2] has been adopted in PSP without any modifications, except for two changes: (1) in the original BSIM parameter names all zeros have been replaced by "O"s, in order to comply with PSP conventions and (2) the BSIM parameters *STK2* and *LODK2* are not available in PSP.

The local PSP parameters affected by the stress equations are **BETN**, **THESAT**, **VFB**, and **CF**.

Note: After modification of the local parameters by the stress equations, clipping is applied according to Section 2.5.6.

Note: If both **SA** and **SB** are set to 0, the stress-equations are *not* computed.

3.5.1 Layout effects for regular shapes

$$R_{\mathrm{A}} = \frac{1}{\mathbf{SA} + 0.5 \cdot L} \tag{3.146}$$

$$R_{\mathrm{B}} = \frac{1}{\mathbf{SB} + 0.5 \cdot L} \tag{3.147}$$

$$R_{\mathrm{A,ref}} = \frac{1}{\mathbf{SAREF} + 0.5 \cdot L} \tag{3.148}$$

$$R_{\mathrm{B,ref}} = \frac{1}{\mathbf{SBREF} + 0.5 \cdot L} \tag{3.149}$$

3.5.2 Layout effects for irregular shapes

For irregular shapes the following effective values for **SA** and **SB** are to be used.

$$\frac{1}{\mathbf{SA}_{\mathrm{eff}} + 0.5 \cdot L} = \sum_{i=1}^{n} \frac{\mathbf{SW}_i}{W} \cdot \frac{1}{\mathbf{SA}_i + 0.5 \cdot L} \tag{3.150}$$

$$\frac{1}{\mathbf{SB}_{\mathrm{eff}} + 0.5 \cdot L} = \sum_{i=1}^{n} \frac{\mathbf{SW}_i}{W} \cdot \frac{1}{\mathbf{SB}_i + 0.5 \cdot L} \tag{3.151}$$

Note: These values have to be supplied *manually* or by a layout extraction tool!

3.5.3 Calculation of parameter modifications

Mobility-related equations

$$\begin{aligned} K_{\mathrm{u0}} = \Bigg(1 &+ \frac{\mathbf{LKUO}}{(L + \Delta L_{\mathrm{PS}})^{\mathbf{LLODKUO}}} + \frac{\mathbf{WKUO}}{(W + \Delta W_{\mathrm{OD}} + \mathbf{WLOD})^{\mathbf{WLODKUO}}} \\ &+ \frac{\mathbf{PKUO}}{(L + \Delta L_{\mathrm{PS}})^{\mathbf{LLODKUO}} \cdot (W + \Delta W_{\mathrm{OD}} + \mathbf{WLOD})^{\mathbf{WLODKUO}}}\Bigg) \\ &\cdot \left[1 + \mathbf{TKU0} \cdot \left(\frac{T_{\mathrm{KD}}}{T_{\mathrm{KR}}} - 1\right)\right] \end{aligned} \tag{3.152}$$

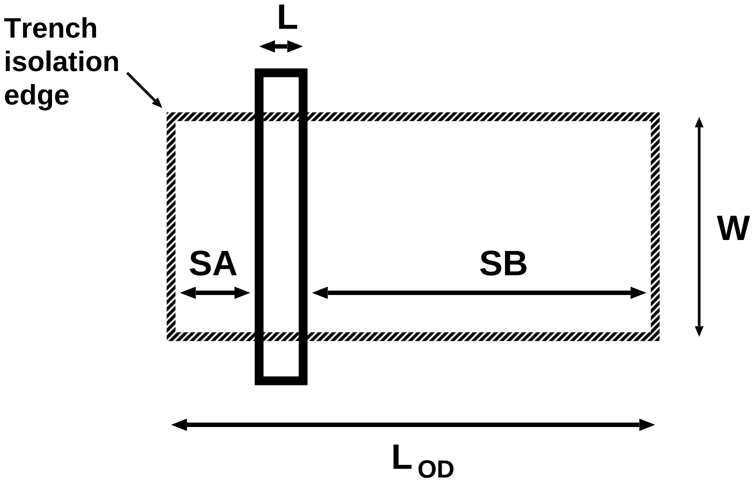


Figure 3.2: Typical layout of a MOSFET. Note that $L_{\mathrm{OD}} = \mathbf{SA} + \mathbf{SB} + L$, where OD is the active region definition.

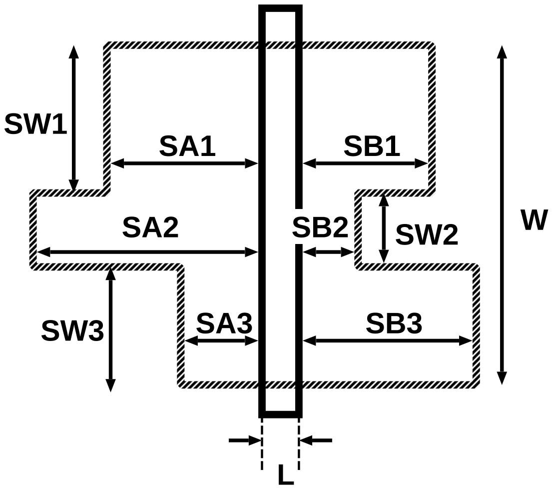


Figure 3.3: A typical layout of MOS devices with more instance parameters ($\mathbf{SW}_i$, $\mathbf{SA}_i$ and $\mathbf{SB}_i$) in addition to the traditional L and W.

$$\rho_\beta = \frac{\mathbf{KU0}}{K_{\rm u0}} \cdot (R_{\rm A} + R_{\rm B}) \tag{3.153}$$

$$\rho_{\beta,\rm ref} = \frac{\mathbf{KU0}}{K_{\rm u0}} \cdot (R_{\rm A,ref} + R_{\rm B,ref}) \tag{3.154}$$

$$\mathbf{BETN} = \frac{1+\rho_\beta}{1+\rho_{\beta,\rm ref}} \cdot \mathbf{BETN}_{\rm ref} \tag{3.155}$$

$$\mathbf{THESAT} = \frac{1+\rho_\beta}{1+\rho_{\beta,\rm ref}} \cdot \frac{1+\mathbf{KVSAT}\cdot\rho_{\beta,\rm ref}}{1+\mathbf{KVSAT}\cdot\rho_\beta} \cdot \mathbf{THESAT}_{\rm ref} \tag{3.156}$$

Threshold-voltage-related equations

$$\begin{aligned} K_{\rm vth0} = 1 &+ \frac{\mathbf{LKVTH0}}{(L+\Delta L_{\rm PS})^{\mathbf{LLODKVTH}}} + \frac{\mathbf{WKVTH0}}{(W+\Delta W_{\rm OD}+\mathbf{WLOD})^{\mathbf{WLODKVTH}}} \\ &+ \frac{\mathbf{PKVTH0}}{(L+\Delta L_{\rm PS})^{\mathbf{LLODVTH}}\cdot(W+\Delta W_{\rm OD}+\mathbf{WLOD})^{\mathbf{WLODVTH}}} \end{aligned} \tag{3.157}$$

$$\Delta R = R_{\rm A} + R_{\rm B} - R_{\rm A,ref} - R_{\rm B,ref} \tag{3.158}$$

$$\mathbf{VFB} = \mathbf{VFB}_{\rm ref} + \mathbf{KVTH0}\cdot\frac{\Delta R}{K_{\rm vth0}} \tag{3.159}$$

$$\mathbf{CF} = \mathbf{CF}_{\rm ref} + \mathbf{STETA0}\cdot\frac{\Delta R}{K_{\rm vth0}^{\mathbf{LODETA0}}} \tag{3.160}$$

Section 4

PSP Model Equations

4.1 Internal Parameters (including Temperature Scaling)

In this section, bias-independent internal parameters will be calculated, including temperature scaling. These parameters are computed from local parameters. Local parameters are (as usual) denoted by capital characters in bold font, whereas the internal parameters are denoted by symbols in bold font.

Transistor temperature

$$T_{\mathrm{KR}} = T_0 + \mathbf{TR} \tag{4.1}$$

$$T_{\mathrm{KD}} = T_0 + T_{\mathrm{A}} + \mathbf{DTA} \tag{4.2}$$

$$\Delta T = T_{\mathrm{KD}} - T_{\mathrm{KR}} \tag{4.3}$$

$$\boldsymbol{\phi}_{\mathbf{T}} = \frac{k_{\mathrm{B}} \cdot T_{\mathrm{KD}}}{q} \tag{4.4}$$

Local process parameters

$$\boldsymbol{\phi}^{*}_{\mathbf{T}} = \boldsymbol{\phi}_{\mathbf{T}} \cdot \left(1 + \mathbf{CT} \cdot \frac{T_{\mathrm{KR}}}{T_{\mathrm{KD}}}\right) \tag{4.5}$$

$$\boldsymbol{V}_{\mathbf{FB}} = \mathbf{VFB} + \mathbf{STVFB} \cdot \Delta T \tag{4.6}$$

$$E_{\mathrm{g}}/q = 1.179 - 9.025 \cdot 10^{-5} \cdot T_{\mathrm{KD}} - 3.05 \cdot 10^{-7} \cdot {T_{\mathrm{KD}}}^2 \tag{4.7}$$

$$r_{\mathrm{T}} = \left(1.045 + 4.5 \cdot 10^{-4} \cdot T_{\mathrm{KD}}\right) \cdot \left(0.523 + 1.4 \cdot 10^{-3} \cdot T_{\mathrm{KD}} - 1.48 \cdot 10^{-6} \cdot {T_{\mathrm{KD}}}^2\right) \tag{4.8}$$

$$n_{\mathrm{i}} = 2.5 \cdot 10^{25} \cdot {r_{\mathrm{T}}}^{3/4} \cdot \left(T_{\mathrm{KD}}/300\right)^{3/2} \cdot \exp\left(-\frac{E_{\mathrm{g}}/q}{2 \cdot \boldsymbol{\phi}_{\mathbf{T}}}\right) \tag{4.9}$$

$$\phi_{\mathrm{B}}^{\mathrm{cl}} = \mathrm{MAX}\left(\mathbf{DPHIB} + 2 \cdot \boldsymbol{\phi}_{\mathbf{T}} \cdot \ln\left[\mathbf{NEFF}/n_{\mathrm{i}}\right],\, 0.05\right) \tag{4.10}$$

$$C_{\mathrm{ox}} = \epsilon_{\mathrm{ox}}/\mathbf{TOX} \tag{4.11}$$

$$\gamma_0 = \sqrt{2 \cdot q \cdot \epsilon_{\mathrm{Si}} \cdot \mathbf{NEFF}}/C_{\mathrm{ox}} \tag{4.12}$$

$$G_0^{\mathrm{cl}} = \gamma_0/\sqrt{\boldsymbol{\phi}_{\mathbf{T}}} \tag{4.13}$$

Polysilicon depletion parameter

$$\boldsymbol{k_\mathrm{P}} = \begin{cases} \text{if } \mathbf{NP} \leq 1 \text{ or } \mathbf{NP} \geq 10^{28} & \begin{cases} \boldsymbol{k_\mathrm{P}} = 0 \end{cases} \\ \\ \text{if } 1 < \mathbf{NP} < 10^{28} & \begin{cases} \mathrm{NP}_1 = \mathrm{MAX}(\mathbf{NP},\, 8 \cdot 10^7/\mathbf{TOX}^2) \\ \mathrm{NP}_2 = \mathrm{MAX}(\mathrm{NP}_1,\, 3 \cdot 10^{25}) \\ \boldsymbol{k_\mathrm{P}} = 2 \cdot \boldsymbol{\phi_\mathrm{T}} \cdot C_\mathrm{ox}^2/(q \cdot \epsilon_\mathrm{Si} \cdot \mathrm{NP}_2) \end{cases} \end{cases} \tag{4.14}$$

Quantum-mechanical correction parameters

$$\boldsymbol{q_\mathrm{lim}} = 10 \cdot \boldsymbol{\phi_\mathrm{T}} \tag{4.15}$$

$$\boldsymbol{q_\mathrm{q}} = \begin{cases} 0.4 \cdot \mathbf{QMC} \cdot QM_\mathrm{N} \cdot C_\mathrm{ox}^{2/3} & \text{for NMOS} \\ \\ 0.4 \cdot \mathbf{QMC} \cdot QM_\mathrm{P} \cdot C_\mathrm{ox}^{2/3} & \text{for PMOS} \end{cases} \tag{4.16}$$

$$q_\mathrm{b0} = \gamma_0 \cdot \sqrt{\phi_\mathrm{B}^\mathrm{cl}} \tag{4.17}$$

$$\boldsymbol{\phi_\mathrm{B}} = \phi_\mathrm{B}^\mathrm{cl} + 0.75 \cdot \boldsymbol{q_\mathrm{q}} \cdot q_\mathrm{b0}^{2/3} \tag{4.18}$$

$$\boldsymbol{G_0} = G_0^\mathrm{cl} \cdot \left(1 + \boldsymbol{q_\mathrm{q}} \cdot q_\mathrm{b0}^{-1/3}\right) \tag{4.19}$$

V_SB**-clipping parameters**

$$\boldsymbol{\phi_\mathrm{X}} = 0.95 \cdot \boldsymbol{\phi_\mathrm{B}} \tag{4.20}$$

$$\boldsymbol{a_\phi} = 2.5 \cdot 10^{-3} \cdot \boldsymbol{\phi_\mathrm{B}^2} \tag{4.21}$$

$$\boldsymbol{b_\phi} = 2.5 \cdot 10^{-3} \cdot \boldsymbol{\phi_\mathrm{B}^2} \tag{4.22}$$

$$\boldsymbol{\phi_\mathrm{X}^\star} = 0.5 \cdot \sqrt{\boldsymbol{b_\phi}} \tag{4.23}$$

$$\boldsymbol{\phi_\mathrm{X}^*} = \mathrm{MINA}\left(\boldsymbol{\phi_\mathrm{X}} - \boldsymbol{\phi_\mathrm{X}^\star},\, 0,\, \boldsymbol{a_\phi}\right) \tag{4.24}$$

Local process parameters in gate overlap regions

$$\gamma_\mathrm{ov} = \sqrt{2 \cdot q \cdot \epsilon_\mathrm{Si} \cdot \mathbf{NOV}} \cdot \mathbf{TOXOV}/\epsilon_\mathrm{ox} \tag{4.25}$$

$$\boldsymbol{G_\mathrm{ov}} = \gamma_\mathrm{ov}/\sqrt{\boldsymbol{\phi_\mathrm{T}}} \tag{4.26}$$

$$\boldsymbol{\xi_\mathrm{ov}} = 1 + \boldsymbol{G_\mathrm{ov}}/\sqrt{2} \tag{4.27}$$

$$\boldsymbol{x_\mathrm{mrgov}} = 10^{-5} \cdot \boldsymbol{\xi_\mathrm{ov}} \tag{4.28}$$

Mobility parameters

$$\boldsymbol{\beta} = \mathbf{BETN} \cdot C_{\mathrm{ox}} \cdot (T_{\mathrm{KR}}/T_{\mathrm{KD}})^{\mathbf{STBET}} \tag{4.29}$$

$$\boldsymbol{\theta_{\mu}} = \mathbf{THEMU} \cdot (T_{\mathrm{KR}}/T_{\mathrm{KD}})^{\mathbf{STTHEMU}} \tag{4.30}$$

$$\boldsymbol{\mu}_{\mathbf{E}} = \mathbf{MUE} \cdot (T_{\mathrm{KR}}/T_{\mathrm{KD}})^{\mathbf{STMUE}} \tag{4.31}$$

$$\boldsymbol{X}_{\mathbf{cor}} = \mathbf{XCOR} \cdot (T_{\mathrm{KR}}/T_{\mathrm{KD}})^{\mathbf{STXCOR}} \tag{4.32}$$

$$\boldsymbol{C}_{\mathbf{S}} = \mathbf{CS} \cdot (T_{\mathrm{KR}}/T_{\mathrm{KD}})^{\mathbf{STCS}} \tag{4.33}$$

$$\boldsymbol{E}_{\mathbf{eff0}} = 10^{-8} \cdot C_{\mathrm{ox}}/\epsilon_{\mathrm{Si}} \tag{4.34}$$

$$\boldsymbol{\eta_{\mu}} = \begin{cases} 1/2 \cdot \mathbf{FETA} & \text{for NMOS} \\ \\ 1/3 \cdot \mathbf{FETA} & \text{for PMOS} \end{cases} \tag{4.35}$$

Series resistance parameter

$$R_{\mathrm{s}} = \mathbf{RS} \cdot (T_{\mathrm{KR}}/T_{\mathrm{KD}})^{\mathbf{STRS}} \tag{4.36}$$

$$\boldsymbol{\theta}_{\mathbf{R}} = 2 \cdot \boldsymbol{\beta} \cdot R_{\mathrm{s}} \tag{4.37}$$

Velocity saturation parameter

$$\boldsymbol{\theta}_{\mathbf{sat}} = \mathbf{THESAT} \cdot (T_{\mathrm{KR}}/T_{\mathrm{KD}})^{\mathbf{STTHESAT}} \tag{4.38}$$

Impact-ionization parameter

$$\boldsymbol{a}_{\mathbf{2}} = \mathbf{A2} \cdot (T_{\mathrm{KD}}/T_{\mathrm{KR}})^{\mathbf{STA2}} \tag{4.39}$$

Gate current parameters

$$\boldsymbol{I}_{\mathbf{GINV}} = \mathbf{IGINV} \cdot (T_{\mathrm{KD}}/T_{\mathrm{KR}})^{\mathbf{STIG}} \tag{4.40}$$

$$\boldsymbol{I}_{\mathbf{GOV}} = \mathbf{IGOV} \cdot (T_{\mathrm{KD}}/T_{\mathrm{KR}})^{\mathbf{STIG}} \tag{4.41}$$

$$\boldsymbol{B} = \frac{4}{3} \cdot \frac{\mathbf{TOX}}{\hbar} \cdot \sqrt{2 \cdot q \cdot m_0 \cdot \mathbf{CHIB}} = 6.830909 \cdot 10^{9} \cdot \mathbf{TOX} \cdot \sqrt{\mathbf{CHIB}} \tag{4.42}$$

$$\boldsymbol{B}_{\mathbf{ov}} = \boldsymbol{B} \cdot \mathbf{TOXOV/TOX} \tag{4.43}$$

$$\boldsymbol{GC}_{\mathbf{Q}} = \begin{cases} -0.99 \cdot \dfrac{\mathbf{GC2}}{2 \cdot \mathbf{GC3}} & \text{for } \mathbf{GC3} < 0 \\ \\ 0 & \text{for } \mathbf{GC3} \geq 0 \end{cases} \tag{4.44}$$

$$\boldsymbol{\alpha}_{\mathbf{b}} = \frac{E_{\mathrm{g}}/q + \boldsymbol{\phi}_{\mathbf{B}}}{2} \tag{4.45}$$

$$\boldsymbol{D}_{\mathbf{ch}} = \mathbf{GCO} \cdot \boldsymbol{\phi}_{\mathbf{T}}^{*} \tag{4.46}$$

$$\boldsymbol{D}_{\mathbf{ov}} = \mathbf{GCO} \cdot \boldsymbol{\phi}_{\mathbf{T}} \tag{4.47}$$

Gate-induced drain leakage parameters

$$\boldsymbol{A}_{\mathbf{GIDL}} = \mathbf{AGIDL} \cdot \left(\frac{2 \cdot 10^{-9}}{\mathbf{TOXOV}} \right)^2 \tag{4.48}$$

$$\boldsymbol{B}_{\mathbf{GIDL}} = \mathbf{BGIDL} \cdot \mathrm{MAX} \left(\left[1 + \mathbf{STBGIDL} \cdot \Delta T \right], 0 \right) \cdot \left(\frac{\mathbf{TOXOV}}{2 \cdot 10^{-9}} \right) \tag{4.49}$$

Noise parameter

$$\boldsymbol{N}_{\mathbf{T}} = \mathbf{FNT} \cdot 4 \cdot k_{\mathrm{B}} \cdot T_{\mathrm{KD}} \tag{4.50}$$

Additional internal parameters

$$\boldsymbol{x}_{\mathbf{1}} = 1.25 \tag{4.51}$$

$$\boldsymbol{x}_{\mathbf{g1}} = \boldsymbol{x}_{\mathbf{1}} + \boldsymbol{G}_{\mathbf{ov}} \cdot \sqrt{\exp(-\boldsymbol{x}_{\mathbf{1}}) + \boldsymbol{x}_{\mathbf{1}} - 1} \tag{4.52}$$

4.2 Model Equations

In this section, the model equations of the PSP-model are given. Use is made of the applied terminal bias values $V_{\rm GS}$, $V_{\rm DS}$ and $V_{\rm SB}$, the local parameters listed in Section 2.5.6 and the internal parameters introduced in Section 4.1. Local parameters are denoted by capital characters in bold font, whereas internal (bias-independent) parameters are denoted by symbols in bold font.

The definitions of the auxiliary functions MINA(.), MAXA(.), $\chi(.)$ and $\sigma_{1,2}(.)$ can be found in Appendix A.

4.2.1 Conditioning of Terminal Voltages

$$\phi_{\rm V} = {\rm MINA}\left(V_{\rm SB},\, V_{\rm SB}+V_{\rm DS},\, \boldsymbol{b_{\phi}}\right) + \boldsymbol{\phi_{\rm X}} \tag{4.53}$$

$$V_{\rm SB}^{*} = V_{\rm SB} - {\rm MINA}\left(\phi_{\rm V},\, 0,\, \boldsymbol{a_{\phi}}\right) + \boldsymbol{\phi_{\rm X}^{*}} \tag{4.54}$$

$$V_{\rm DB}^{*} = V_{\rm DS} + V_{\rm SB}^{*} \tag{4.55}$$

$$V_{\rm dsx} = \sqrt{{V_{\rm DS}}^{2} + 0.01} - 0.1 \tag{4.56}$$

$$V_{\rm sbx} = V_{\rm SB}^{*} + \frac{V_{\rm DS} - V_{\rm dsx}}{2} \tag{4.57}$$

Drain-induced barrier lowering:

$$\Delta V_{\rm G} = \textbf{CF} \cdot V_{\rm dsx} \cdot \left(1 + \textbf{CFB} \cdot V_{\rm sbx}\right) \tag{4.58}$$

$$V_{\rm GB}^{*} = V_{\rm GS} + V_{\rm SB}^{*} + \Delta V_{\rm G} - \boldsymbol{V_{\rm FB}} \tag{4.59}$$

$$x_{\rm g} = V_{\rm GB}^{*} / \boldsymbol{\phi_{\rm T}^{*}} \tag{4.60}$$

4.2.2 Bias-Dependent Body Factor

$$D_{\rm nsub} = \textbf{DNSUB} \cdot {\rm MAXA}\big(0,\, V_{\rm GS} + V_{\rm SB} - \textbf{VNSUB},\, \textbf{NSLP}\big) \tag{4.61}$$

$$G = \boldsymbol{G_{0}} \cdot \sqrt{1 + D_{\rm nsub}} \tag{4.62}$$

4.2.3 Surface Potential at Source Side and Related Variables

$$\xi = 1 + G/\sqrt{2} \tag{4.63}$$

$$x_{\rm ns} = \frac{\boldsymbol{\phi_{\rm B}} + V_{\rm SB}^{*}}{\boldsymbol{\phi_{\rm T}^{*}}} \tag{4.64}$$

$$\Delta_{\rm ns} = \exp\left(-x_{\rm ns}\right) \tag{4.65}$$

$$x_{\rm mrg} = 10^{-5} \cdot \xi \tag{4.66}$$

$$\text{if } x_{\mathrm{g}} < -x_{\mathrm{mrg}} \begin{cases} y_{\mathrm{g}} = -x_{\mathrm{g}} \\ z = 1.25 \cdot y_{\mathrm{g}}/\xi \\ \eta = \left[z + 10 - \sqrt{(z-6)^2 + 64}\right]/2 \\ a = \left(y_{\mathrm{g}} - \eta\right)^2 + G^2 \cdot (\eta + 1) \\ c = 2 \cdot (y_{\mathrm{g}} - \eta) - G^2 \\ \tau = -\eta + \ln\left(a/G^2\right) \\ y_0 = \sigma_1(a,\, c,\, \tau,\, \eta) \\ \Delta_0 = \exp\left(y_0\right) \\ p = 2 \cdot (y_{\mathrm{g}} - y_0) + G^2 \cdot \left[\Delta_0 - 1 + \Delta_{\mathrm{ns}} \cdot \left(1 - \chi'(y_0) - 1/\Delta_0\right)\right] \\ q = \left(y_{\mathrm{g}} - y_0\right)^2 + G^2 \cdot \left[y_0 - \Delta_0 + 1 + \Delta_{\mathrm{ns}} \cdot \left(1 + \chi(y_0) - 1/\Delta_0 - 2 \cdot y_0\right)\right] \\ x_{\mathrm{s}} = -y_0 - \dfrac{2 \cdot q}{p + \sqrt{p^2 - 2 \cdot q \cdot \left\{2 - G^2 \cdot \left[\Delta_0 + \Delta_{\mathrm{ns}} \cdot \left(1/\Delta_0 - \chi''(y_0)\right)\right]\right\}}} \end{cases} \tag{4.67}$$

$$\text{if } |x_{\mathrm{g}}| \le x_{\mathrm{mrg}} \left\{ \; x_{\mathrm{s}} = \frac{x_{\mathrm{g}}}{\xi} \cdot \left[1 + G \cdot x_{\mathrm{g}} \cdot \frac{1 - \Delta_{\mathrm{ns}}}{\xi^2 \cdot 6 \cdot \sqrt{2}}\right] \right. \tag{4.68}$$

$$\text{if } x_{\mathrm{g}} > x_{\mathrm{mrg}} \begin{cases} \hat{x}_{\mathrm{g1}} = \boldsymbol{x_1} + G \cdot \sqrt{\exp(-\boldsymbol{x_1}) + \boldsymbol{x_1} - 1} \\ \bar{x} = \dfrac{x_{\mathrm{g}}}{\xi} \cdot \left[1 + x_{\mathrm{g}} \cdot (\xi \cdot \boldsymbol{x_1} - \hat{x}_{\mathrm{g1}})/\hat{x}_{\mathrm{g1}}^2\right] \\ x_0 = x_{\mathrm{g}} + G^2/2 - G \cdot \sqrt{x_{\mathrm{g}} + G^2/4 - 1 + \exp(-\bar{x})} \\ b_{\mathrm{x}} = x_{\mathrm{ns}} + 3 \\ \eta = \mathrm{MINA}(x_0,\, b_{\mathrm{x}},\, 5) - \left(b_{\mathrm{x}} - \sqrt{b_{\mathrm{x}}^2 + 5}\right)/2 \\ a = (x_{\mathrm{g}} - \eta)^2 - G^2 \cdot \left[\exp(-\eta) + \eta - 1 - \Delta_{\mathrm{ns}} \cdot \left(\eta + 1 + \chi(\eta)\right)\right] \\ b = 1 - G^2/2 \cdot \left[\exp(-\eta) - \Delta_{\mathrm{ns}} \cdot \chi''(\eta)\right] \\ c = 2 \cdot (x_{\mathrm{g}} - \eta) + G^2 \cdot \left[1 - \exp(-\eta) - \Delta_{\mathrm{ns}} \cdot \left(1 + \chi'(\eta)\right)\right] \\ \tau = x_{\mathrm{ns}} - \eta + \ln\left(a/G^2\right) \\ y_0 = \sigma_2(a,\, b,\, c,\, \tau,\, \eta) \\ \Delta_0 = \exp\left(y_0\right) \\ p = 2 \cdot (x_{\mathrm{g}} - y_0) + G^2 \cdot \left[1 - 1/\Delta_0 + \Delta_{\mathrm{ns}} \cdot \left(\Delta_0 - 1 - \chi'(y_0)\right)\right] \\ q = \left(x_{\mathrm{g}} - y_0\right)^2 - G^2 \cdot \left[y_0 + 1/\Delta_0 - 1 + \Delta_{\mathrm{ns}} \cdot \left(\Delta_0 - y_0 - 1 - \chi(y_0)\right)\right] \\ x_{\mathrm{s}} = y_0 + \dfrac{2 \cdot q}{p + \sqrt{p^2 - 2 \cdot q \cdot \left\{2 - G^2 \cdot \left[1/\Delta_0 + \Delta_{\mathrm{ns}} \cdot \left(\Delta_0 - \chi''(y_0)\right)\right]\right\}}} \end{cases} \tag{4.69}$$

Eqs. (4.70)-(4.72) are only calculated for $x_{\mathrm{g}} > 0$.

$$E_{\mathrm{s}} = \exp\left(-x_{\mathrm{s}}\right) \tag{4.70}$$

$$D_\mathrm{s} = [1/E_\mathrm{s} - x_\mathrm{s} - 1 - \chi(x_\mathrm{s})] \cdot \Delta_\mathrm{ns} \tag{4.71}$$

$$P_\mathrm{s} = x_\mathrm{s} - 1 + E_\mathrm{s} \tag{4.72}$$

$$x_\mathrm{gs} = \begin{cases} x_\mathrm{g} - x_\mathrm{s} & \text{for } x_\mathrm{g} \leq 0 \\ \\ G \cdot \sqrt{D_\mathrm{s} + P_\mathrm{s}} & \text{for } x_\mathrm{g} > 0 \end{cases} \tag{4.73}$$

$$\psi_\mathrm{ss} = \boldsymbol{\phi}^*_\mathbf{T} \cdot x_\mathrm{s} \tag{4.74}$$

4.2.4 Drain Saturation Voltage

Eqs. (4.75)-(4.95) are only calculated for $x_\mathrm{g} > 0$.

$$q_\mathrm{is} = \frac{G^2 \cdot \boldsymbol{\phi}^*_\mathbf{T} \cdot D_\mathrm{s}}{x_\mathrm{gs} + G \cdot \sqrt{P_\mathrm{s}}} \tag{4.75}$$

$$\alpha_\mathrm{s} = 1 + \frac{G \cdot (1 - E_\mathrm{s})}{2 \cdot \sqrt{P_\mathrm{s}}} \tag{4.76}$$

$$q_\mathrm{bs} = \boldsymbol{\phi}^*_\mathbf{T} \cdot G \cdot \sqrt{P_\mathrm{s}} \tag{4.77}$$

$$\rho_\mathrm{b} = \begin{cases} 1 + \mathbf{RSB} \cdot V_\mathrm{sbx} & \text{for } \mathbf{RSB} \geq 0 \\ \\ \dfrac{1}{1 - \mathbf{RSB} \cdot V_\mathrm{sbx}} & \text{for } \mathbf{RSB} < 0 \end{cases} \tag{4.78}$$

$$\rho_\mathrm{g,s} = \begin{cases} \dfrac{1}{1 + \mathbf{RSG} \cdot q_\mathrm{is}} & \text{for } \mathbf{RSG} \geq 0 \\ \\ 1 - \mathbf{RSG} \cdot q_\mathrm{is} & \text{for } \mathbf{RSG} < 0 \end{cases} \tag{4.79}$$

$$\rho_\mathrm{s} = \boldsymbol{\theta}_\mathbf{R} \cdot \rho_\mathrm{b} \cdot \rho_\mathrm{g,s} \cdot q_\mathrm{is} \tag{4.80}$$

$$\mu_\mathrm{x} = \frac{1 + \boldsymbol{X}_\mathbf{cor} \cdot V_\mathrm{sbx}}{1 + 0.2 \cdot \boldsymbol{X}_\mathbf{cor} \cdot V_\mathrm{sbx}} \tag{4.81}$$

$$E_\mathrm{eff,s} = \boldsymbol{E}_\mathbf{eff0} \cdot \left(q_\mathrm{bs} + \boldsymbol{\eta}_{\boldsymbol{\mu}} \cdot q_\mathrm{is}\right) \tag{4.82}$$

$$G_\mathrm{mob,s} = \frac{1 + \left(\boldsymbol{\mu}_\mathbf{E} \cdot E_\mathrm{eff,s}\right)^{\boldsymbol{\theta}_{\boldsymbol{\mu}}} + \boldsymbol{C}_\mathbf{S} \cdot \left(\dfrac{q_\mathrm{bs}}{q_\mathrm{is} + q_\mathrm{bs}}\right)^2 + \rho_\mathrm{s}}{\mu_\mathrm{x}} \tag{4.83}$$

$$\xi_\mathrm{tb} = \begin{cases} 1 + \mathbf{THESATB} \cdot V_\mathrm{sbx} & \text{for } \mathbf{THESATB} \geq 0 \\ \\ \dfrac{1}{1 - \mathbf{THESATB} \cdot V_\mathrm{sbx}} & \text{for } \mathbf{THESATB} < 0 \end{cases} \tag{4.84}$$

$$w_\mathrm{sat,s} = \frac{100 \cdot q_\mathrm{is} \cdot \xi_\mathrm{tb}}{100 + q_\mathrm{is} \cdot \xi_\mathrm{tb}} \tag{4.85}$$

$$\theta^*_{\mathrm{sat,s}} = \begin{cases} \dfrac{\boldsymbol{\theta}_{\mathbf{sat}}}{G_{\mathrm{mob,s}}} \cdot (1 + \mathbf{THESATG} \cdot w_{\mathrm{sat,s}}) & \text{for } \mathbf{THESATG} \geq 0 \\ \\ \dfrac{\boldsymbol{\theta}_{\mathbf{sat}}}{G_{\mathrm{mob,s}}} \cdot \dfrac{1}{1 - \mathbf{THESATG} \cdot w_{\mathrm{sat,s}}} & \text{for } \mathbf{THESATG} < 0 \end{cases} \tag{4.86}$$

$$\phi_\infty = q_{\mathrm{is}}/\alpha_{\mathrm{s}} + \boldsymbol{\phi}^*_{\mathbf{T}} \tag{4.87}$$

$$y_{\mathrm{sat}} = \begin{cases} \theta^*_{\mathrm{sat,s}} \cdot \phi_\infty/\sqrt{2} & \text{for NMOS} \\ \\ \dfrac{\theta^*_{\mathrm{sat,s}} \cdot \phi_\infty/\sqrt{2}}{\sqrt{1 + \theta^*_{\mathrm{sat,s}} \cdot \phi_\infty/\sqrt{2}}} & \text{for PMOS} \end{cases} \tag{4.88}$$

$$z_{\mathrm{a}} = \frac{2}{1 + \sqrt{1 + 4 \cdot y_{\mathrm{sat}}}} \tag{4.89}$$

$$\phi_0 = \phi_\infty \cdot z_{\mathrm{a}} \cdot \left[1 + 0.86 \cdot z_{\mathrm{a}} \cdot y_{\mathrm{sat}} \cdot \frac{1 - z_{\mathrm{a}}^2 \cdot y_{\mathrm{sat}}}{1 + 4 \cdot z_{\mathrm{a}}^3 \cdot y_{\mathrm{sat}}^2}\right] \tag{4.90}$$

$$a_{\mathrm{sat}} = x_{\mathrm{gs}} + G^2/2 \tag{4.91}$$

$$\phi_2 = \frac{\boldsymbol{\phi}^*_{\mathbf{T}} \cdot 0.98 \cdot G^2 \cdot D_{\mathrm{s}}}{a_{\mathrm{sat}} + \sqrt{a_{\mathrm{sat}}^2 - 0.98 \cdot G^2 \cdot D_{\mathrm{s}}}} \tag{4.92}$$

$$\phi_{\mathrm{sat}} = \frac{2 \cdot \phi_0 \cdot \phi_2}{\phi_0 + \phi_2 + \sqrt{(\phi_0 + \phi_2)^2 - 3.96 \cdot \phi_0 \cdot \phi_2}} \tag{4.93}$$

$$V_{\mathrm{dsat}} = \phi_{\mathrm{sat}} - \boldsymbol{\phi}^*_{\mathbf{T}} \cdot \ln\left[1 + \frac{\phi_{\mathrm{sat}} \cdot \left(\phi_{\mathrm{sat}} - 2 \cdot a_{\mathrm{sat}} \cdot \boldsymbol{\phi}^*_{\mathbf{T}}\right)}{G^2 \cdot D_{\mathrm{s}} \cdot \boldsymbol{\phi}^{*\,2}_{\mathbf{T}}}\right] \tag{4.94}$$

$$V_{\mathrm{dse}} = \frac{V_{\mathrm{DS}}}{\left[1 + (V_{\mathrm{DS}}/V_{\mathrm{dsat}})^{\mathbf{AX}}\right]^{1/\mathbf{AX}}} \tag{4.95}$$

4.2.5 Surface Potential at Drain Side and Related Variables

Eqs. (4.96)-(4.105) are only calculated for $x_{\mathrm{g}} > 0$.

$$x_{\mathrm{nd}} = \frac{\boldsymbol{\phi}_{\mathbf{B}} + V^*_{\mathrm{SB}} + V_{\mathrm{dse}}}{\boldsymbol{\phi}^*_{\mathbf{T}}} \tag{4.96}$$

$$k_{\mathrm{ds}} = \exp\left(-V_{\mathrm{dse}}/\boldsymbol{\phi}^*_{\mathbf{T}}\right) \tag{4.97}$$

$$\Delta_{\mathrm{nd}} = \Delta_{\mathrm{ns}} \cdot k_{\mathrm{ds}} \tag{4.98}$$

$$\text{if } x_{\mathrm{g}} \leq x_{\mathrm{mrg}} \left\{ \; x_{\mathrm{d}} = \frac{x_{\mathrm{g}}}{\xi} \cdot \left[1 + G \cdot x_{\mathrm{g}} \cdot \frac{1 - \Delta_{\mathrm{nd}}}{\xi^2 \cdot 6 \cdot \sqrt{2}}\right] \right. \tag{4.99}$$

$$\text{if } x_\mathrm{g} > x_\mathrm{mrg} \begin{cases} b_\mathrm{x} = x_\mathrm{nd} + 3.0 \\ \eta = \mathrm{MINA}(x_0,\, b_\mathrm{x},\, 5) - \left(b_\mathrm{x} - \sqrt{b_\mathrm{x}^2+5}\right)/2 \\ a = (x_\mathrm{g}-\eta)^2 - G^2\cdot[\exp(-\eta)+\eta-1-\Delta_\mathrm{nd}\cdot(\eta+1+\chi(\eta))] \\ b = 1 - G^2/2\cdot[\exp(-\eta)-\Delta_\mathrm{nd}\cdot\chi''(\eta)] \\ c = 2\cdot(x_\mathrm{g}-\eta)+G^2\cdot[1-\exp(-\eta)-\Delta_\mathrm{nd}\cdot(1+\chi'(\eta))] \\ \tau = x_\mathrm{nd}-\eta+\ln\left(a/G^2\right) \\ y_0 = \sigma_2(a,\,b,\,c,\,\tau,\,\eta) \\ \Delta_0 = \exp\left(y_0\right) \\ p = 2\cdot(x_\mathrm{g}-y_0)+G^2\cdot[1-1/\Delta_0+\Delta_\mathrm{nd}\cdot(\Delta_0-1-\chi'(y_0))] \\ q = \left(x_\mathrm{g}-y_0\right)^2 - G^2\cdot[y_0+1/\Delta_0-1+\Delta_\mathrm{nd}\cdot(\Delta_0-y_0-1-\chi(y_0))] \\ x_\mathrm{d} = y_0 + \dfrac{2\cdot q}{p+\sqrt{p^2-2\cdot q\cdot\{2-G^2\cdot[1/\Delta_0+\Delta_\mathrm{nd}\cdot(\Delta_0-\chi''(y_0))]\}}} \end{cases} \tag{4.100}$$

$$x_\mathrm{ds} = x_\mathrm{d} - x_\mathrm{s} \tag{4.101}$$

$$\text{if } x_\mathrm{ds} < 10^{-10} \begin{cases} p = 2\cdot x_\mathrm{gs} + G^2\cdot[1-E_\mathrm{s}+\Delta_\mathrm{nd}\cdot(1/E_\mathrm{s}-1-\chi'(x_\mathrm{s}))] \\ q = G^2\cdot(1-k_\mathrm{ds})\cdot D_\mathrm{s} \\ \xi = 1-G^2/2\cdot[E_\mathrm{s}+\Delta_\mathrm{nd}\left(1/E_\mathrm{s}-\chi''(x_\mathrm{s})\right)] \\ x_\mathrm{ds} = \dfrac{2\cdot q}{p+\sqrt{p^2-4\cdot\xi\cdot q}} \\ x_\mathrm{d} = x_\mathrm{s}+x_\mathrm{ds} \end{cases} \tag{4.102}$$

$$E_\mathrm{d} = \exp\left(-x_\mathrm{d}\right) \tag{4.103}$$

$$D_\mathrm{d} = \left(1/E_\mathrm{d} - x_\mathrm{d} - 1 - \chi(x_\mathrm{d})\right)\cdot\Delta_\mathrm{nd} \tag{4.104}$$

$$\Delta\psi = \boldsymbol{\phi}_\mathbf{T}^{*}\cdot x_\mathrm{ds} \tag{4.105}$$

$$\psi_\mathrm{sd} = \boldsymbol{\phi}_\mathbf{T}^{*}\cdot x_\mathrm{d} \tag{4.106}$$

4.2.6 Mid-Point Surface Potential and Related Variables

$$\text{if } x_\mathrm{g} > 0 \begin{cases} x_\mathrm{m} = \left(x_\mathrm{s}+x_\mathrm{d}\right)/2 \\ E_\mathrm{m} = \sqrt{E_\mathrm{s}\cdot E_\mathrm{d}} \\ \bar{D} = \left(D_\mathrm{s}+D_\mathrm{d}\right)/2 \\ D_\mathrm{m} = \bar{D} + x_\mathrm{ds}^2/8\cdot\left(E_\mathrm{m}-2/G^2\right) \\ P_\mathrm{m} = x_\mathrm{m}-1+E_\mathrm{m} \\ x_\mathrm{gm} = G\cdot\sqrt{D_\mathrm{m}+P_\mathrm{m}} \end{cases} \tag{4.107}$$

$$\text{if } x_\mathrm{g} \le 0 \begin{cases} x_\mathrm{m} = x_\mathrm{s} \\ \\ x_\mathrm{gm} = x_\mathrm{g} - x_\mathrm{s} \end{cases} \tag{4.108}$$

4.2.7 Polysilicon Depletion

Eqs. (4.109)-(4.123) are only calculated for $\boldsymbol{k}_\mathbf{P} > 0$ and $x_\mathrm{g} > 0$ (otherwise $\eta_\mathrm{p} = 1$):

$$x_\mathrm{m}^{(0)} = x_\mathrm{m}, \qquad x_\mathrm{ds}^{(0)} = x_\mathrm{ds}, \qquad D_\mathrm{m}^{(0)} = D_\mathrm{m}, \qquad E_\mathrm{m}^{(0)} = E_\mathrm{m}, \tag{4.109}$$

$$d_0 = 1 - E_\mathrm{m}^{(0)} + 2 \cdot x_\mathrm{gm}/G^2 \tag{4.110}$$

$$\eta_\mathrm{p} = 1/\sqrt{1 + \boldsymbol{k}_\mathbf{P} \cdot x_\mathrm{gm}} \tag{4.111}$$

$$x_\mathrm{pm} = \boldsymbol{k}_\mathbf{P} \cdot \left[\frac{\eta_\mathrm{p} \cdot x_\mathrm{gm}}{1 + \eta_\mathrm{p}}\right]^2 \cdot \frac{D_\mathrm{m}^{(0)}}{D_\mathrm{m}^{(0)} + P_\mathrm{m}} \tag{4.112}$$

$$p = 2 \cdot (x_\mathrm{gm} - x_\mathrm{pm}) + G^2 \cdot \left(1 - E_\mathrm{m}^{(0)} + D_\mathrm{m}^{(0)}\right) \tag{4.113}$$

$$q = x_\mathrm{pm} \cdot (x_\mathrm{pm} - 2 \cdot x_\mathrm{gm}) \tag{4.114}$$

$$\xi_\mathrm{p} = 1 - G^2/2 \cdot \left(E_\mathrm{m}^{(0)} + D_\mathrm{m}^{(0)}\right) \tag{4.115}$$

$$u_\mathrm{p} = \frac{p \cdot q}{p^2 - \xi_\mathrm{p} \cdot q} \tag{4.116}$$

$$x_\mathrm{m} = x_\mathrm{m}^{(0)} + u_\mathrm{p} \tag{4.117}$$

$$E_\mathrm{m} = E_\mathrm{m}^{(0)} \cdot \exp\left(-u_\mathrm{p}\right) \tag{4.118}$$

$$D_\mathrm{m} = D_\mathrm{m}^{(0)} \cdot \exp\left(u_\mathrm{p}\right) \tag{4.119}$$

$$P_\mathrm{m} = x_\mathrm{m} - 1 + E_\mathrm{m} \tag{4.120}$$

$$x_\mathrm{gm} = G \cdot \sqrt{D_\mathrm{m} + P_\mathrm{m}} \tag{4.121}$$

$$x_\mathrm{ds} = x_\mathrm{ds}^{(0)} \cdot \frac{\exp\left(u_\mathrm{p}\right) \cdot \left[\bar{D} + d_0\right]}{1 - E_\mathrm{m} + 2 \cdot x_\mathrm{gm} \cdot \eta_\mathrm{p}/G^2 + \exp\left(u_\mathrm{p}\right) \cdot \bar{D}} \tag{4.122}$$

$$\Delta\psi = \boldsymbol{\phi}_\mathbf{T}^* \cdot x_\mathrm{ds} \tag{4.123}$$

4.2.8 Potential Mid-Point Inversion Charge and Related Variables

Eqs. (4.124)-(4.131) are only calculated for $x_{\mathrm{g}} > 0$.

$$q_{\mathrm{im}} = \frac{G^2 \cdot \boldsymbol{\phi}_{\mathbf{T}}^* \cdot D_{\mathrm{m}}}{x_{\mathrm{gm}} + G \cdot \sqrt{P_{\mathrm{m}}}} \tag{4.124}$$

$$\alpha_{\mathrm{m}} = \eta_{\mathrm{p}} + \frac{G \cdot (1 - E_{\mathrm{m}})}{2 \cdot \sqrt{P_{\mathrm{m}}}} \tag{4.125}$$

$$q_{\mathrm{im}}^* = q_{\mathrm{im}} + \boldsymbol{\phi}_{\mathbf{T}}^* \cdot \alpha_{\mathrm{m}} \tag{4.126}$$

$$q_{\mathrm{bm}} = \boldsymbol{\phi}_{\mathbf{T}}^* \cdot G \cdot \sqrt{P_{\mathrm{m}}} \tag{4.127}$$

Series resistance:

$$\rho_{\mathrm{g}} = \begin{cases} \dfrac{1}{1 + \textbf{RSG} \cdot q_{\mathrm{im}}} & \text{for } \textbf{RSG} \geq 0 \\ \\ 1 - \textbf{RSG} \cdot q_{\mathrm{im}} & \text{for } \textbf{RSG} < 0 \end{cases} \tag{4.128}$$

$$\rho_{\mathrm{s}} = \boldsymbol{\theta}_{\mathbf{R}} \cdot \rho_{\mathrm{b}} \cdot \rho_{\mathrm{g}} \cdot q_{\mathrm{im}} \tag{4.129}$$

Mobility reduction:

$$E_{\mathrm{eff}} = \boldsymbol{E}_{\mathbf{eff0}} \cdot \left(q_{\mathrm{bm}} + \boldsymbol{\eta}_{\boldsymbol{\mu}} \cdot q_{\mathrm{im}}\right) \tag{4.130}$$

$$G_{\mathrm{mob}} = \frac{1 + \left(\boldsymbol{\mu}_{\mathbf{E}} \cdot E_{\mathrm{eff}}\right)^{\boldsymbol{\theta}_{\boldsymbol{\mu}}} + \boldsymbol{C}_{\mathbf{S}} \cdot \left(\frac{q_{\mathrm{bm}}}{q_{\mathrm{im}} + q_{\mathrm{bm}}}\right)^2 + \rho}{\mu_{\mathrm{x}}} \tag{4.131}$$

4.2.9 Drain-Source Channel Current

Eqs. (4.132)-(4.143) are only calculated for $x_{\mathrm{g}} > 0$:

Channel length modulation:

$$R_1 = q_{\mathrm{im}} / q_{\mathrm{im}}^* \tag{4.132}$$

$$R_2 = \boldsymbol{\phi}_{\mathbf{T}}^* \cdot \alpha_{\mathrm{m}} / q_{\mathrm{im}}^* \tag{4.133}$$

$$T_1 = \ln \left(\frac{1 + \dfrac{V_{\mathrm{DS}} - \Delta\psi}{\textbf{VP}}}{1 + \dfrac{V_{\mathrm{dse}} - \Delta\psi}{\textbf{VP}}} \right) \tag{4.134}$$

$$T_2 = \ln \left(1 + \frac{V_{\mathrm{dsx}} - \Delta\psi}{\textbf{VP}} \right) \tag{4.135}$$

$$\Delta L / L = \textbf{ALP} \cdot T_1 \tag{4.136}$$

$$G_{\Delta L} = \frac{1}{1 + \Delta L / L + (\Delta L / L)^2} \tag{4.137}$$

$$\Delta L_1 / L = \left[\textbf{ALP} + \frac{\textbf{ALP1}}{q_{\mathrm{im}}^*} \cdot R_1 \right] \cdot T_1 + \textbf{ALP2} \cdot q_{\mathrm{bm}} \cdot R_2^2 \cdot T_2 \tag{4.138}$$

$$F_{\Delta L} = \left[1 + \Delta L_1/L + (\Delta L_1/L)^2\right] \cdot G_{\Delta L} \tag{4.139}$$

Velocity saturation:

$$w_{\rm sat} = \frac{100 \cdot q_{\rm im} \cdot \xi_{\rm tb}}{100 + q_{\rm im} \cdot \xi_{\rm tb}} \tag{4.140}$$

$$\theta^*_{\rm sat} = \begin{cases} \dfrac{\boldsymbol{\theta_{\rm sat}}}{G_{\rm mob,s} \cdot G_{\Delta L}} \cdot (1 + \mathbf{THESATG} \cdot w_{\rm sat}) & \text{for } \mathbf{THESATG} \geq 0 \\[2ex] \dfrac{\boldsymbol{\theta_{\rm sat}}}{G_{\rm mob,s} \cdot G_{\Delta L}} \cdot \dfrac{1}{1 - \mathbf{THESATG} \cdot w_{\rm sat}} & \text{for } \mathbf{THESATG} < 0 \end{cases} \tag{4.141}$$

$$z_{\rm sat} = \begin{cases} (\theta^*_{\rm sat} \cdot \Delta\psi)^2 & \text{for NMOS} \\[2ex] \dfrac{(\theta^*_{\rm sat} \cdot \Delta\psi)^2}{1 + \theta^*_{\rm sat} \cdot \Delta\psi} & \text{for PMOS} \end{cases} \tag{4.142}$$

$$G_{\rm vsat} = \frac{G_{\rm mob} \cdot G_{\Delta L}}{2} \cdot \left(1 + \sqrt{1 + 2 \cdot z_{\rm sat}}\right) \tag{4.143}$$

Drain-Source channel current:

$$I_{\rm DS} = \begin{cases} 0 & \text{for } x_{\rm g} \leq 0 \\[2ex] \boldsymbol{\beta} \cdot F_{\Delta L} \cdot \dfrac{q^*_{\rm im}}{G_{\rm vsat}} \cdot \Delta\psi & \text{for } x_{\rm g} > 0 \end{cases} \tag{4.144}$$

4.2.10 Auxiliary Variables for Calculation of Intrinsic Charges and Gate Current

Eqs. (4.145)-(4.147) are only calculated for $x_{\rm g} > 0$.

$$V_{\rm oxm} = \boldsymbol{\phi}^*_{\mathbf{T}} \cdot x_{\rm gm} \tag{4.145}$$

$$\alpha'_{\rm m} = \alpha_{\rm m} \cdot \left[1 + \frac{z_{\rm sat}}{2} \cdot \left(\frac{G_{\rm mob} \cdot G_{\Delta L}}{G_{\rm vsat}}\right)^2\right] \tag{4.146}$$

$$H = \frac{G_{\rm mob} \cdot G_{\Delta L}}{G_{\rm vsat}} \cdot \frac{q^*_{\rm im}}{\alpha'_{\rm m}} \tag{4.147}$$

4.2.11 Impact Ionization or Weak-Avalanche

The equations in this Section are only calculated when **SWIMPACT** $= 1$ and $x_{\rm g} > 0$.

$$a^*_2 = \boldsymbol{a_2} \cdot \left[1 + \mathbf{A4} \cdot \left(\sqrt{V^*_{\rm SB} + \boldsymbol{\phi}_{\mathbf{B}}} - \sqrt{\boldsymbol{\phi}_{\mathbf{B}}}\right)\right] \tag{4.148}$$

$$\Delta V_{\rm sat} = V_{\rm DS} - \mathbf{A3} \cdot \Delta\psi \tag{4.149}$$

$$M_{\rm avl} = \begin{cases} 0 & \text{for } \Delta V_{\rm sat} \leq 0 \\[2ex] \mathbf{A1} \cdot \Delta V_{\rm sat} \cdot \exp\left(-\dfrac{a^*_2}{\Delta V_{\rm sat}}\right) & \text{for } \Delta V_{\rm sat} > 0 \end{cases} \tag{4.150}$$

$$I_{\rm avl} = M_{\rm avl} \cdot I_{\rm DS} \tag{4.151}$$

4.2.12 Surface Potential in Gate Overlap Regions

$$x_{\mathrm{ov}}\left(x_{\mathrm{g}}\right) = \begin{cases} \text{if } x_{\mathrm{g}} < -\boldsymbol{x_{\mathrm{mrgov}}} \begin{cases} y_{\mathrm{g}} = -x_{\mathrm{g}} \\ z = \boldsymbol{x_1} \cdot y_{\mathrm{g}}/\boldsymbol{\xi_{\mathrm{ov}}} \\ \eta = \left[z + 10 - \sqrt{(z-6)^2 + 64}\right] \Big/ 2 \\ a = \left(y_{\mathrm{g}} - \eta\right)^2 + \boldsymbol{G_{\mathrm{ov}}^2} \cdot (\eta + 1) \\ c = 2 \cdot \left(y_{\mathrm{g}} - \eta\right) - \boldsymbol{G_{\mathrm{ov}}^2} \\ \tau = -\eta + \ln\left(a/\boldsymbol{G_{\mathrm{ov}}^2}\right) \\ y_0 = \sigma_1(a,\, c,\, \tau,\, \eta) \\ \Delta_0 = \exp\left(y_0\right) \\ p = 2 \cdot \left(y_{\mathrm{g}} - y_0\right) + \boldsymbol{G_{\mathrm{ov}}^2} \cdot \left(\Delta_0 - 1\right) \\ q = \left(y_{\mathrm{g}} - y_0\right)^2 + \boldsymbol{G_{\mathrm{ov}}^2} \cdot \left(y_0 - \Delta_0 + 1\right) \\ x_{\mathrm{ov}} = -y_0 - \dfrac{2 \cdot q}{p + \sqrt{p^2 - 2 \cdot q \cdot \left(2 - \boldsymbol{G_{\mathrm{ov}}^2} \cdot \Delta_0\right)}} \end{cases} \\ \text{if } \left|x_{\mathrm{g}}\right| < \boldsymbol{x_{\mathrm{mrgov}}} \begin{cases} x_{\mathrm{ov}} = x_{\mathrm{g}}/\boldsymbol{\xi_{\mathrm{ov}}} \end{cases} \\ \text{if } x_{\mathrm{g}} > \boldsymbol{x_{\mathrm{mrgov}}} \begin{cases} \bar{x} = x_{\mathrm{g}}/\boldsymbol{\xi_{\mathrm{ov}}} \cdot \left[1 + x_{\mathrm{g}} \cdot \left(\boldsymbol{\xi_{\mathrm{ov}}} \cdot \boldsymbol{x_1} - \boldsymbol{x_{\mathrm{g1}}}\right)/\boldsymbol{x_{\mathrm{g1}}^2}\right] \\ \omega = 1 - \exp\left(-\bar{x}\right) \\ x_0 = x_{\mathrm{g}} + \boldsymbol{G_{\mathrm{ov}}^2}/2 - \boldsymbol{G_{\mathrm{ov}}} \cdot \sqrt{x_{\mathrm{g}} + \boldsymbol{G_{\mathrm{ov}}^2}/4 - \omega} \\ \Delta_0 = \exp\left(-x_0\right) \\ p = 2 \cdot \left(x_{\mathrm{g}} - x_0\right) + \boldsymbol{G_{\mathrm{ov}}^2} \cdot \left(1 - \Delta_0\right) \\ q = \left(x_{\mathrm{g}} - x_0\right)^2 - \boldsymbol{G_{\mathrm{ov}}^2} \cdot \left(x_0 + \Delta_0 - 1\right) \\ x_{\mathrm{ov}} = x_0 + \dfrac{2 \cdot q}{p + \sqrt{p^2 - 2 \cdot q \cdot \left(2 - \boldsymbol{G_{\mathrm{ov}}^2} \cdot \Delta_0\right)}} \end{cases} \end{cases} \tag{4.152}$$

$$\psi_{\mathrm{sov}} = -\boldsymbol{\phi_{\mathrm{T}}} \cdot x_{\mathrm{ov}}\left(-\frac{V_{\mathrm{GS}}}{\boldsymbol{\phi_{\mathrm{T}}}}\right) \tag{4.153}$$

$$\psi_{\mathrm{dov}} = -\boldsymbol{\phi_{\mathrm{T}}} \cdot x_{\mathrm{ov}}\left(-\frac{V_{\mathrm{GS}} - V_{\mathrm{DS}}}{\boldsymbol{\phi_{\mathrm{T}}}}\right) \tag{4.154}$$

$$V_{\mathrm{ov_0}} = V_{\mathrm{GS}} - \psi_{\mathrm{sov}} \tag{4.155}$$

$$V_{\mathrm{ov_L}} = V_{\mathrm{GS}} - V_{\mathrm{DS}} - \psi_{\mathrm{dov}} \tag{4.156}$$

4.2.13 Gate Current

The equations in this Section are only calculated when **SWIGATE** $= 1$.

Source/Drain gate overlap current:

$$I_{\mathrm{Gov}}(V_{\mathrm{GX}},\, \psi_{\mathrm{ov}},\, V_{\mathrm{ov}}) = \begin{cases} V_{\mathrm{ov}}^{*} = \sqrt{V_{\mathrm{ov}}^{2} + 10^{-6}} \\[1ex] \psi_{\mathrm{tov}} = \mathrm{MINA}\left(0,\, V_{\mathrm{ov}} + \boldsymbol{D}_{\textbf{ov}},\, 0.01\right) \\[1ex] z_{\mathrm{g}} = \begin{cases} \mathrm{MINA}\left(\dfrac{V_{\mathrm{ov}}^{*}}{\textbf{CHIB}},\, \boldsymbol{GC}_{\mathbf{Q}},\, 10^{-6}\right) & \text{for } \textbf{GC3} < 0 \\[2ex] \dfrac{V_{\mathrm{ov}}^{*}}{\textbf{CHIB}} & \text{for } \textbf{GC3} \geq 0 \end{cases} \\[4ex] \Delta_{\mathrm{Siov}} = \exp\left(\dfrac{3.0 \cdot \boldsymbol{\phi}_{\mathbf{T}} + \psi_{\mathrm{ov}} + \psi_{\mathrm{tov}}}{\boldsymbol{\phi}_{\mathbf{T}}}\right) \\[3ex] F_{\mathrm{Sov}} = \ln\left[\dfrac{1 + \Delta_{\mathrm{Siov}}}{1 + \Delta_{\mathrm{Siov}} \cdot \exp\left(-V_{\mathrm{GX}}/\boldsymbol{\phi}_{\mathbf{T}}\right)}\right] \\[3ex] I_{\mathrm{Gov}} = \boldsymbol{I}_{\textbf{GOV}} \cdot F_{\mathrm{Sov}} \cdot \\[1ex] \qquad \exp\left(\boldsymbol{B}_{\textbf{ov}} \cdot \left[-\dfrac{3}{2} + z_{\mathrm{g}} \cdot \left(\textbf{GC2} + \textbf{GC3} \cdot z_{\mathrm{g}}\right)\right]\right) \end{cases} \tag{4.157}$$

$$I_{\mathrm{GSov}} = I_{\mathrm{Gov}}\left(V_{\mathrm{GS}},\, \psi_{\mathrm{sov}},\, V_{\mathrm{ov}_0}\right) \tag{4.158}$$

$$I_{\mathrm{GDov}} = I_{\mathrm{Gov}}\left(V_{\mathrm{GS}} - V_{\mathrm{DS}}\,,\, \psi_{\mathrm{dov}},\, V_{\mathrm{ov}_{\mathrm{L}}}\right) \tag{4.159}$$

Gate-channel current:

$$V_{\mathrm{m}} = V_{\mathrm{SB}}^{*} + \boldsymbol{\phi}_{\mathbf{T}}^{*} \cdot \left[\frac{x_{\mathrm{ds}}}{2} - \ln\left(\frac{1 + \exp(x_{\mathrm{ds}} - V_{\mathrm{dse}}/\boldsymbol{\phi}_{\mathbf{T}}^{*})}{2}\right)\right] \tag{4.160}$$

$$\psi_{\mathrm{t}} = \mathrm{MINA}\left(0,\, V_{\mathrm{oxm}} + \boldsymbol{D}_{\textbf{ch}},\, 0.01\right) \tag{4.161}$$

$$V_{\mathrm{oxm}}^{*} = \sqrt{V_{\mathrm{oxm}}^{2} + 10^{-6}} \tag{4.162}$$

$$z_{\mathrm{g}} = \begin{cases} \mathrm{MINA}\left(\dfrac{V_{\mathrm{oxm}}^{*}}{\textbf{CHIB}},\, \boldsymbol{GC}_{\mathbf{Q}},\, 10^{-6}\right) & \text{for } \textbf{GC3} < 0 \\[2ex] \dfrac{V_{\mathrm{oxm}}^{*}}{\textbf{CHIB}} & \text{for } \textbf{GC3} \geq 0 \end{cases} \tag{4.163}$$

$$\Delta_{\mathrm{Si}} = \exp\left(x_{\mathrm{m}} - \frac{\boldsymbol{\alpha}_{\mathbf{b}} + V_{\mathrm{m}} - \psi_{\mathrm{t}}}{\boldsymbol{\phi}_{\mathbf{T}}^{*}}\right) \tag{4.164}$$

$$F_{\mathrm{S}} = \ln\left[\frac{1 + \Delta_{\mathrm{Si}}}{1 + \Delta_{\mathrm{Si}} \cdot \exp\left(-\dfrac{V_{\mathrm{GS}} + V_{\mathrm{SB}}^{*} - V_{\mathrm{m}}}{\boldsymbol{\phi}_{\mathbf{T}}^{*}}\right)}\right] \tag{4.165}$$

$$I_{\mathrm{GCO}} = \boldsymbol{I}_{\mathbf{GINV}} \cdot F_{\mathrm{S}} \cdot \exp\left(\boldsymbol{B} \cdot [-3/2 + z_{\mathrm{g}} \cdot (\mathbf{GC2} + \mathbf{GC3} \cdot z_{\mathrm{g}})]\right) \tag{4.166}$$

$$\text{if } x_{\mathrm{g}} > 0 \begin{cases} u_0 = \mathbf{CHIB}/\left[\boldsymbol{B} \cdot (\mathbf{GC2} + 2 \cdot \mathbf{GC3} \cdot z_{\mathrm{g}})\right] \\ x = \Delta\psi/\left(2 \cdot u_0\right) \\ b = u_0/H \\ B_{\mathrm{g}} = b \cdot (1-b)/2 \\ A_{\mathrm{g}} = 1/2 - 3 \cdot B_{\mathrm{g}} \\ p_{\mathrm{gc}} = (1-b) \cdot \dfrac{\sinh(x)}{x} + b \cdot \cosh(x) \\ p_{\mathrm{gd}} = \dfrac{p_{\mathrm{gc}}}{2} - B_{\mathrm{g}} \cdot \sinh(x) - A_{\mathrm{g}} \cdot \dfrac{\sinh(x)}{x} \cdot \left[\coth(x) - \dfrac{1}{x}\right] \end{cases} \tag{4.167}$$

$$\text{if } x_{\mathrm{g}} \leq 0 \begin{cases} p_{\mathrm{gc}} = 1 \\ p_{\mathrm{gd}} = 1/2 \end{cases} \tag{4.168}$$

$$S_{\mathrm{g}} = \frac{1}{2} \cdot \left(1 + \frac{x_{\mathrm{g}}}{\sqrt{x_{\mathrm{g}}^2 + 10^{-6}}}\right) \tag{4.169}$$

$$I_{\mathrm{GC}} = I_{\mathrm{GCO}} \cdot p_{\mathrm{gc}} \cdot S_{\mathrm{g}} \tag{4.170}$$

$$I_{\mathrm{GCD}} = I_{\mathrm{GCO}} \cdot p_{\mathrm{gd}} \cdot S_{\mathrm{g}} \tag{4.171}$$

$$I_{\mathrm{GCS}} = I_{\mathrm{GC}} - I_{\mathrm{GCD}} \tag{4.172}$$

$$I_{\mathrm{GB}} = I_{\mathrm{GCO}} \cdot p_{\mathrm{gc}} \cdot (1 - S_{\mathrm{g}}) \tag{4.173}$$

4.2.14 Gate-Induced Drain/Source Leakage Current

The equations in this section are only calculated when **SWGIDL** $= 1$.

$$I_{\mathrm{gixl}}(V_{\mathrm{ov}}, V) = \begin{cases} V_{\mathrm{tov}} = \sqrt{V_{\mathrm{ov}}^2 + \mathbf{CGIDL}^2 \cdot V^2 + 10^{-6}} \\ t = V \cdot V_{\mathrm{tov}} \cdot V_{\mathrm{ov}} \\ I_{\mathrm{gixl}} = \begin{cases} -\boldsymbol{A}_{\mathbf{GIDL}} \cdot t \cdot \exp\left(-\dfrac{\boldsymbol{B}_{\mathbf{GIDL}}}{V_{\mathrm{tov}}}\right) & \text{for } V_{\mathrm{ov}} > 0 \\ 0 & \text{for } V_{\mathrm{ov}} \leq 0 \end{cases} \end{cases} \tag{4.174}$$

$$I_{\mathrm{gisl}} = I_{\mathrm{gixl}}(V_{\mathrm{ov}_0}, V_{\mathrm{SB}}) \tag{4.175}$$

$$I_{\mathrm{gidl}} = I_{\mathrm{gixl}}(V_{\mathrm{ov}_{\mathrm{L}}}, V_{\mathrm{DS}} + V_{\mathrm{SB}}) \tag{4.176}$$

4.2.15 Total Terminal Currents

$$I_{\mathrm{D}} = I_{\mathrm{DS}} + I_{\mathrm{avl}} - I_{\mathrm{GDov}} - I_{\mathrm{GCD}} + I_{\mathrm{gidl}} \tag{4.177}$$

$$I_{\mathrm{S}} = -I_{\mathrm{DS}} - I_{\mathrm{GSov}} - I_{\mathrm{GCS}} + I_{\mathrm{gisl}} \tag{4.178}$$

$$I_{\mathrm{G}} = I_{\mathrm{GC}} + I_{\mathrm{GB}} + I_{\mathrm{GDov}} + I_{\mathrm{GSov}} \tag{4.179}$$

$$I_{\mathrm{B}} = -I_{\mathrm{avl}} - I_{\mathrm{GB}} - I_{\mathrm{gidl}} - I_{\mathrm{gisl}} \tag{4.180}$$

4.2.16 Quantum-Mechanical Corrections

$$q_{\mathrm{eff}} = \begin{cases} V_{\mathrm{oxm}} & \text{for } x_{\mathrm{g}} \leq 0 \\ \\ q_{\mathrm{bm}} + \boldsymbol{\eta_{\mu}} \cdot q_{\mathrm{im}} & \text{for } x_{\mathrm{g}} > 0 \end{cases} \tag{4.181}$$

$$C_{\mathrm{OX}}^{\mathrm{qm}} = \begin{cases} \mathbf{COX} & \text{for } \boldsymbol{q_{\mathrm{q}}} = 0 \\ \\ \dfrac{\mathbf{COX}}{1 + \boldsymbol{q_{\mathrm{q}}} / \left({q_{\mathrm{eff}}}^2 + {\boldsymbol{q_{\mathrm{lim}}}}^2\right)^{1/6}} & \text{for } \boldsymbol{q_{\mathrm{q}}} > 0 \end{cases} \tag{4.182}$$

4.2.17 Intrinsic Charge Model

$$\text{if } x_{\mathrm{g}} > 0 \begin{cases} F_{\mathrm{j}} = \Delta\psi / \left(2 \cdot H\right) \\ q_{\Delta L} = \left(1 - G_{\Delta L}\right) \cdot \left(q_{\mathrm{im}} - \alpha_{\mathrm{m}} \cdot \Delta\psi/2\right) \\ q_{\Delta L}^{*} = q_{\Delta L} \cdot \left(1 + G_{\Delta L}\right) \\ Q_{\mathrm{G}}^{(i)} = C_{\mathrm{OX}}^{\mathrm{qm}} \cdot \left[V_{\mathrm{oxm}} + \dfrac{\eta_{\mathrm{p}} \cdot \Delta\psi}{2} \cdot \left(\dfrac{G_{\Delta L}}{3} \cdot F_{\mathrm{j}} + G_{\Delta L} - 1\right)\right] \\ Q_{\mathrm{I}}^{(i)} = -C_{\mathrm{OX}}^{\mathrm{qm}} \cdot \left[G_{\Delta L} \cdot \left(q_{\mathrm{im}} + \dfrac{\alpha \cdot \Delta\psi}{6} \cdot F_{\mathrm{j}}\right) + q_{\Delta L}\right] \\ Q_{\mathrm{D}}^{(i)} = -\dfrac{C_{\mathrm{OX}}^{\mathrm{qm}}}{2} \cdot \left[G_{\Delta L}^{2} \cdot \left(q_{\mathrm{im}} + \dfrac{\alpha \cdot \Delta\psi}{6} \cdot \left[\dfrac{F_{\mathrm{j}}^{2}}{5} + F_{\mathrm{j}} - 1\right]\right) + q_{\Delta L}^{*}\right] \end{cases} \tag{4.183}$$

$$\text{if } x_{\mathrm{g}} \leq 0 \begin{cases} Q_{\mathrm{G}}^{(i)} & = C_{\mathrm{OX}}^{\mathrm{qm}} \cdot V_{\mathrm{oxm}} \\ Q_{\mathrm{I}}^{(i)} & = 0 \\ Q_{\mathrm{D}}^{(i)} & = 0 \end{cases} \tag{4.184}$$

$$Q_{\mathrm{S}}^{(i)} = Q_{\mathrm{I}}^{(i)} - Q_{\mathrm{D}}^{(i)} \tag{4.185}$$

$$Q_{\mathrm{B}}^{(i)} = -Q_{\mathrm{I}}^{(i)} - Q_{\mathrm{G}}^{(i)} \tag{4.186}$$

4.2.18 Extrinsic Charge Model

The charges of the source and drain overlap regions:

$$Q_{\mathrm{sov}} = \mathbf{CGOV} \cdot \left(V_{\mathrm{GS}} - \psi_{\mathrm{sov}}\right) \tag{4.187}$$

$$Q_{\mathrm{dov}} = \mathbf{CGOV} \cdot \left(V_{\mathrm{GS}} - V_{\mathrm{DS}} - \psi_{\mathrm{dov}}\right) \tag{4.188}$$

The charge of the bulk overlap region

$$Q_{\mathrm{bov}} = \mathbf{CGBOV} \cdot \left(V_{\mathrm{GS}} - V_{\mathrm{SB}}\right) \tag{4.189}$$

Outer fringe charge:

$$Q_{\mathrm{ofs}} = \mathbf{CFR} \cdot V_{\mathrm{GS}} \tag{4.190}$$

$$Q_{\mathrm{ofd}} = \mathbf{CFR} \cdot \left(V_{\mathrm{GS}} - V_{\mathrm{DS}}\right) \tag{4.191}$$

4.2.19 Total Terminal Charges

$$Q_{\mathrm{G}}=Q_{\mathrm{G}}^{(i)}+Q_{\mathrm{sov}}+Q_{\mathrm{dov}}+\Delta Q_{\mathrm{G}}+Q_{\mathrm{ofs}}+Q_{\mathrm{ofd}}+Q_{\mathrm{bov}} \tag{4.192}$$

$$Q_{\mathrm{S}}=Q_{\mathrm{S}}^{(i)}-Q_{\mathrm{sov}}+\Delta Q_{\mathrm{S}}-Q_{\mathrm{ofs}} \tag{4.193}$$

$$Q_{\mathrm{D}}=Q_{\mathrm{D}}^{(i)}-Q_{\mathrm{dov}}+\Delta Q_{\mathrm{D}}-Q_{\mathrm{ofd}} \tag{4.194}$$

$$Q_{\mathrm{B}}=Q_{\mathrm{B}}^{(i)}-Q_{\mathrm{bov}} \tag{4.195}$$

4.2.20 Noise Model

Eqs. (4.196)-(4.212) are only calculated for $x_\mathrm{g} > 0$. In these equations f_op represents the operation frequency of the transistor and $j = \sqrt{-1}$.

$$N^* = \frac{C_\mathrm{ox}}{q} \cdot \alpha_\mathrm{m} \cdot \boldsymbol{\phi_\mathrm{T}} \tag{4.196}$$

$$N^*_\mathrm{m} = \frac{C_\mathrm{ox}}{q} \cdot q^*_\mathrm{im} \tag{4.197}$$

$$\Delta N = \frac{C_\mathrm{ox}}{q} \cdot \alpha_\mathrm{m} \cdot \Delta\psi \tag{4.198}$$

$$S_\mathrm{fl} = \frac{q \cdot \boldsymbol{\phi}_\mathbf{T}^2 \cdot \boldsymbol{\beta} \cdot I_\mathrm{DS}}{f_\mathrm{op} \cdot C_\mathrm{ox} \cdot G_\mathrm{vsat} \cdot N^*} \cdot \left[(\mathbf{NFA} - \mathbf{NFB} \cdot N^* + \mathbf{NFC} \cdot N^{*\,2}) \cdot \ln\left(\frac{N^*_\mathrm{m} + \Delta N/2}{N^*_\mathrm{m} - \Delta N/2}\right) + \Big(\mathbf{NFB} + \mathbf{NFC} \cdot [N^*_\mathrm{m} - 2 \cdot N^*]\Big) \cdot \Delta N \right] \tag{4.199}$$

$$H_0 = \frac{q^*_\mathrm{im}}{\alpha_\mathrm{m}} \tag{4.200}$$

$$t_1 = \frac{q_\mathrm{im}}{q^*_\mathrm{im}} \tag{4.201}$$

$$t_2 = \left(\frac{\Delta\psi}{12 \cdot H_0}\right)^2 \tag{4.202}$$

$$R = \frac{H_0}{H} - 1 \tag{4.203}$$

$$l_\mathrm{c} = 1 - 12 \cdot t_2 \cdot R \tag{4.204}$$

$$g_\mathrm{ideal} = \frac{\boldsymbol{\beta} \cdot q^*_\mathrm{im}}{G_\mathrm{vsat}} \cdot F_{\Delta L} \tag{4.205}$$

$$C_\mathrm{Geff} = \left(\frac{G_\mathrm{vsat}}{G_\mathrm{mob} \cdot G_{\Delta L}}\right)^2 \cdot C^\mathrm{qm}_\mathrm{OX} \cdot \eta_\mathrm{p} \tag{4.206}$$

$$m_\mathrm{id} = \frac{g_\mathrm{ideal}}{l_\mathrm{c}^2} \cdot [t_1 + 12 \cdot t_2 - 24 \cdot (1 + t_1) \cdot t_2 \cdot R] \tag{4.207}$$

$$S_\mathrm{id} = \boldsymbol{N_\mathrm{T}} \cdot m_\mathrm{id} \tag{4.208}$$

$$m_\mathrm{ig} = \frac{1}{l_\mathrm{c}^2 \cdot g_\mathrm{ideal}} \cdot \left[\frac{t_1}{12} - t_2 \cdot \left(t_1 + \frac{1}{5} - 12 \cdot t_2\right) - \frac{8}{5} \cdot t_2 \cdot (t_1 + 1 - 12 \cdot t_2) \cdot R\right] \tag{4.209}$$

$$S_\mathrm{ig} = \boldsymbol{N_\mathrm{T}} \cdot \frac{(2 \cdot \pi \cdot f_\mathrm{op} \cdot C_\mathrm{Geff})^2 \cdot m_\mathrm{ig}}{1 + (2 \cdot \pi \cdot f_\mathrm{op} \cdot C_\mathrm{Geff} \cdot m_\mathrm{ig})^2} \tag{4.210}$$

$$m_{\mathrm{igid}} = \frac{\sqrt{t_2}}{l_{\mathrm{c}}^2} \cdot \left[1 - 12 \cdot t_2 - \left(t_1 + \frac{96}{5} \cdot t_2 - 12 \cdot t_1 \cdot t_2\right) \cdot R\right] \tag{4.211}$$

$$S_{\mathrm{igid}} = \boldsymbol{N_{\mathrm{T}}} \cdot \frac{2 \cdot \pi \cdot j \cdot f_{\mathrm{op}} \cdot C_{\mathrm{Geff}} \cdot m_{\mathrm{igid}}}{1 + 2 \cdot \pi \cdot j \cdot f_{\mathrm{op}} \cdot C_{\mathrm{Geff}} \cdot m_{\mathrm{ig}}} \tag{4.212}$$

Gate current shot noise:

$$S_{\mathrm{igs}} = 2 \cdot q \cdot (I_{\mathrm{GCS}} + I_{\mathrm{GSov}}) \tag{4.213}$$

$$S_{\mathrm{igd}} = 2 \cdot q \cdot (I_{\mathrm{GCD}} + I_{\mathrm{GDov}}) \tag{4.214}$$

Avalanche current shot noise:

$$S_{\mathrm{avl}} = 2 \cdot q \cdot (1 + M_{\mathrm{avl}}) \cdot I_{\mathrm{avl}} \tag{4.215}$$

Section 5

Non-quasi-static RF model

5.1 Introduction

For high-frequency modeling and fast transient simulations, a special version of the PSP model is available, which enables the simulation of non-quasi-static (NQS) effects, and includes several parasitic resistances.

5.2 NQS-effects

In the PSP-NQS model, NQS-effects are introduced by applying the one-dimensional current continuity equation ($\partial I/\partial y \propto -\partial\rho/\partial t$) to the channel. A full numerical solution of this equation is too inefficient for compact modeling, therefore an approximate technique is used. The channel is partitioned into $N+1$ sections of equal length by assigning N equidistant *collocation points*. The charge density (per unit channel area) along the channel is then approximated by a cubic spline through these collocation points, assuring that both the charge and its first and second spatial derivatives are continuous along the channel. Within this approximation, the current continuity equation reduces to a system of N coupled first order ordinary differential equations, from which the channel charge at each collocation point can be found:

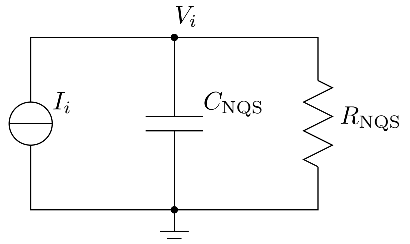
$$\left\{\begin{array}{ccl} \dfrac{\mathrm{d}Q_1}{\mathrm{d}t} & = & f_1(Q_1,\ldots,Q_N) \\ \vdots & & \vdots \\ \dfrac{\mathrm{d}Q_N}{\mathrm{d}t} & = & f_N(Q_1,\ldots,Q_N) \end{array}\right. \tag{5.1}$$

Here, Q_i is the charge density at the i-th collocation point and f_i are functions, which contain the *complete* PSP-charge model. These equations are implemented by the definition of appropriate subcircuits (see left part of Fig. 5.1) and solved by the circuit simulator. Finally, the four terminal charges are calculated from the channel charges, using the Ward-Dutton partitioning scheme for the source and drain charges.

A full description of the PSP-NQS model is given in Section 5.5. More background information can be found in literature [3, 4].

5.3 Parasitics circuit

To facilitate RF-simulations, the PSP-NQS model contains a small network of parasitic elements: a gate resistance and four bulk resistances. Note that the junction diodes are no longer directly connected to the bulk terminal of the intrinsic MOS-transistor. The complete circuit is shown on the right side of Fig. 5.1.



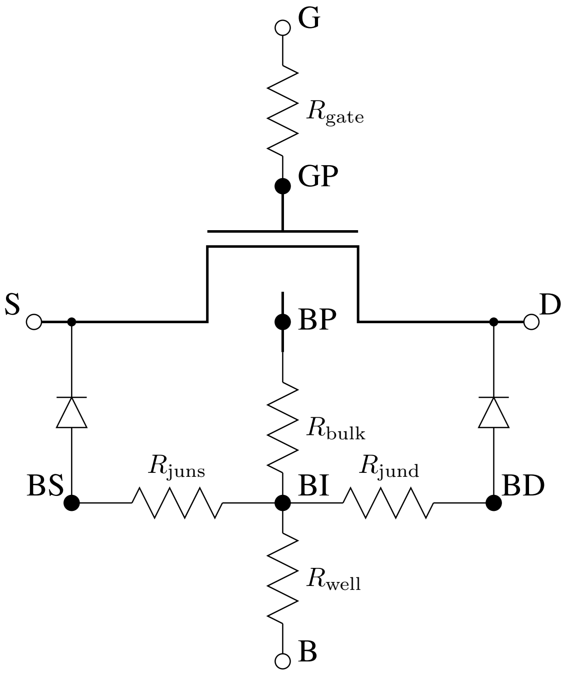


Figure 5.1: *Above:* The subcircuit used to solve one of the differential equations of Eq. (5.1). The current is set to $I_i = C_{\mathrm{NQS}} \cdot f(V_1, \ldots, V_N)$, where the voltage V_i represents the charge density Q_i at the i-th collocation point and is solved by the circuit simulator. N of these circuits are defined and they are coupled through the dependence of I_i on the voltages of the other circuits. The resistance R_{NQS} has a very large value and is present only for convergence purposes. *Right:* The full network of parasitic elements in the PSP-NQS model. The large full dots indicate the five additional internal nodes.

The PSP-model includes the thermal (white) noise of these parasitic resistances.

$$S_{\mathrm{R_G}} = 4 \cdot k_{\mathrm{B}} \cdot T_{\mathrm{KD}} \cdot R_{\mathrm{gate}} \tag{5.2}$$

$$S_{\mathrm{R_{BULK}}} = 4 \cdot k_{\mathrm{B}} \cdot T_{\mathrm{KD}} \cdot R_{\mathrm{bulk}} \tag{5.3}$$

$$S_{\mathrm{R_{WELL}}} = 4 \cdot k_{\mathrm{B}} \cdot T_{\mathrm{KD}} \cdot R_{\mathrm{well}} \tag{5.4}$$

$$S_{\mathrm{R_{JUNS}}} = 4 \cdot k_{\mathrm{B}} \cdot T_{\mathrm{KD}} \cdot R_{\mathrm{juns}} \tag{5.5}$$

$$S_{\mathrm{R_{JUND}}} = 4 \cdot k_{\mathrm{B}} \cdot T_{\mathrm{KD}} \cdot R_{\mathrm{jund}} \tag{5.6}$$

5.4 NQS and RF parameters

The PSP-NQS model has a few additional parameters, which are described in the tables below. The allowed values for the parameter **SWNQS** are 0, 1, 2, 3, 5, and 9. If **SWNQS** $= 0$, then NQS effects are switched off, i.e. the intrinsic MOS model is identical to the standard PSP-model (however, the parasitics-circuit is still in place). If **SWNQS** is nonzero, it indicates the number of collocation points to be used in the NQS-calculations. A higher value increases the accuracy, but leads to an increased computational burden.

5.4.1 Additional Parameters for global NQS model

No.	Name	Unit	Default	Min.	Max.	Description
0	**SWNQS**	–	0	0	9	Switch for NQS effects / number of collocation points
1	**MUNQSO**	–	1	–	–	Relative mobility for NQS modeling
2	**RGO**	Ω	10^{-3}	–	–	Gate resistance R_{gate}
3	**RBULKO**	Ω	10^{-3}	–	–	Bulk resistance R_{bulk}
4	**RWELLO**	Ω	10^{-3}	–	–	Well resistance R_{well}
5	**RJUNSO**	Ω	10^{-3}	–	–	Source-side bulk resistance R_{juns}
6	**RJUNDO**	Ω	10^{-3}	–	–	Drain-side bulk resistance R_{jund}

5.4.2 Additional Parameters for local NQS model

No.	Name	Unit	Default	Min.	Max.	Description
0	**SWNQS**	–	0	0	9	Switch for NQS effects / number of collocation points
1	**MUNQS**	–	1	0	–	Relative mobility for NQS modeling
2	**RG**	Ω	10^{-3}	10^{-6}	–	Gate resistance R_{gate}
3	**RBULK**	Ω	10^{-3}	10^{-6}	–	Bulk resistance R_{bulk}
4	**RWELL**	Ω	10^{-3}	10^{-6}	–	Well resistance R_{well}
5	**RJUNS**	Ω	10^{-3}	10^{-6}	–	Source-side bulk resistance R_{juns}
6	**RJUND**	Ω	10^{-3}	10^{-6}	–	Drain-side bulk resistance R_{jund}

5.4.3 Geometrical Scaling Rules

Although the parasitic resistances are (in general) dependent on geometry, the actual form of this dependency will be strongly influenced by the device layout. For this reason, L and W dependence of these resistances is currently *not* included in PSP; the correct values must be supplied manually for each geometry.

The following (trivial) scaling-rules are included for the NQS-model.

$$\mathbf{MUNQS} = \mathbf{MUNQSO} \tag{5.7}$$

$$\mathbf{RG} = \mathbf{RGO} \tag{5.8}$$

$$\mathbf{RBULK} = \mathbf{RBULKO} \tag{5.9}$$

$$\mathbf{RWELL} = \mathbf{RWELLO} \tag{5.10}$$

$$\mathbf{RJUNS} = \mathbf{RJUNSO} \tag{5.11}$$

$$\mathbf{RJUND} = \mathbf{RJUNDO} \tag{5.12}$$

Note: After calculation of the local parameters, clipping is applied according to Section 5.4.2.

5.5 NQS Model Equations

In this section, several symbols and notations are used which were defined in Section 4. Moreover, y denotes the (normalized) position along the channel ($y = 0$ is source side, $y = 1$ is drain side), while x denotes the surface potential (normalized to $\phi_{\mathbf{T}}^{*}$) at a certain position.

5.5.1 Internal constants

Eqs. (5.13)–(5.18) are independent of bias conditions and time. Consequently, they have to be computed only once.

Note: In PSP 101.0 and before, only **SWNQS** $= 0, 1, 2, 3, 5, 9$ are allowed!

$$n = \textbf{SWNQS} + 1 \tag{5.13}$$

$$h = 1/n \tag{5.14}$$

The matrix A is a square $(n + 1) \times (n + 1)$-matrix with elements $A_{i,j}$ $(0 \leq i, j \leq n)$, which are used in Eq. 5.36. They are computed using the following algorithm (adapted from [5]):

1. Initial values:

$$A_{i,j} = 0 \qquad \text{for } 0 \leq i, j \leq n \tag{5.15}$$

$$v_i = 0 \qquad \text{for } 0 \leq i \leq n \tag{5.16}$$

2. First loop:

$$\left.\begin{aligned} & p = 2 + v_{i-1}/2 \\ & v_i = -1/(2 \cdot p) \\ & A_{i,i-1} = 1/h \\ & A_{i,i} = -2/h \\ & A_{i,i+1} = 1/h \\ & A_{i,j} = \frac{1}{p} \cdot (3 \cdot A_{i,j}/h - A_{i-1,j}/2) \quad \Big\}\text{for } j = 0 \ldots n \end{aligned}\right\} \text{for } i = 1 \ldots (n-1) \tag{5.17}$$

3. Second loop (back substitution):

$$\left. A_{i,j} = v_i \cdot A_{i+1,j} + A_{i,j} \qquad \text{for } j = 0 \ldots n \right\} \text{for } i = (n-1) \ldots 0 \tag{5.18}$$

5.5.2 Position independent quantities

The following quantities depend on the bias conditions, but are constant along the channel:

$$\text{if } x_\mathrm{g} > 0 \begin{cases} y_\mathrm{m} = \dfrac{1}{2} \cdot \left(1 + \dfrac{\Delta\psi}{4 \cdot H}\right) \\ \\ p_\mathrm{d} = \dfrac{x_\mathrm{gm}}{x_\mathrm{g} - x_\mathrm{m}} \\ \\ G_\mathrm{p} = G/p_\mathrm{d} \end{cases} \tag{5.19}$$

$$\text{if } x_\mathrm{g} \le 0 \begin{cases} y_\mathrm{m} = 1/2 \\ p_\mathrm{d} = 1 \\ G_\mathrm{p} = G \end{cases} \tag{5.20}$$

$$a_\mathrm{p} = 1 + G_\mathrm{p}/\sqrt{2} \tag{5.21}$$

$$p_\mathrm{mrg} = 10^{-5} \cdot a_\mathrm{p} \tag{5.22}$$

5.5.3 Position dependent surface potential and charge

Interpolated (quasi-static) surface potential along the channel:

$$\Psi(y) = x_\mathrm{m} + \frac{H}{\boldsymbol{\phi}^*_\mathbf{T}} \cdot \left(1 - \sqrt{1 - \frac{2 \cdot \Delta\psi}{H} \cdot (y - y_\mathrm{m})}\right) \tag{5.23}$$

Normalized bulk-charge and its first two derivatives as functions of surface potential:

$$q_\mathrm{b}(x) = -\mathrm{sgn}(x) \cdot G_\mathrm{p} \cdot \sqrt{\exp(-x) + x - 1} \tag{5.24}$$

$$q_\mathrm{b}'(x) = \frac{G_\mathrm{p}^2 \cdot [1 - \exp(-x)]}{2 \cdot q_\mathrm{b}(x)} \tag{5.25}$$

$$q_\mathrm{b}''(x) = q_\mathrm{b}'(x) + \frac{q_\mathrm{b}'(x)^2 - G_\mathrm{p}^2/2}{q_\mathrm{b}(x)} \tag{5.26}$$

Surface potential as a function of normalized inversion charge (note that these equations are identical to Eq. (4.152), despite the different notation and physical background):

$$
\Pi(x_{\mathrm{g}}) = \begin{cases}
\text{if } x_{\mathrm{g}} < -p_{\mathrm{mrg}} & \begin{cases}
y_{\mathrm{g}} = -x_{\mathrm{g}} \\
z = 1.25 \cdot y_{\mathrm{g}} / a_{\mathrm{p}} \\
\eta = \left[z + 10 - \sqrt{(z-6)^2 + 64} \right] / 2 \\
a = \left(y_{\mathrm{g}} - \eta \right)^2 + G_{\mathrm{p}}^2 \cdot (\eta + 1) \\
c = 2 \cdot (y_{\mathrm{g}} - \eta) - G_{\mathrm{p}}^2 \\
\tau = -\eta + \ln \left(a / G_{\mathrm{p}}^2 \right) \\
y_0 = \sigma_1(a,\, c,\, \tau,\, \eta) \\
\Delta_0 = \exp(y_0) \\
\xi = 1 - G_{\mathrm{p}}^2 \cdot \Delta_0 / 2 \\
p = 2 \cdot (y_{\mathrm{g}} - y_0) + G_{\mathrm{p}}^2 \cdot (\Delta_0 - 1) \\
q = \left(y_{\mathrm{g}} - y_0 \right)^2 + G_{\mathrm{p}}^2 \cdot (y_0 - \Delta_0 + 1) \\
\Pi = -y_0 - \dfrac{2 \cdot q}{p + \sqrt{p^2 - 4 \cdot q \cdot \xi}}
\end{cases} \\
\text{if } |x_{\mathrm{g}}| \leq p_{\mathrm{mrg}} & \begin{cases}
\Pi = \dfrac{x_{\mathrm{g}}}{a_{\mathrm{p}}}
\end{cases} \\
\text{if } x_{\mathrm{g}} > x_{\mathrm{mrg}} & \begin{cases}
\hat{x}_{\mathrm{g1}} = \boldsymbol{x_1} + G \cdot \sqrt{\exp(-\boldsymbol{x_1}) + \boldsymbol{x_1} - 1} \\
\bar{x} = \dfrac{x_{\mathrm{g}}}{a_{\mathrm{p}}} \cdot \left[1 + x_{\mathrm{g}} \cdot (\boldsymbol{x_1} \cdot a_{\mathrm{p}} / \hat{x}_{\mathrm{g1}} - 1) / \hat{x}_{\mathrm{g1}} \right] \\
x_0 = x_{\mathrm{g}} + G_{\mathrm{p}}^2 / 2 - G_{\mathrm{p}} \cdot \sqrt{x_{\mathrm{g}} + G_{\mathrm{p}}^2 / 4 - 1 + \exp(-\bar{x})} \\
\Delta_0 = \exp(-x_0) \\
\xi = 1 - G_{\mathrm{p}}^2 \cdot \Delta_0 / 2 \\
p = 2 \cdot (x_{\mathrm{g}} - x_0) + G_{\mathrm{p}}^2 \cdot (1 - \Delta_0) \\
q = (x_{\mathrm{g}} - x_0)^2 - G_{\mathrm{p}}^2 \cdot (x_0 + \Delta_0 - 1) \\
\Pi = x_0 + \dfrac{2 \cdot q}{p + \sqrt{p^2 - 4 \cdot q \cdot \xi}}
\end{cases}
\end{cases} \tag{5.27}
$$

$$
X(x_{\mathrm{g}}, q_{\mathrm{inv}}) = \Pi(x_{\mathrm{g}} + q_{\mathrm{inv}} / p_{\mathrm{d}}) \tag{5.28}
$$

Auxiliary functions:

$$
q(x) = -p_{\mathrm{d}} \cdot (x_{\mathrm{g}} - x) - q_{\mathrm{b}}(x) \tag{5.29}
$$

$$
\psi(q, q_{x1}) = \frac{q}{q_{x1}} - 1 \tag{5.30}
$$

$$
\phi(q, q_{x1}, q_{x2}) = \left(1 - \frac{q \cdot q_{x2}}{q_{x1}^2} \right) / q_{x1} \tag{5.31}
$$

Normalized right-hand-side of continuity equation:

$$f(x_\mathrm{g}, q, q', q'') = \begin{cases} x_\mathrm{z} = X(x_\mathrm{g}, q) \\ q_{x1} = \dfrac{\partial q}{\partial x}(x_\mathrm{z}) = p_\mathrm{d} - q'_\mathrm{b}(x_\mathrm{z}) \\ q_{x2} = \dfrac{\partial^2 q}{\partial x^2}(x_\mathrm{z}) = -q''_\mathrm{b}(x_\mathrm{z}) \\ f_0 = \psi(q, q_{x1}) \cdot q'' + \phi(q, q_{x1}, q_{x2}) \cdot q'^2 \\ x_{y1} = \dfrac{\partial x_\mathrm{z}}{\partial y} = q'/q_{x1} \\ z_\mathrm{sat} = \begin{cases} \left(\theta^*_\mathrm{sat} \cdot \boldsymbol{\phi}^*_\mathbf{T} \cdot x_{y1}\right)^2 & \text{for NMOS} \\ \dfrac{\left(\theta^*_\mathrm{sat} \cdot \boldsymbol{\phi}^*_\mathbf{T} \cdot x_{y1}\right)^2}{1 + \theta^*_\mathrm{sat} \cdot \Delta\psi} & \text{for PMOS} \end{cases} \\ \zeta = \sqrt{1 + 2 \cdot z_\mathrm{sat}} \\ F_\mathrm{vsat} = 2/(1+\zeta) \\ f = F_\mathrm{vsat} \cdot \left[f_0 - F_\mathrm{vsat} \cdot \dfrac{z_\mathrm{sat}}{\zeta} \cdot \psi(q, q_{x1}) \cdot (q'' - x_{y1}^2 \cdot q''_\mathrm{b}(x_\mathrm{z}))\right] \end{cases} \tag{5.32}$$

Normalization constant:

$$T_\mathrm{norm} = \frac{\mathbf{MUNQS} \cdot \boldsymbol{\phi}^*_\mathbf{T} \cdot \boldsymbol{\beta}}{C^\mathrm{qm}_\mathrm{OX} \cdot G_\mathrm{mob} \cdot G_{\Delta L}} \tag{5.33}$$

5.5.4 Cubic spline interpolation

Using cubic spline interpolation, the spatial derivatives $\frac{\partial q_i}{\partial y}(t)$ and $\frac{\partial^2 q_i}{\partial y^2}(t)$ can be expressed as functions of the $q_i(t)$.

$$q''_0 = 0 \tag{5.34}$$

$$q''_n = 0 \tag{5.35}$$

$$q''_i = \sum_{j=0}^{n} A_{i,j} \cdot q_i \qquad \text{for } 1 \le i \le n-1 \tag{5.36}$$

$$q'_i = \frac{q_{i+1} - qi}{h} - \frac{h}{6} \cdot (2 \cdot q''_i + q''_{i+1}) \qquad \text{for } 1 \le i \le n-1 \tag{5.37}$$

5.5.5 Continuity equation

Initial value for the q_i ($0 \le i \le n$). These values are used for the DC operating point.

$$x_{i,0} = \Psi(i \cdot h) \tag{5.38}$$

$$q_{i,0} = q(x_{i,0}) \tag{5.39}$$

Note: $x_{0,0} = x_\mathrm{s}$ and $x_{n,0} = x_\mathrm{d}$. Moreover, these values coincide with those in the quasi-static part of PSP.

The core of the NQS-model is the solution of $q(y,t)$ from the charge continuity equation along the channel. By approximating the y-dependence by a cubic spline through a number of collocation points, the problem is reduced to solving the $q_i(t)$ from the following set of coupled differential equations.

$$\boxed{\begin{cases} \dfrac{\partial q_i}{\partial t}(t) + T_\mathrm{norm} \cdot f\left(x_\mathrm{g},\, q_i(t),\, \dfrac{\partial q_i}{\partial y}(t),\, \dfrac{\partial^2 q_i}{\partial y^2}(t)\right) = 0 & \text{for } 1 \le i \le n-1 \\ q_i(0) = q_{i,0} & \end{cases}} \tag{5.40}$$

Note that the boundary points $q_0(t) = q(x_\mathrm{s}) = q_\mathrm{is}$ and $q_n(t) = q(x_\mathrm{d}) = q_\mathrm{id}$ remain fixed to their quasi-static values; they are not solved from the equation above.

The set of differential equations defined above is solved by the circuit simulator via the subcircuits shown in the left part of Fig. 5.1.

5.5.6 Non-quasi-static terminal charges

Once the q_i are known, the NQS terminal can be computed:

$$S_0 = \sum_{i=1}^{n-1} q_i \tag{5.41}$$

$$S_2 = \sum_{i=1}^{n-1} q_i'' \tag{5.42}$$

$$q_\mathrm{I}^\mathrm{NQS} = \int_0^1 q(y)\,\mathrm{d}y = h \cdot S_0 + \frac{h}{2} \cdot (u_0 + u_n) - \frac{h^3}{12} \cdot S_2 \tag{5.43}$$

$$U_0 = \sum_{i=1}^{n-1} i \cdot q_i \tag{5.44}$$

$$U_2 = \sum_{i=1}^{n-1} i \cdot q_i'' \tag{5.45}$$

$$q_\mathrm{D}^\mathrm{NQS} = \int_0^1 y \cdot q(y)\,\mathrm{d}y = h^2 \cdot U_0 + \frac{h^2}{6} \cdot [q_0 + (3n-1)u_n] - \frac{h^4}{12} \cdot U_2 \tag{5.46}$$

$$q_\mathrm{S}^\mathrm{NQS} = q_\mathrm{I}^\mathrm{NQS} - q_\mathrm{D}^\mathrm{NQS} \tag{5.47}$$

Currently, only **SWNQS** $= 0, 1, 2, 3, 5, 9$ are allowed. For odd values of **SWNQS** the gate charge is integrated along the channel using “Simpson’s rule”. If **SWNQS** $= 2$, “Simpson’s 3/8-rule” is used.

- If **SWNQS** is odd (that is, n is even):

$$q_\mathrm{G}^\mathrm{NQS} = p_\mathrm{d} \cdot \left[x_\mathrm{g} - \frac{h}{3} \cdot \left(X(x_\mathrm{g}, q_0) + 4 \cdot \sum_{i=1}^{n/2} X(x_\mathrm{g}, q_{2i-1}) + 2 \cdot \sum_{i=1}^{n/2-1} X(x_\mathrm{g}, q_{2i}) + X(x_\mathrm{g}, q_n)\right)\right] \tag{5.48}$$

- If **SWNQS** $= 2$ (that is, $n = 3$):

$$q_{\mathrm{G}}^{\mathrm{NQS}} = p_{\mathrm{d}} \cdot \left[x_{\mathrm{g}} - \frac{3 \cdot h}{8} \cdot \left(X(x_{\mathrm{g}}, q_0) + 3 \cdot X(x_{\mathrm{g}}, q_1) + 3 \cdot X(x_{\mathrm{g}}, q_2) + X(x_{\mathrm{g}}, q_3)\right)\right] \tag{5.49}$$

Convert back to conventional units:

$$Q_{\mathrm{S}}^{\mathrm{NQS}} = C_{\mathrm{OX}}^{\mathrm{qm}} \cdot \boldsymbol{\phi}_{\mathbf{T}}^{*} \cdot q_{\mathrm{S}}^{\mathrm{NQS}} \tag{5.50}$$

$$Q_{\mathrm{D}}^{\mathrm{NQS}} = C_{\mathrm{OX}}^{\mathrm{qm}} \cdot \boldsymbol{\phi}_{\mathbf{T}}^{*} \cdot q_{\mathrm{D}}^{\mathrm{NQS}} \tag{5.51}$$

$$Q_{\mathrm{G}}^{\mathrm{NQS}} = C_{\mathrm{OX}}^{\mathrm{qm}} \cdot \boldsymbol{\phi}_{\mathbf{T}}^{*} \cdot q_{\mathrm{G}}^{\mathrm{NQS}} \tag{5.52}$$

$$Q_{\mathrm{B}}^{\mathrm{NQS}} = -(Q_{\mathrm{S}}^{\mathrm{NQS}} + Q_{\mathrm{D}}^{\mathrm{NQS}} + Q_{\mathrm{G}}^{\mathrm{NQS}}) \tag{5.53}$$

Section 6

Embedding

6.1 Model selection

Circuit simulators have different ways for the user to determine which model must be used for simulation. Typically, model selection is either done by *name* or by assigning a value to the parameter **LEVEL**. The method to be used is prescribed by the circuit simulator vendor.

If selection is done by name, the value of the parameter **LEVEL** is generally ignored. When Verilog-A code is used, model selection is always done by name.

For the SiMKit and the Verilog-A code provided by the PSP model developers, the method and values to be used are given in the table below. For other implementations, the method/value provided by the circuit simulator vendor is to be used.

Simulator	**Model selection by**	**Global (geom.)**	**Global (binning)**	**Local**
Spectre	name	`psp1010`	`psp1011`	`psp101e`
Pstar	**LEVEL**	1010	1011	101
ADS	name	`psp1010`	`psp1011`	`psp101e`
Verilog-A	name	`psp101va`	`psp101bva`	`psp101eva`

6.2 Embedding PSP in a Circuit Simulator

In CMOS technologies both n- and p-channel MOS transistors are supported. It is convenient to use the same set of equations 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 internally as an n-channel transistor. Nevertheless, the electrical behavior of electrons and holes is not exactly the same (e.g., the mobility and tunneling behavior), and consequently slightly different equations have to be used in case of n- or p-type transistors.

Designers are used to the standard terminology of source, drain, gate and bulk. Therefore, in the context of a circuit simulator it is traditionally possible to address, say, the drain of MOST number 17, even if in reality the corresponding source is at a higher potential (n-channel case). More strongly, most circuit simulators provide for model evaluation values for V_{DS}, V_{GS}, and V_{SB} based on an a priori assignment of source, drain, and bulk, independent of the actual bias conditions. Since PSP assumes that saturation occurs at the drain side of the MOSFET, the basic model cannot cope with bias conditions that correspond to $V_{\mathrm{DS}} < 0$. Again a transformation of the bias conditions is necessary. In this case, the transformation corresponds to internally reassigning source and drain, applying the standard electrical model, and then reassigning the currents and charges to the original terminals. In PSP care has been taken to preserve symmetry with respect to drain and source at $V_{\mathrm{DS}} = 0$. In other words, no singularities will occur in the higher-order derivatives at $V_{\mathrm{DS}} = 0$.

In detail, for correct embedding of PSP into a circuit simulator, the following procedure—illustrated in Fig. 6.1—is followed. It is assumed that the simulator provides the nodal potentials V_D^e, V_G^e, V_S^e and V_B^e based on an a priori assignment of drain, gate, source and bulk.

Step 1 The voltages V'_DS, V'_GS, and V'_SB are calculated from the nodal potentials provided by the circuit simulator. In the same step, the value of the parameter **TYPE** is used to deal with the polarity of the device. From here onwards, all transistors can be treated as n-channel devices.

Step 2 Depending on the sign of V'_DS, 'source-drain interchange' is performed. At this level, the voltages comply to all the requirements for input quantities of PSP.

Step 3 All the internal output quantities (i.e. channel current, weak-avalanche current, gate current, nodal charges, and noise-power spectral densities) are evaluated using the standard PSP equations (Section 4) and the internal voltages.

Step 4 The internal output quantities are corrected for a possible source-drain interchange.

Step 5 External output are corrected for a possible p-channel transformation and **MULT** is applied. The quantities of the intrinsic MOSFET and the junctions are combined.

In general, separate parameter sets are used for n- and p-channel transistors, which are distinguished by the value of **TYPE**. 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 therefore not be included in the simulator.

6.3 Integration of JUNCAP2 in PSP

Introduction

The JUNCAP2 model 200.1 is an integral part of PSP 101.0. In addition, it is available as a stand-alone model. A complete description of the JUNCAP2-model (including all model equations) can be found in the documentation of JUNCAP2's stand alone version. In this section, only the integration of JUNCAP2 in PSP is described.

Topology

In a MOS transistor, there are two junctions: one between source and bulk, and one between drain and bulk. In case of an n-channel MOSFET, the junction anode corresponds to the MOSFET bulk terminal, and the junction cathodes correspond to the source and the drain. In case of a p-channel MOSFET, it is the other way around: now the junction cathode corresponds to the MOSFET bulk terminal, and the junction anodes correspond to the source and the drain. The connections are schematically given in Fig. 6.2. In PSP, this change of junction terminal connections in case of a p-MOSFET is handled automatically via the **TYPE** parameter.

In most cases, the MOSFET is operated in such a way that the junctions are either biased in the reverse mode of operation or not biased at all. In some applications, however, the source-bulk junction has a small forward bias. This is also the case in partially depleted SOI (PDSOI).

As indicated in Fig. 6.1, the interchange of source and drain for $V_\mathrm{DS} < 0$ (as explained above for the intrinsic MOS model) does *not* apply to the junctions. For example, **ABDRAIN** always refers to junction between the bulk and the terminal known as 'drain' to the simulator, independent of the sign of V_DS.

Global and local model level

As explained in the introduction, the PSP model has a local and a global level. The JUNCAP2 model is a geometrically scaled model, i.e. it is valid for a range of junction geometries (as described by the geometrical parameters **AB**, **LS**, and **LG**). It has turned out that it is very unnatural to create a local parameter set for

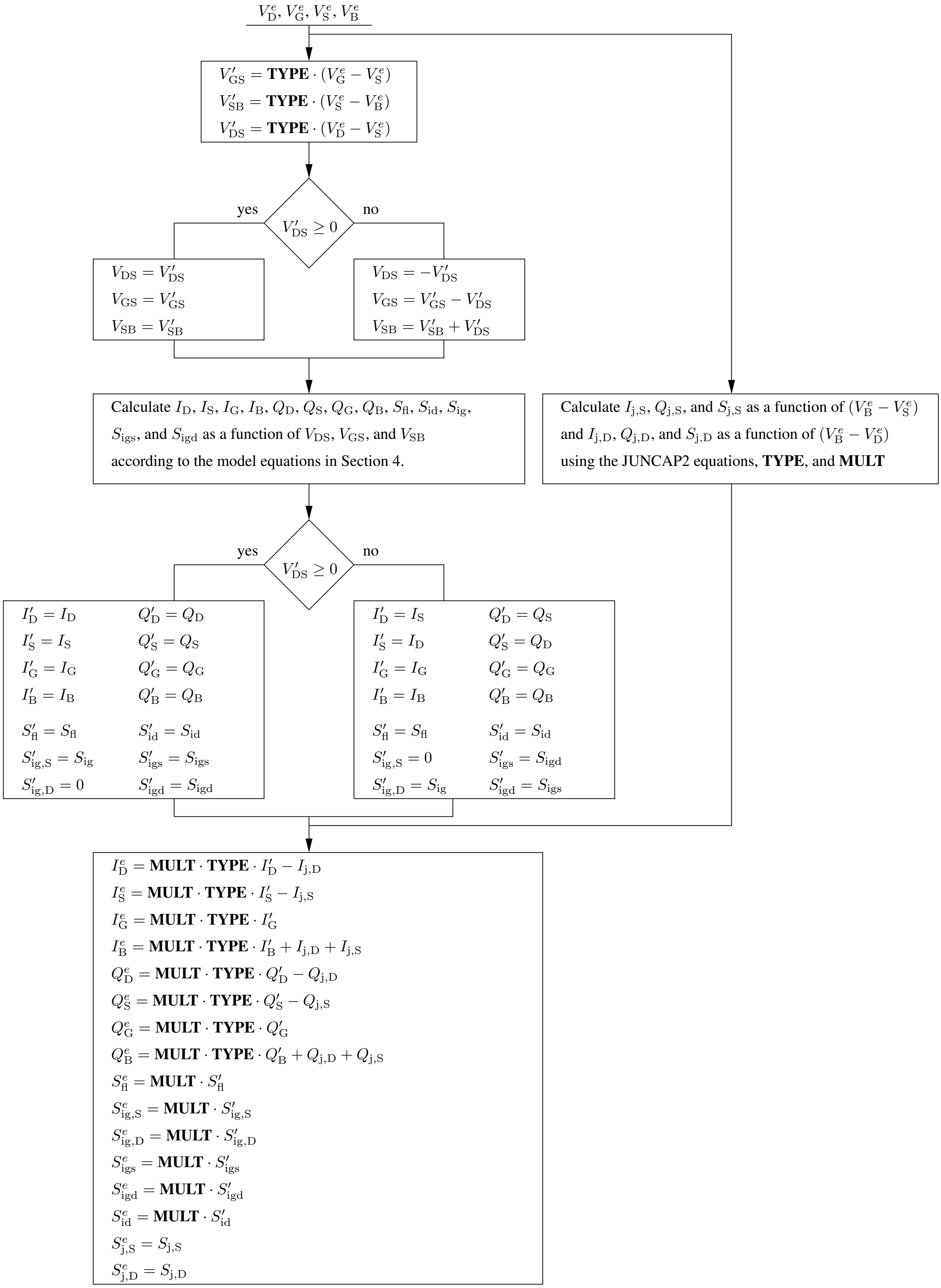


Figure 6.1: Schematic overview of source-drain interchange and handling of **TYPE** and **MULT**. Note that **TYPE** and **MULT** are included in the JUNCAP2 model equations.

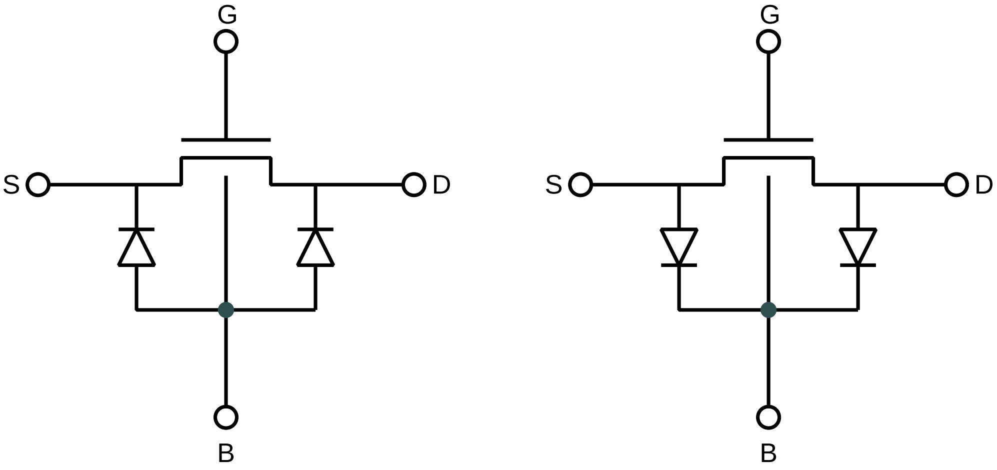


Figure 6.2: Topology of the PSP model. *Left:* n-channel MOSFET; *Right:* p-channel MOSFET. In PSP, the correct diode polarity is automatically chosen via the **TYPE**-parameter.

JUNCAP2, valid for one particular junction geometry: such a parameter set would have as many parameters as the global parameter set, and would be of no use. (Note that, in contrast, the local model for the intrinsic MOSFET is very useful in, e.g., parameter extraction; this is not the case for JUNCAP2.)

Therefore, the JUNCAP2 model is connected in exactly the same way to both the local and global model levels of PSP. That means that the resulting PSP local model is valid for a MOSFET with one particular channel width and length, but with arbitrary junction geometry.

Parameters

Both junctions in the MOSFET are modeled with the same set of JUNCAP2 parameters. In the PSP model, the geometrical parameters **AB**, **LS**, and **LG** need to be specified for both source and drain. They will be denoted as **ABSOURCE**, **LSSOURCE**, and **LGSOURCE** for the source junction, and **ABDRAIN**, **LSDRAIN**, and **LGDRAIN** for the drain junction. For compatibility with BSIM instance parameters, there is also an option to use **AS**, **AD**, **PS**, and **PD**. The complete list of instance parameters (PSP and JUNCAP2) can be found in Sections 2.5.1 and 2.5.2.

The parameter **MULT** is merged with the parameter **MULT** of the intrinsic MOSFET model. In other words, both intrinsic currents, charges, and noise as well as junction currents, charges and noise are multiplied by one single parameter **MULT**. Beside **MULT**, also the parameters **DTA** and **TYPE** are shared by the intrinsic MOSFET model and the junction model. For clarity, we mention here that the reference temperatures of the intrinsic MOSFET model and junction model are *not* merged; they each have their own value and name (**TR** and **TRJ**, respectively). The currents, charges and spectral noise densities of the source and drain junctions are labeled $I_{\mathrm{j,S}}$, $Q_{\mathrm{j,S}}$, $S_{\mathrm{j,S}}$, $I_{\mathrm{j,D}}$, $Q_{\mathrm{j,D}}$, and $S_{\mathrm{j,D}}$ in Fig. 6.1.

6.4 Verilog-A versus C

As mentioned in Section 1.3, two implementations of the PSP-model are distributed: in Verilog-A language and in C-language (as part of the SiMKit). The C-version is automatically generated from the Verilog-A version by a software package called ADMS [1]. This procedure guarantees that the two implementations contain identical model equations.

Nevertheless, there are a few minor differences between the two, which are due to certain limitations of either the Verilog-A language or the circuit simulators supported in the SiMKit-framework. These differences are described below.

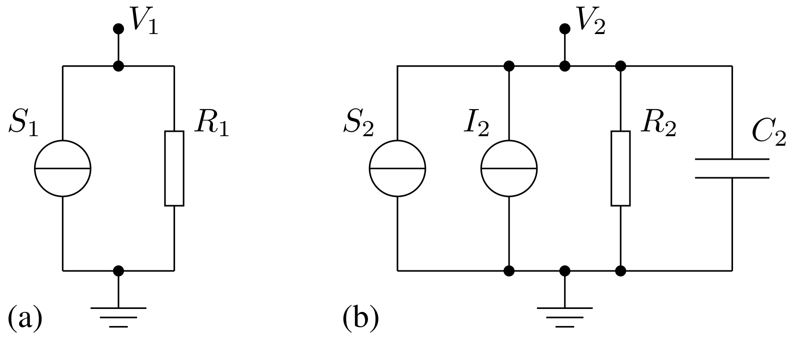


Figure 6.3: The two subcircuits used in PSP's Verilog-A implementation to model the correct frequency dependence of induced gate noise and its correlation with the channel thermal noise.

6.4.1 Implementation of GMIN

In both implementations, there is an additional term in Eqs. (4.177) and (4.178), resulting in

$$I_{\mathrm{D}} = I_{\mathrm{DS}} + I_{\mathrm{avl}} - I_{\mathrm{GDov}} - I_{\mathrm{GCD}} + I_{\mathrm{gidl}} + G_{\mathrm{min}} \cdot V_{\mathrm{DS}} \tag{6.1}$$

and

$$I_{\mathrm{S}} = -I_{\mathrm{DS}} - I_{\mathrm{GSov}} - I_{\mathrm{GCS}} + I_{\mathrm{gisl}} - G_{\mathrm{min}} \cdot V_{\mathrm{DS}}. \tag{6.2}$$

In the SiMKit, G_{min} is a variable which is accessible by the circuit simulator. This allows the circuit simulator to improve the convergence properties of a circuit by making use of so-called 'G_{min}-stepping'.

In the Verilog-A version of PSP, G_{min} is set to a fixed value $G_{\mathrm{min}} = 1 \cdot 10^{-15}$ S.[1]

6.4.2 Implementation of the noise-equations

First, the Verilog-A implementation of the noise equations is described in this section. Then, the C-implementation is derived from this by a sequence of approximations.

Verilog-A

In Verilog-A, the possibilities to directly model the frequency-dependence of noise spectral density are limited. Moreover, the only way to include correlation between noise sources is by using (extra) internal nodes. Consequently, the calculation for the description of thermal noise in the channel, induced gate noise, and their correlation is implemented using the subcircuits depicted in Fig. 6.3. The first subcircuit (a) contains a parallel connection of a white noise current source S_1 and a resistor R_1. The voltage over the elements is denoted by V_1. The second subcircuit (b) contains a parallel connection of a voltage-controlled current source I_2, a white-noise current source S_2, a resistor R_2, and a capacitor C_2. The nodal voltage is V_2. The parameters of these components are given in the table below.

---

[1] If supported by the circuit simulator, Verilog-A version 2.2 allows the value of G_{min} to be accessed by the circuit simulator. Once this feature is generally available in Verilog-A compilers, it will be included in PSP as well.

Name	Component	Quantity	Value
R_1	Resistor	Resistance	$1\,\Omega$
R_2	Resistor	Resistance	$1\,\Omega$
S_1	White noise source	Noise current spectral density	C_{igid}
S_2	White noise source	Noise current spectral density	$S_{\mathrm{ig}}^{0}\cdot(1-C_{\mathrm{igid}})$
C_2	Capacitor	Capacitance	$m_{\mathrm{ig}}\cdot C_{\mathrm{Geff}}$
I_2	Voltage-controlled current source	Current	$-\sqrt{S_{\mathrm{ig}}^{0}}\cdot V_1$

The values of m_{ig} and C_{Geff} are given by Eqs. (4.206) and (4.209), respectively. Furthermore,

$$S_{\mathrm{ig}}^{0}=\frac{\boldsymbol{N_{\mathrm{T}}}}{m_{\mathrm{ig}}} \tag{6.3}$$

and

$$C_{\mathrm{igid}}=\frac{m_{\mathrm{igid}}}{\sqrt{m_{\mathrm{ig}}\cdot m_{\mathrm{id}}}}, \tag{6.4}$$

where m_{id} and m_{igid} are given by Eqs. (4.207) and (4.211).

Subcircuit (a) contains a single white noise source, from which the correlated parts of the channel noise and induced gate noise are derived. Now, the thermal noise in the channel is modeled by two contributions:

1. An uncorrelated white noise source with current spectral density $S_{\mathrm{id}}\cdot(1-C_{\mathrm{igid}})$.
2. A white noise source with spectral power density $S_{\mathrm{id}}\cdot C_{\mathrm{igid}}$ which is fully correlated with S_1.

Subcircuit (b) contains a current noise source S_2 and a voltage controlled current source I_2, the current of which is controlled by V_1. The result is that I_2 acts as white noise source which is fully correlated with S_1 (and thus with the second component of the channel noise above). Summarizing, the induced gate noise is modeled by two contributions:

1. An uncorrelated white noise source with current spectral density $S_{\mathrm{ig}}^{0}\cdot(1-C_{\mathrm{igid}})$.
2. A white noise source with current spectral density $S_{\mathrm{ig}}^{0}\cdot C_{\mathrm{igid}}$, which is fully correlated with S_1.

These two noise sources in subcircuit (b) are in series with a parallel combination of a resistor and a capacitor. The noise in the current through C_2 has the correct frequency dependence and is used to describe the induced gate noise in the MOSFET.

The total noise current spectral density of the two noise sources S_2 and I_2 is equal to $S_{\mathrm{ig}}^{0}\cdot(1-C_{\mathrm{igid}})+S_{\mathrm{ig}}^{0}\cdot C_{\mathrm{igid}}=S_{\mathrm{ig}}^{0}$. Therefore, the total noise spectral density of the current through the capacitor C_2 is given by

$$S_{\mathrm{ig}}=\left|\frac{j\cdot\omega\cdot C_2\cdot R_2}{1+j\cdot\omega\cdot C_2\cdot R_2}\right|^2\cdot S_{\mathrm{ig}}^{0}, \tag{6.5}$$

(where $\omega=2\cdot\pi\cdot f_{\mathrm{op}}$ and $j=\sqrt{-1}$) which is indeed exactly equivalent to Eq. (4.210).

Similarly, the cross-correlation noise spectrum of (i) the current through C_2 induced by noise source I_2 and (ii) the correlated part of the channel noise is given by

$$S_{\mathrm{igid}}=\left(\frac{j\cdot\omega\cdot C_2\cdot R_2}{1+j\cdot\omega\cdot C_2\cdot R_2}\cdot\sqrt{S_{\mathrm{ig}}^{0}}\cdot C_{\mathrm{igid}}\right)\cdot\left(\sqrt{S_{\mathrm{id}}}\cdot C_{\mathrm{igid}}\right), \tag{6.6}$$

which is, in turn, equivalent to Eq. (4.212).

This shows that the implementation of PSP's noise model in Verilog-A naturally yields the desired correlations and frequency dependence. However, it is at the cost of two additional internal nodes.

Note once more that the equations in Section 4.2.20 exactly reflect the results of the Verilog-A implementation described above.

SiMKit C-code

Contrary to the limitation of Verilog-A language, most circuit simulators are able to directly deal with correlated and frequency dependent noise—without the use of additional internal nodes. In order to minimize the simulation time of the model, C-implementations should therefore avoid the use of such internal nodes whenever possible.

In the frequency dependence of S_{ig} and S_{igid} one can roughly distinguish two regions: a frequency dependent part at low frequencies and a constant part at high frequencies. The transition between the two regions occurs at

$$f_{\mathrm{cross}} = \frac{1}{2 \cdot \pi \cdot C_{\mathrm{Geff}} \cdot m_{\mathrm{ig}}}. \tag{6.7}$$

Eqs. (4.210) and (4.212) ensure a smooth transition between the two regions.

As mentioned before, circuit simulators are typically able to deal with correlated noise without using additional internal nodes. However, to achieve this, two approximations are made:

1. The frequency dependence is split in a frequency dependent (power law; $\propto f_{\mathrm{op}}^2$ for S_{ig} and $\propto f_{\mathrm{op}}$ for S_{igid}) and a frequency independent part.
2. Only the imaginary part of S_{igid} is considered.

Applying these approximations, it is found from Eq. (4.210) that

$$S_{\mathrm{ig}} = \begin{cases} \dfrac{\boldsymbol{N}_{\mathbf{T}}}{m_{\mathrm{ig}}} \cdot \left(\dfrac{f_{\mathrm{op}}}{f_{\mathrm{cross}}} \right)^2 & \text{for } f_{\mathrm{op}} \leq f_{\mathrm{cross}} \\[2ex] \dfrac{\boldsymbol{N}_{\mathbf{T}}}{m_{\mathrm{ig}}} & \text{for } f_{\mathrm{op}} > f_{\mathrm{cross}} \end{cases} \tag{6.8}$$

Similarly, the imaginary part of Eq. (4.212) is approximated as

$$\mathrm{Im}(S_{\mathrm{igid}}) = \begin{cases} \dfrac{\boldsymbol{N}_{\mathbf{T}}}{m_{\mathrm{ig}}} \cdot m_{\mathrm{igid}} \cdot \dfrac{f_{\mathrm{op}}}{f_{\mathrm{cross}}} & \text{for } f_{\mathrm{op}} \leq f_{\mathrm{cross}} \\[2ex] \dfrac{\boldsymbol{N}_{\mathbf{T}}}{m_{\mathrm{ig}}} \cdot m_{\mathrm{igid}} & \text{for } f_{\mathrm{op}} > f_{\mathrm{cross}} \end{cases} \tag{6.9}$$

while $\mathrm{Re}(S_{\mathrm{igid}})$ is set to zero for all frequencies.

In the SiMKit-implementation of PSP, the values above are passed to the circuit simulator to be used in noise calculations.

Section 7

Parameter extraction

The parameter extraction strategy for PSP consists of four main steps:

1. Measurements
2. Extraction of local parameters at room temperature
3. Extraction of temperature scaling parameters
4. Extraction of geometry scaling (global) parameters

The above steps will be briefly described in the following sections. Note that the description of the extraction procedure is not 'complete' in the sense that only the most important parameters are discussed and in cases at hand it may be advantageous (or even necessary) to use an adapted procedure.

Throughout this section, bias and current conditions are given for an n-channel transistor only; for a p-channel transistor, all voltages and currents should be multiplied by -1.

As explained in the introduction, the hierarchical setup of PSP (local and global level) allows for the two-step parameter extraction procedure described in this section; this is the recommended method of operation. Nevertheless, it is possible to skip the first steps and start extracting global parameters directly. This procedure is not described here, but the directions below may still be useful.

7.1 Measurements

The parameter extraction routine consists of six different DC-measurements (two of which are optional) and two capacitance measurements.[1] Measurement V and VI are only used for extraction of gate-current, avalanche, and GIDL/GISL parameters.

- **Measurement I** ("idvg"): I_D vs. V_GS
  $V_\mathrm{GS} = 0 \ldots V_\mathrm{sup}$ (with steps of maximum 50 mV).
  $V_\mathrm{DS} =$ 25 or 50 mV
  $V_\mathrm{BS} = 0 \ldots - V_\mathrm{sup}$ (3 or more values)

- **Measurement II** ("idvgh"): I_D vs. V_GS
  $V_\mathrm{GS} = 0 \ldots V_\mathrm{sup}$ (with steps of maximum 50 mV).
  $V_\mathrm{DS} = V_\mathrm{sup}$
  $V_\mathrm{BS} = 0 \ldots - V_\mathrm{sup}$ (3 or more values)

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[1] The bias conditions to be used for the measurements are dependent on the supply voltage of the process. Of course it is advisable to restrict the range of voltages to this supply voltage V_sup. Otherwise physical effects atypical for normal transistor operation—and therefore less well described by PSP—may dominate the characteristics.

- **Measurement III** ("idvd"): I_D vs. V_DS
  $V_\mathrm{GS} = 0 \ldots V_\mathrm{sup}$ (3 or more values)
  $V_\mathrm{DS} = 0 \ldots V_\mathrm{sup}$ (with steps of maximum 50 mV).
  $V_\mathrm{BS} = 0$ V

- **Measurement IV** ("idvdh", optional):I_D vs. V_DS
  $V_\mathrm{GS} = 0 \ldots V_\mathrm{sup}$ (3 or more values)
  $V_\mathrm{DS} = 0 \ldots V_\mathrm{sup}$ (with steps of maximum 50 mV).
  $V_\mathrm{BS} = -V_\mathrm{sup}$

- **Measurement V** ("igvg"): I_G and I_B vs. V_GS
  $V_\mathrm{GS} = -V_\mathrm{sup} \ldots V_\mathrm{sup}$ (with steps of maximum 50 mV).
  $V_\mathrm{DS} = 0 \ldots V_\mathrm{sup}$ (3 or more values)
  $V_\mathrm{BS} = 0$ V

- **Measurement VI** ("igvgh", optional): I_G and I_B vs. V_GS
  $V_\mathrm{GS} = -V_\mathrm{sup} \ldots V_\mathrm{sup}$ (with steps of maximum 50 mV).
  $V_\mathrm{DS} = 0 \ldots V_\mathrm{sup}$ (3 or more values)
  $V_\mathrm{BS} = -V_\mathrm{sup}$

- **Measurement VII** ("cggvg"): C_GG vs. V_GS
  $V_\mathrm{GS} = -V_\mathrm{sup} \ldots V_\mathrm{sup}$ (with steps of maximum 50 mV).
  $V_\mathrm{DS} = 0$ V
  $V_\mathrm{BS} = 0$ V

- **Measurement VIII** ("ccgvg"): C_CG vs. V_GS
  $V_\mathrm{GS} = -V_\mathrm{sup} \ldots V_\mathrm{sup}$ (with steps of maximum 50 mV).
  $V_\mathrm{DS} = 0$ V
  $V_\mathrm{BS} = 0$ V

For the extraction procedure, the transconductance g_m (for Measurement I and II) and the output conductance g_DS (for Measurement III and IV) are obtained by numerical differentiation of the measured I-V-curves. Furthermore, I_min is the smallest current which can reliably measured by the system (noise limit) and I_T is defined as 10% of the largest measured value of $|I_\mathrm{D}|$ in Measurement I. The latter will be used to make a rough distinction between the subthreshold and superthreshold region.

The channel-to-gate capacitance C_CG in Measurement VIII is the summation of the drain-to-gate capacitance C_DG and the source-to-gate capacitance C_SG (i.e., source and drain are short-circuited); it is needed to extract overlap capacitance parameters.

The local parameter extraction measurements I through VI have to be performed at room temperature for every device. In addition, capacitance measurements VII and VIII need to be performed for at least a long/wide and a short/wide (i.e., $L = L_\mathrm{min}$) transistor (at room temperature). Furthermore, for the extraction of temperature scaling parameters measurements I, III, and V have to be performed at different temperatures (at least two extra, typically $-40\,^\circ$C and $125\,^\circ$C) for at least a long wide and a short wide transistor.

7.2 Extraction of local parameters at room temperature

General remarks

The simultaneous determination of *all* local parameters for a specific device 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 small groups, where each parameter group can be determined using specific measurements. In this section, such a procedure will be outlined.

The extraction of local parameters is performed for every device. In order to ensure that the temperature scaling relations do not affect the behavior at room temperature, the reference temperature **TR** should be set equal to room temperature.

Before starting the parameter extraction procedure, one should make sure that **SWIGATE**, **SWIMPACT**, **SWGIDL**, **SWJUNCAP**, and **TYPE** are set to the desired value. Moreover, **QMC** should be set to 1, in order to include quantum mechanical corrections in the simulations.

It is not the case that all local parameters are extracted for every device. Several parameters are only extracted for one or a few devices, while they are kept fixed for all other devices. Moreover, a number of parameters can generally be kept fixed at their default values and need only occasionally be used for fine-tuning in the optimization procedure. Details are given later in this section.

As a special case, it is generally not necessary to extract values for **AX**. In stead, they can be calculated from Eq. (3.53), using **AX0** ~ 18 and **AXL** ~ 0.25. It may be necessary to tune the latter value such that the value of **AX** is between 2 and 3 for the shortest channel in the technology under study.

It is recommended to start the extraction procedure with the long(est) wide(st) device, then the shortest device with the same width, followed by all remaining devices of the same width in order of decreasing length. Then the next widest-channel devices are extracted, where the various lengths are handled in the same order. In this way, one works ones way down to the narrowest channel devices.

AC-parameters

Some parameters (such as **TOX** and **NP**) that do affect the DC-behavior of a MOSFET can only be extracted accurately from C-V-measurements.[2] This should be done before the actual parameter extraction from DC-measurements is started. In Tables 7.1 and 7.2 the extraction procedure for the AC-parameters is given.

Table 7.1: AC-parameter extraction procedure for a long channel MOSFET.

Step	Optimized parameters	Fitted on	Abs./Rel.	Conditions
1	**VFB**,**NEFF**, **DPHIB**, **NP**, **COX**	VII: $C_{\rm GG}$	Relative	–
2	Repeat Step 1			

Table 7.2: AC-parameter extraction procedure for a short channel MOSFET. The values of **VFB** and **NP** are taken from the long-channel case.

Step	Optimized parameters	Fitted on	Abs./Rel.	Conditions
1	**NEFF**, **DPHIB**, **COX**	VII: $C_{\rm GG}$	Relative	–
2	**CGOV**, **NOV**	VIII: $C_{\rm CG}$	Relative	$V_{\rm GS} < 0$
3	Repeat Steps 1 and 2			

Starting from the default parameter set and setting **TOX** to a reasonable value (as known from technology), **VFB**, **NEFF**, **DPHIB**, **COX**, and **NP** can be extracted from $C_{\rm GG}$ in Measurement VII for a long, wide device.

Next, **NOV** and **CGOV** can be extracted from $C_{\rm CG}$ in Measurement VIII for a short, wide device (see also Table 7.1), where **VFB** and **NP** are taken from the long channel case. In general, one can assume **TOXOV** $=$ **TOX**.

The value of **TOX** can be determined from **COX** $= \epsilon_{\rm ox} \cdot L \cdot W/$**TOX**. If the device is sufficiently long and wide, drawn length and width can be used in this formula. Even better, if Measurement VII is available for a

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[2] Although parameter **NOV** *can* be determined from overlap gate current, it is nonetheless more accurately determined from Measurement VIII.

Table 7.3: Initial values for local parameter extraction for a *long*-channel device. For parameters which are not listed in this table, the default value (as given in Section 2.5.6) can be used as initial value.

Parameter	Initial value
BETN	$0.03 \cdot W/L$
RS	0
THESAT	0.1
AX	12
A1	0

few short/wide devices of different lengths, one can extract **TOX** and ΔL from a series of extracted values of **COX** vs. $L_{\rm draw}$.

Some remarks:

- If C-V-measurements are not available, one could revert to values known from the fabrication process. Note that **TOX** and **TOXOV** are *physical* oxide thicknesses; poly-depletion and quantum-mechanical effects are taken care of by the model. If the gate dielectric is not pure SiO_2, one should manually compensate for the deviating dielectric constant.
- In general, **VFB** and **NP** can be assumed independent of channel length and width (so, the long/wide-channel values can be used for all other devices as well). Only if no satisfactory fits are obtained, one could allow for a length dependence (for **NP**) or length *and* width dependence (for **VFB**). Then, one should proceed by extracting **VFB** and/or **NP** from capacitance measurements for various channel geometries, fit Eq. (3.11) / Eq. (3.25) to the result and use interpolated values in the DC parameter extraction procedure.
- The value of parameter **TOX** profoundly influences both the DC- and AC-behavior of the PSP-model and thus the values of many other parameters. It is therefore very important that this parameter is determined (as described above) and *fixed* before the rest of the extraction procedure is started.

If desired (e.g., for RF-characterization), parameters for several parasitic capacitances (gate-bulk overlap, fringe capacitance, etc.) can be extracted as well (**CGBOV** and **CFR**). However, this requires additional capacitance measurements.

The obtained values of **VFB**, **TOX**, **TOXOV**, **NP**, and **NOV** can now be used in the DC-parameter extraction procedure. The above values of **NEFF** and **DPHIB** can be disregarded; they will be determined more accurately from the DC-measurements.

DC-parameters

Before the optimization is started a reasonably good starting value has to be determined, both for the parameters to be extracted and for the parameters which remain constant. For most parameters to be extracted for a *long* channel device, the default values from Section 2.5.6 can be taken as initial values. Exceptions are given in Table 7.3. Starting from these values, the optimization procedure following the scheme below is performed. This method yields a proper set of parameters after the repetition indicated as the final step in the scheme. Experiments with transistors of several processes show that repeating those steps more than once is generally not necessary.

For an accurate extraction of parameter values, the parameter set for a long-channel transistor has to be determined first. In the long-channel case most of the mobility related parameters (i.e. **MUE** and **THEMU**) and the gate tunneling parameters (**GCO**, **GC2**, and **GC3**) are determined and subsequently fixed for the shorter-channel devices.

Table 7.4: DC-parameter extraction procedure for a long-channel MOSFET. The parameters **VFB**, **TOX**, **TOXOV**, **NP**, and **NOV** must be taken from C-V-measurements. The optimization is either performed on the absolute or relative deviation between model and measurements, as shown in the table.

Step	Optimized parameters	Fitted on	Abs./Rel.	Conditions
1	**NEFF**, **BETN**, **MUE**, **THEMU**^{a}	I: I_D	Absolute	–
2	**NEFF**, **DPHIB**, **CT**	I: I_D	Relative	$I_\mathrm{min} < I_\mathrm{D} < I_\mathrm{T}$
3	**MUE**, **THEMU**^{a}, **CS**, **XCOR**, **BETN**	I: I_D, g_m	Absolute	–
4	**THESAT**	III: I_D	Absolute	–
5	**ALP**, **ALP1**, **ALP2**, **VP**^{a}, **(AX)**	III: g_DS	Relative	–
6	**THESAT**	II: I_D	Absolute	–
7	**IGINV**, **GC2**^{a}, **GC3**^{a}	V: I_G	Relative	$I_\mathrm{G} > I_\mathrm{min}$
8	**IGOV**, (**GCO**^{a})	V: I_G	Relative	$V_\mathrm{GS} < 0$ V, $I_\mathrm{G} < -I_\mathrm{min}$
9	**A1**, **A2**^{a}, **A3**	V: I_B	Relative	$V_\mathrm{GS} > 0$ V, $I_\mathrm{B} < -I_\mathrm{min}$
10	**A4**	VI: I_B	Relative	$V_\mathrm{GS} > 0$ V, $I_\mathrm{B} < -I_\mathrm{min}$
11	**AGIDL**, **BGIDL**^{a}	V: I_B	Relative	$V_\mathrm{GS} < 0$ V, $I_\mathrm{B} < -I_\mathrm{min}$
12	**CGIDL**^{a}	VI: I_B	Relative	$V_\mathrm{GS} < 0$ V, $I_\mathrm{B} < -I_\mathrm{min}$
13	Repeat Steps 2 – 12			

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[a] Only extracted for the *widest* long channel device and fixed for all other geometries.

In Table 7.4 the complete DC extraction procedure for long-channel transistors is given. The magnitude of the simulated I_D and the overall shape of the simulated I_D-V_GS-curve is roughly set in Step 1. Next the parameters **NEFF**, **DPHIB**, and **CT**—which are important for the subthreshold behavior—are optimized in Step 2, neglecting short-channel effects such as drain-induced barrier-lowering (DIBL). After that, the mobility parameters are optimized in Step 3, neglecting the influence of series-resistance. In Step 4 a preliminary value of the velocity saturation parameter is obtained, and subsequently the conductance parameters **ALP**, **ALP1**, **ALP2**, and **VP** are determined in Step 5. A more accurate value of **THESAT** can now be obtained using Step 6. The gate current parameters are determined in Steps 7 and 8, where it should be noted that **GCO** should only be extracted if the influence of gate-to-bulk tunneling is visible in the measurements. This is usually the case if $V_\mathrm{sup} \gtrsim |$**VFB**$|$. This is followed by the weak-avalanche parameters in Step 9 and (optionally) 10, and finally, the gate-induced leakage current parameters are optimized in Step 11 and (optionally) 12.

For short-channel devices, the extracted values of the next-longer device can be used as initial values. This includes the carrier mobility parameters and the gate tunneling probability factors of the long-channel device, which are subsequently kept fixed. Next, the extraction procedure as given in Table 7.5 is executed, which applies to all devices that are not 'long'.

Note that—once the value of **THESATG** and **THESATB** have been determined from the shortest widest channel device—steps 4, 5, and 6 of the long-channel extraction procedure (Table 7.4) must be repeated to obtain updated values for **THESAT**, **ALP**, **ALP1**, and **ALP2**.

7.3 Extraction of Temperature Scaling Parameters

For a specific device, the temperature scaling parameters can be extracted after determination of the local parameters at room temperature. In order to do so, measurements I, II and IV need to be performed at various temperature values (at least two values different from room temperature, typically −40 °C and 125 °C), at least for a long wide device and a short wide device. If the reference temperature **TR** has been chosen equal to room temperature (as recommended in Section 7.2), the modeled behavior at room temperature is insensitive to the value of the temperature scaling parameters. As a first-order estimate of the temperature scaling parameter values, the default values as given in Section 2.5.6 can be used. Again the parameter extraction scheme is

Table 7.5: DC-parameter extraction procedure for a short-channel MOSFET. Parameters **MUE**, **THEMU**, **VP**, **GCO**, **GC2**, **GC3**, **A2**, **A4**, **BGIDL**, and **CGIDL** are taken from the corresponding long-channel case. The optimization is either performed on the absolute or relative deviation between model and measurements, as indicated in the table.

Step	Optimized parameters	Fitted on	Abs./Rel.	Conditions
1	**NEFF**, **DPHIB**, **BETN**, **RS**[a]	I: I_{D}	Absolute	–
2	**NEFF**, **DPHIB**, **CT**	I: I_{D}	Relative	$I_{\mathrm{min}} < I_{\mathrm{D}} < I_{\mathrm{T}}$
3	**BETN**, **RS**[a], **XCOR**	I: I_{D}, g_{m}	Absolute	–
4	**THESAT**	III: I_{D}	Absolute	–
5	**ALP**, **ALP1**, **ALP2**, **CF**, (**AX**)	III: g_{DS}	Relative	–
6	**CFB**[b]	IV: g_{DS}	Relative	–
7	**THESAT**, **THESATG**[b], **THESATB**[b]	II: I_{D}, g_{m}	Absolute	–
8	**IGINV**, **IGOV**	V: I_{G}	Relative	$\lvert I_{\mathrm{G}}\rvert > I_{\mathrm{min}}$
9	**A1**, **A3**	V: I_{B}	Relative	$V_{\mathrm{GS}} > 0$ V, $I_{\mathrm{B}} < -I_{\mathrm{min}}$
10	**AGIDL**	V: I_{B}	Relative	$V_{\mathrm{GS}} < 0$ V, $I_{\mathrm{B}} < -I_{\mathrm{min}}$
11	Repeat Steps 2 – 10			

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[a] Only extracted for the *shortest* channel of each width and fixed for all other geometries.
[b] Only extracted for the *shortest widest* device and fixed for all other geometries.

Table 7.6: Temperature scaling parameter extraction procedure for a long wide channel MOSFET. This scheme only makes sense if measurements have been performed at one or (preferably) more temperatures which differ from room temperature.

Step	Optimized parameters	Fitted on	Abs./Rel.	Conditions
1	**STVFB**[a]	I: I_{D}	Relative	$I_{\mathrm{D}} < I_{\mathrm{T}}$
2	**STBETN**[a], **STMUE**, **STTHEMU**, **STCS**, **STXCOR**	I: I_{D}	Absolute	–
3	**STTHESAT**[a]	II: I_{D}	Absolute	–
4	**STIG**	V: I_{G}	Relative	$\lvert I_{\mathrm{G}}\rvert > I_{\mathrm{min}}$
5	**STA2**	V: I_{B}	Relative	$V_{\mathrm{GS}} > 0$ V, $I_{\mathrm{B}} < -I_{\mathrm{min}}$
6	**STBGIDL**	V: I_{B}	Relative	$V_{\mathrm{GS}} < 0$ V, $I_{\mathrm{B}} < -I_{\mathrm{min}}$

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[a] Also extracted for one or more long *narrow* devices.

slightly different for the long-channel and for the short-channel case.

For an accurate extraction, the temperature scaling parameters for a long-wide-channel device have to be determined first. In the long-wide-channel case the carrier mobility parameters can be determined, and they are subsequently fixed for all other devices. In Table 7.6 the appropriate extraction procedure is given. In Step 1 the subthreshold temperature dependence is optimized, followed by the optimization of mobility reduction parameters in Step 2. Next the temperature dependence of velocity saturation is optimized in Step 3. In the subsequent steps, parameters for the temperature dependence of the gate current, the impact ionization current and gate-induced drain leakage are determined. The determined values of the mobility reduction temperature scaling parameters (i.e., **STMUE**, **STTHEMU**, **STCS**, and **STXCOR**) are copied to all other devices and kept fixed during the remainder of the temperature-scaling parameter extraction procedure. Step 1 and 2 could then be performed on one or more long narrow devices as well (for **STVFB**, **STBETN**, and **STTHESAT** only).

Next the extraction procedure as given in Table 7.7 is carried out for several short devices of different widths.

Table 7.7: Temperature scaling parameter extraction procedure for short-channel MOSFETs (both wide and narrow). This scheme only makes sense if measurements have been performed at one or (preferably) more temperatures which differ from room temperature.

Step	**Optimized parameters**	**Fitted on**	**Abs./Rel.**	**Conditions**
1	**STVFB**	I: I_D	Relative	$V_\mathrm{GS} < V_\mathrm{T}$
2	**STBETN**, **STRS**[a]	I: I_D	Absolute	$V_\mathrm{GS} > V_\mathrm{T}$
3	**STTHESAT**	II: I_D	Absolute	–

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[a] Only extracted for a short *narrow* device and fixed for all other geometries.

Preferably, the extraction is done first for a short narrow device, such that the determined value of **STRS** can be used during the extraction of the wider devices.

7.4 Extraction of Geometry Scaling Parameters

The aim of the complete extraction procedure is the determination of the geometry scaling parameters (global parameters), i.e., a single set of parameters (see Section 2.5.3) which gives a good description of the MOSFET-behavior over the full geometry range of a CMOS technology.

Determination of ΔL and ΔW

An extremely important part of the geometry scaling extraction scheme is an accurate determination of ΔL and ΔW, see Eqs. (3.5) and (3.6).[3] Since it affects the DC-, the AC- as well as the noise model and, moreover, it can heavily influence the quality of the resulting global parameter set, it is very important that this step is carried out with care.

Traditionally, ΔW can be determined from the extrapolated zero-crossing in **BETN** versus mask width W. In a similar way ΔL can be determined from $1/$**BETN** versus mask length L. For modern MOS devices with pocket implants, however, it has been found that the above ΔL extraction method is no longer valid [6, 7]. Another, more accurate method is to measure the gate-to-bulk capacitance C_GB in accumulation for different channel lengths [7, 8]. In this case the extrapolated zero-crossing in the C_GB versus mask length L curve will give ΔL. Similarly, the extracted values for **COX** (from the procedure in Table 7.1 and 7.2) vs. mask length L may be used for this purpose. Unfortunately for CMOS technologies in which gate current is non-negligible, capacitance measurements may be hampered by gate current [9]. In this case gate current parameter **IGINV** plotted as a function of channel length L may be used to extract ΔL [9]. If possible, ΔL extraction from C-V-measurements is the preferred method.

Finally, **LOV** can be obtained from (a series of) extracted values of **CGOV** from one or more short devices.

From local to global

First of all, the global parameters **TYPE**, **QMC**, and the 'switch'-parameters should be set to the appropriate value. Next, parameters for which no geometrical scaling rules exist must be taken directly from the local set (this applies to **TR**, **TOXO**, **VNSUBO**, **NSLPO**, **DNSUBO**, **TOXOVO**, **NOVO**, **CFBO**, **STMUEO**, **THEMUO**, **STTHEMUO**, **STCSO**, **STXCORO**, **FETAO**, **STRSO**, **RSBO**, **RSGO**, **THESATBO**, **THESATGO**, **VPO**, **A2O**, **STA2O**, **GCOO**, **STIGO**, **GC2O**, **GC3O**, **CHIBO**, **BGIDLO**, **STBGIDLO**, **CGIDLO**, and **DTA**). Generally, these parameters have been left at their default values or they have been extracted for one device only and subsequently fixed for all other devices. The parameters **LVARO**, **LVARL**, **LVARW**, **WVARO**, **WVARL**, and **WVARW** should be known from technology.

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[3] Note that ΔL_PS and ΔW_OD are expected to be known from the fabrication process. So, in fact, only **LAP** and **WOT** are extracted from the electrical measurements.

Once the values of ΔL and ΔW are firmly established (as described above), **LAP** and **WOT** can be set and the actual extraction procedure of the geometry scaling parameters can be started. It consists of several *independent* sub-steps (which can be carried out in random order), one for each geometry dependent local parameter.

To illustrate such a sub-step, the local parameter **CT** is taken as an example. The relevant geometry scaling equation from Section 3.3 is Eq. (3.26), from which it can be seen that **CTO**, **CTL**, **CTLEXP**, and **CTW** are the global parameters which determine the value of **CT** as a function of L and W. First, the extracted **CT** of each device in a length-series of measured (preferably wide) devices are considered as a function of L. In this context **CTO**, **CTL**, and **CTLEXP** are optimized such that the fit of Eq. (3.26) to the extracted **CT**-values is as good as possible, while keeping **CTW** fixed at 0. Then **CTW** is determined by considering the extracted **CT**-values from a length-series of measured narrow devices. Finally, the four global parameters may be fine-tuned by optimizing all four parameters to all extracted **CT**-values simultaneously. The default values given in Section 2.5.3 are good initial values for the optimization procedure.

All other parameters can be extracted in a similar manner. The local parameters **BETN** and **NEFF** have quite complicated scaling rules, particularly due to the non-uniform doping profiles employed in modern CMOS technologies. Therefore, a few additional guidelines are in place.

- The optimization procedure for **BETN** is facilitated if not **BETN**, but $\mathbf{BETN}_{\rm sq} \overset{\rm def}{=} \mathbf{BETN} \cdot L_{\rm E}/W_{\rm E}$ is considered.
- Starting from the default values, first **UO**, **FBET1**, **LP1**, **FBET2**, and **LP2** should be determined from a length-series of wide devices. Then **BETW1**, **BETW2**, and **WBET** should be determined from a width-series of long devices. Finally, **FBET1W** and **LP1W** can be found by considering some short narrow devices.
- Starting from the default values, first extract **FOL1**, **FOL2**, **NSUBO**, **NPCK**, and **LPCK** from a length-series of wide devices. Here, **NSUBO** determines the long-channel value of **NEFF**. Moreover, **NPCK** and **LPCK** determine the increase of **NEFF** for shorter channels (short channel effect), while **FOL1** and **FOL2** are used to describe the decrease of **NEFF** for very short channels (reverse short channel effect).
- Then **NSUBW** and **WSEG** can be determined form a width-series of long devices. Finally, **NPCKW**, **LPCKW** and **WEGP** are determined from a width-series of short devices.
- Especially for **BETN** and **NEFF** it is advisable—after completing the procedure described above—to fine tune the global parameters found by considering all extracted values of **BETN** (or **NEFF**) simultaneously.

Note that in many cases it may not be necessary to use the full flexibility of PSP's parameter scaling, e.g., for many technologies **NP** and **VFB** may be considered as independent of geometry. If such a geometry-independence is anticipated, the corresponding local parameter should be fixed during local parameter extraction. Only if the resulting global parameter set is not satisfactory, the parameter should be allowed to vary during a subsequent optimization round.

Fine tuning

Once the complete set of global parameters is found, the global model should give an accurate description of the measured I-V-curves and capacitance measurements. Either for fine tuning or to facilitate the extraction of global parameters for which the geometry scaling of the corresponding extracted local parameters is not well-behaved, there are two more things that can be done.

- Local parameters for which the fitting of global parameters was completed satisfactorily could be replaced by the values calculated from the geometrical scaling rules and fixed. Then one could redo (parts of) the local parameter extraction procedure for the remaining local parameters, making them less sensitive for cross-correlations.
- Small groups of global parameters may be fitted directly to the measurements of a well-chosen series of devices, using the global model.

7.5 Summary – Geometrical scaling

Summarizing, for the determination of a full parameter set, the following procedure is recommended.

1. Determine local parameter sets (**VFB**, **NEFF**, ...) for all measured devices, as explained in Section 7.2 and 7.3.
2. Find ΔL and ΔW.
3. Determine the global parameters by fitting the appropriate geometry scaling rules to the extracted local parameters.
4. Finally, the resulting global can be fine-tuned, by fitting the result of the scaling rules and current equations to the measured currents of all devices simultaneously.

7.6 Extraction of Binning Parameters

In this section, expressions will be given for the parameters in the binning scaling rules, **POYYY**, **PLYYY**, **PWYYY**, and **PLWYYY**, as given in Section 3.4. These coefficients will be expressed in terms of parameter values at the corners of bin (see Fig. 7.1). These expressions can be easily found by substituting the parameter values at the bin corners into the binning scaling rules and inverting the resulting four equations. Note once more that this results in a *separate parameter set for each bin*.

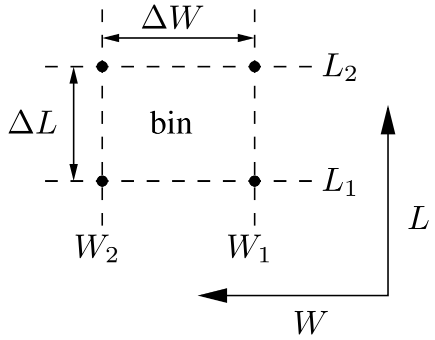

Figure 7.1: Schematic view of a bin, showing the coordinates of the four corners. Note that L_1, L_2, W_1, and W_2 denote the *effective* length and width (L_E and W_E) at the bin corners.

In the expression below, the value of parameter **YYY** at bin corner (L_i, W_j) is denoted by Y_{ij} $(i = 1, 2,$ $j = 1, 2)$. Moreover, $\Delta L = L_2 - L_1$, $\Delta W = W_2 - W_1$, $A = 1/(\Delta L \cdot \Delta W)$.

1. Coefficients for type I scaling

$$\textbf{POYYY} = A \cdot (L_1 \cdot W_1 \cdot Y_{11} - L_1 \cdot W_2 \cdot Y_{12} - L_2 \cdot W_1 \cdot Y_{21} + L_2 \cdot W_2 \cdot Y_{22}) \tag{7.1}$$

$$\textbf{PLYYY} = A \cdot \frac{L_1 \cdot L_2}{L_\mathrm{EN}} \cdot (-W_1 \cdot Y_{11} + W_2 \cdot Y_{12} + W_1 \cdot Y_{21} - W_2 \cdot Y_{22}) \tag{7.2}$$

$$\textbf{PWYYY} = A \cdot \frac{W_1 \cdot W_2}{W_\mathrm{EN}} \cdot (-L_1 \cdot Y_{11} + L_1 \cdot Y_{12} - L_2 \cdot Y_{21} - L_2 \cdot Y_{22}) \tag{7.3}$$

$$\textbf{PLWYYY} = A \cdot \frac{L_1 \cdot L_2 \cdot W_1 \cdot W_2}{L_\mathrm{EN} \cdot W_\mathrm{EN}} \cdot (Y_{11} - Y_{12} - Y_{21} + Y_{22}) \tag{7.4}$$

2. Coefficients for type II scaling

$$\textbf{POYYY} = A \cdot (L_2 \cdot W_2 \cdot Y_{11} - L_2 \cdot W_1 \cdot Y_{12} - L_1 \cdot W_2 \cdot Y_{21} + L_1 \cdot W_1 \cdot Y_{22}) \tag{7.5}$$

$$\textbf{PLYYY} = A \cdot L_{\mathrm{EN}} \cdot (-W_2 \cdot Y_{11} + W_1 \cdot Y_{12} + W_2 \cdot Y_{21} - W_1 \cdot Y_{22}) \tag{7.6}$$

$$\textbf{PWYYY} = A \cdot W_{\mathrm{EN}} \cdot (-L_2 \cdot Y_{11} + L_2 \cdot Y_{12} - L_1 \cdot Y_{21} - L_1 \cdot Y_{22}) \tag{7.7}$$

$$\textbf{PLWYYY} = A \cdot L_{\mathrm{EN}} \cdot W_{\mathrm{EN}} \cdot (Y_{11} - Y_{12} - Y_{21} + Y_{22}) \tag{7.8}$$

3. Coefficients for type III scaling

$$\textbf{POYYY} = A \cdot (-L_1 \cdot W_2 \cdot Y_{11} + L_1 \cdot W_1 \cdot Y_{12} + L_2 \cdot W_2 \cdot Y_{21} - L_2 \cdot W_1 \cdot Y_{22}) \tag{7.9}$$

$$\textbf{PLYYY} = A \cdot \frac{L_1 \cdot L_2}{L_{\mathrm{EN}}} \cdot (W_2 \cdot Y_{11} - W_1 \cdot Y_{12} - W_2 \cdot Y_{21} + W_1 \cdot Y_{22}) \tag{7.10}$$

$$\textbf{PWYYY} = A \cdot W_{\mathrm{EN}} \cdot (L_1 \cdot Y_{11} - L_1 \cdot Y_{12} - L_2 \cdot Y_{21} + L_2 \cdot Y_{22}) \tag{7.11}$$

$$\textbf{PLWYYY} = A \cdot \frac{L_1 \cdot L_2 \cdot W_{\mathrm{EN}}}{L_{\mathrm{EN}}} \cdot (-Y_{11} + Y_{12} + Y_{21} - Y_{22}) \tag{7.12}$$

Note: For L_1, L_2, W_1, and W_2 in the formulas above one must take the *effective* length and width (L_{E} and W_{E}) as defined in Section 3.2.

Section 8

DC Operating Point Output

The DC operating point output facility gives information on the state of a device at its operation point. Beside 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.

All accessible quantities are described in the table below. The symbols in the 'value' column are defined in Section 4. Besides, the following notation is used: $P_\mathrm{D} = 1 + \boldsymbol{k_p} \cdot G/4$, where $\boldsymbol{k_p}$ is defined in Eq. (4.14).

Important note: For *all* operating point output the signs are such as if the device is an NMOS. Moreover, whenever there is a reference to the 'drain', this is always the terminal which is acting as drain for the actual bias conditions. This is even true for variables such as **vds** (which is therefore always nonnegative) and the junction-related variables. The output variable **sdint** shows whether or not this 'drain' is the same as the terminal which was named 'drain' in the simulator.

No.	Name	Unit	Value	Description
0	**ctype**	–	1 for NMOS, -1 for PMOS	Flag for channel-type
1	**sdint**	–	1 if $V'_\mathrm{DS} \geq 0, \; -1$ otherwise	Flag for source-drain interchange
			Current components	
2	**ise**	A	$I_\mathrm{S} - I_\mathrm{JS}$	Total source current
3	**ige**	A	I_G	Total gate current
4	**ide**	A	$I_\mathrm{D} - I_\mathrm{JD}$	Total drain current
5	**ibe**	A	$I_\mathrm{B} + I_\mathrm{JS} + I_\mathrm{JD}$	Total bulk current
6	**ids**	A	I_DS	Drain current, excl. avalanche and tunnel currents
7	**idb**	A	$I_\mathrm{avl} + I_\mathrm{gidl} - I_\mathrm{JD}$	Drain-to-bulk current
8	**isb**	A	$I_\mathrm{gisl} - I_\mathrm{JS}$	Source-to-bulk current
9	**igs**	A	$I_\mathrm{GCS} + I_\mathrm{GSov}$	Gate-source tunneling current
10	**igd**	A	$I_\mathrm{GCD} + I_\mathrm{GDov}$	Gate-drain tunneling current
11	**igb**	A	I_GB	Gate-bulk tunneling current

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No.	Name	Unit	Value	Description
12	**igcs**	A	I_GCS	Gate-channel tunneling current (source component)
13	**igcd**	A	I_GCD	Gate-channel tunneling current (drain component)
14	**iavl**	A	I_avl	Substrate current due to weak-avalanche
15	**igisl**	A	I_gisl	Gate-induced source leakage current
16	**igidl**	A	I_gidl	Gate-induced drain leakage current
Junction currents				
17	**ijs**	A	I_JS	Total source junction current
18	**ijsbot**	A	$I_\mathrm{JS,bot}$	Source junction current, bottom component
19	**ijsgat**	A	$I_\mathrm{JS,gat}$	Source junction current, gate-edge component
20	**ijssti**	A	$I_\mathrm{JS,sti}$	Source junction current, STI-edge component
21	**ijd**	A	I_JD	Total drain junction current
22	**ijdbot**	A	$I_\mathrm{JD,bot}$	Drain junction current, bottom component
23	**ijdgat**	A	$I_\mathrm{JD,gat}$	Drain junction current, gate-edge component
24	**ijdsti**	A	$I_\mathrm{JD,sti}$	Drain junction current, STI-edge component
Voltages				
25	**vds**	V	V_DS	Drain-source voltage
26	**vgs**	V	V_GS	Gate-source voltage
27	**vsb**	V	V_SB	Source-bulk voltage
28	**vto**	V	$\mathbf{VFB} + P_\mathrm{D} \cdot (\boldsymbol{\phi}_\mathbf{B} + 2 \cdot \boldsymbol{\phi}^*_\mathbf{T}) + G \cdot \sqrt{\boldsymbol{\phi}^*_\mathbf{T} \cdot (\boldsymbol{\phi}_\mathbf{B} + 2 \cdot \boldsymbol{\phi}^*_\mathbf{T})}$	Zero-bias threshold voltage
29	**vts**	V	$\mathbf{VFB} + P_\mathrm{D} \cdot (V^*_\mathrm{SB} + \boldsymbol{\phi}_\mathbf{B} + 2 \cdot \boldsymbol{\phi}^*_\mathbf{T}) - V^*_\mathrm{SB} + G \cdot \sqrt{\boldsymbol{\phi}^*_\mathbf{T} \cdot (V^*_\mathrm{SB} + \boldsymbol{\phi}_\mathbf{B} + 2 \cdot \boldsymbol{\phi}^*_\mathbf{T})}$	Threshold voltage including back-bias effects
30	**vth**	V	$\mathbf{vts} - \Delta V_\mathrm{G}$	Threshold voltage including back-bias and drain-bias effects
31	**vgt**	V	$\mathbf{vgs} - \mathbf{vth}$	Effective gate drive voltage including drain- and back-bias effects
32	**vdss**	V	V_dsat	Drain saturation voltage at actual bias
33	**vsat**	V	$V_\mathrm{DS} - V_\mathrm{dsat}$	Saturation limit
(Trans-)conductances				
34	**gm**	A/V	$\partial\mathbf{ide}/\partial V_\mathrm{GS}$	Transconductance
35	**gmb**	A/V	$-\partial\mathbf{ide}/\partial V_\mathrm{SB}$	Substrate-transconductance

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No.	Name	Unit	Value	Description
36	**gds**	A/V	$\partial\textbf{ide}/\partial V_{\mathrm{DS}}$	Output conductance
37	**gjs**	A/V	$-\partial\textbf{ijs}/\partial V_{\mathrm{SB}}$	Source junction conductance
38	**gjd**	A/V	$-(\partial\textbf{ijd}/\partial V_{\mathrm{DS}}+\partial\textbf{ijd}/\partial V_{\mathrm{SB}})$	Drain junction conductance
			Capacitances	
39	**cdd**	F	$\partial Q_{\mathrm{D}}/\partial V_{\mathrm{DS}}$	Drain capacitance
40	**cdg**	F	$-\partial Q_{\mathrm{D}}/\partial V_{\mathrm{GS}}$	Drain-gate capacitance
41	**cds**	F	**cdd** − **cdg** − **cdb**	Drain-source capacitance
42	**cdb**	F	$\partial Q_{\mathrm{D}}/\partial V_{\mathrm{SB}}$	Drain-bulk capacitance
43	**cgd**	F	$-\partial Q_{\mathrm{G}}/\partial V_{\mathrm{DS}}$	Gate-drain capacitance
44	**cgg**	F	$\partial Q_{\mathrm{G}}/\partial V_{\mathrm{GS}}$	Gate capacitance
45	**cgs**	F	**cgg** − **cgd** − **cgb**	Gate-source capacitance
46	**cgb**	F	$\partial Q_{\mathrm{G}}/\partial V_{\mathrm{SB}}$	Gate-bulk capacitance
47	**csd**	F	$-\partial Q_{\mathrm{S}}/\partial V_{\mathrm{DS}}$	Source-drain capacitance
48	**csg**	F	$-\partial Q_{\mathrm{S}}/\partial V_{\mathrm{GS}}$	Source-gate capacitance
49	**css**	F	**csg** + **csd** + **csb**	Source capacitance
50	**csb**	F	$\partial Q_{\mathrm{S}}/\partial V_{\mathrm{SB}}$	Source-bulk capacitance
51	**cbd**	F	$-\partial Q_{\mathrm{B}}/\partial V_{\mathrm{DS}}$	Bulk-drain capacitance
52	**cbg**	F	$-\partial Q_{\mathrm{B}}/\partial V_{\mathrm{GS}}$	Bulk-gate capacitance
53	**cbs**	F	**cbb** − **cbd** − **cbg**	Bulk-source capacitance
54	**cbb**	F	$-\partial Q_{\mathrm{B}}/\partial V_{\mathrm{SB}}$	Bulk capacitance
55	**cgsol**	F	$\partial(Q_{\mathrm{sov}}+Q_{\mathrm{ofs}})/\partial V_{\mathrm{GS}}$	Total gate-source overlap capacitance
56	**cgdol**	F	$\partial(Q_{\mathrm{dov}}+Q_{\mathrm{ofd}})/\partial V_{\mathrm{DS}}$	Total gate-drain overlap capacitance
			Junction capacitances	
57	**cjs**	F	C_{JS}	Total source junction capacitance
58	**cjsbot**	F	$C_{\mathrm{JS,bot}}$	Source junction capacitance, bottom component
59	**cjsgat**	F	$C_{\mathrm{JS,gat}}$	Source junction capacitance, gate-edge component
60	**cjssti**	F	$C_{\mathrm{JS,sti}}$	Source junction capacitance, STI-edge component
61	**cjd**	F	C_{JD}	Total drain junction capacitance
62	**cjdbot**	F	$C_{\mathrm{JD,bot}}$	Drain junction capacitance, bottom component
63	**cjdgat**	F	$C_{\mathrm{JD,gat}}$	Drain junction capacitance, gate-edge component
64	**cjdsti**	F	$C_{\mathrm{JD,sti}}$	Drain junction capacitance, STI-edge component

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No.	Name	Unit	Value	Description
			Miscellaneous	
65	**weff**	m	W_E	Effective channel width for geometrical models
66	**leff**	m	L_E	Effective channel length for geometrical models
67	**u**	-	$\mathbf{gm}/\mathbf{gds}$	Transistor gain
68	**rout**	Ω	$1/\mathbf{gds}$	Small-signal output resistance
69	**vearly**	V	$\lvert\mathbf{ide}\rvert/\mathbf{gds}$	Equivalent Early voltage
70	**beff**	A/V^2	$2 \cdot \lvert\mathbf{ide}\rvert/\mathbf{vgt}^2$	Gain factor
71	**fug**	Hz	$\mathbf{gm}/[2 \cdot \pi \cdot (\mathbf{cgg} + \mathbf{cgsol} + \mathbf{cgdol})]$	Unity gain frequency at actual bias
			Noise	
72	**sqrtsff**	V/$\sqrt{\mathrm{Hz}}$	$\sqrt{S_\mathrm{fl}(1\ \mathrm{kHz})}/\mathbf{gm}$	Input-referred RMS white noise voltage density at 1 kHz
73	**sqrtsfw**	V/$\sqrt{\mathrm{Hz}}$	$\sqrt{S_\mathrm{id}}/\mathbf{gm}$	Input-referred RMS white noise voltage density
74	**sid**	A^2/Hz	S_id	Channel thermal noise current density
75	**sig**	A^2/Hz	$S_\mathrm{ig}(1\ \mathrm{kHz})$	Induced gate noise current density at 1 kHz
76	**cigid**	–	$\dfrac{m_\mathrm{igid}}{\sqrt{m_\mathrm{ig} \cdot m_\mathrm{id}}}$	Imaginary part of correlation coefficient between S_ig and S_id
77	**fknee**	Hz	$1\mathrm{Hz} \cdot S_\mathrm{fl}(1\mathrm{Hz})/S_\mathrm{id}$	Cross-over frequency above which white noise is dominant
78	**sigs**	A^2/Hz	S_igs	Gate-source current noise spectral density
79	**sigd**	A^2/Hz	S_igd	Gate-drain current noise spectral density
80	**siavl**	A^2/Hz	S_avl	Impact ionization current noise spectral density
81	**ssi**	A^2/Hz	$S_\mathrm{S,I}$	Total source junction current noise spectral density
82	**sdi**	A^2/Hz	$S_\mathrm{D,I}$	Total drain junction current noise spectral density

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Appendix A

Auxiliary Equations

In this Appendix, some auxiliary functions which are used in the model equations are defined.

The MINA-smoothing function:

$$\text{MINA}\,(x,\,y,\,a) = \frac{1}{2} \cdot \left[x + y - \sqrt{(x-y)^2 + a}\right] \tag{A.1}$$

The MAXA-smoothing function:

$$\text{MAXA}\,(x,\,y,\,a) = \frac{1}{2} \cdot \left[x + y + \sqrt{(x-y)^2 + a}\right] \tag{A.2}$$

The functions $\chi(y)$, its derivatives, σ_1, and σ_2, which are used in the explicit approximation of surface potential:

$$\chi(y) = \frac{y^2}{2 + y^2} \tag{A.3}$$

$$\chi'(y) = \frac{4y}{(2 + y^2)^2} \tag{A.4}$$

$$\chi''(y) = \frac{8 - 12y^2}{(2 + y^2)^3} \tag{A.5}$$

$$\nu = a + c \tag{A.6}$$

$$\mu_1 = \frac{v^2}{\tau} + \frac{c^2}{2} - a \tag{A.7}$$

$$\sigma_1\,(a,\,c,\,\tau,\,\eta) = \frac{a \cdot \nu}{\mu_1 + (c^2/3 - a) \cdot c \cdot \nu/\mu_1} + \eta \tag{A.8}$$

$$\mu_2 = \frac{v^2}{\tau} + \frac{c^2}{2} - a \cdot b \tag{A.9}$$

$$\sigma_2\,(a,\,b,\,c,\,\tau,\,\eta) = \frac{a \cdot \nu}{\mu_2 + (c^2/3 - a \cdot b) \cdot c \cdot \nu/\mu_2} + \eta \tag{A.10}$$