

User's Manual - NXP / CEA-Leti

Issued: 12/2017

PSP 103.6

**The PSP model is a joint development of CEA-Leti and
NXP Semiconductors**

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Keywords: PSP Model, compact modeling, MOSFET, CMOS, circuit simulation, integrated circuits

Abstract: The PSP model is a compact MOSFET model intended for analog, RF, and digital design. It is jointly developed by NXP Semiconductors and CEA-Leti. (From 2011 to 2015, it was jointly developed by NXP Semiconductors and Delft University of Technology. Until 2011, it was jointly developed by NXP Semiconductors and Arizona State University. The roots of PSP lie in both *MOS Model 11* (developed by NXP Semiconductors) and *SP* (developed at the Pennsylvania State University and later at Arizona 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. The source/drain junction model, c.q. the JUNCAP2 model, is fully integrated in 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.

Since December 2015, CEA-Leti replaces Delft University of Technology as the supporting institution.

Silicon Integration Initiative (Si2) - Compact Model Coalition In-Code Statement

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CMC In-Code Statement Revision:

103.6 (PSP), 12/14/2017

200.5.0 (JUNCAP),9/9/2016

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.

June 2006 Release of PSP 102.0 (which includes JUNCAP2 200.1) as part of SiMKit 2.3.2. PSP 102.0 is backward compatible with PSP 101.0 in all practical cases, provided a simple transformation to the parameter set is applied (see description below). 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.

Global parameter sets for PSP 101.0 can be transformed to PSP 102.0 by replacing **DPHIBL** (in 102.0 parameter set) by **DPHIBO · DPHIBL** (from 101.0 parameter set). After this transformation, the simulation results of PSP 102.0 are identical to those of PSP 101.0 in all practical situations.

October 2006 Release of PSP 102.1 (which includes JUNCAP2 200.2) as part of SiMKit 2.4. PSP 102.1 is backward compatible with PSP 102.0. SiMKit 2.4 includes a preliminary implementation of the PSP-NQS model. Similar to the previous version, a Verilog-A implementation of the PSP-model is available as well.

October 2007 Release of PSP 102.2 (which includes JUNCAP2 200.3). PSP 102.2 is backward compatible with PSP 102.1. This release provides an express version of JUNCAP2.

April 2008 Release of PSP 102.3 (which includes JUNCAP2 200.3) as part of SiMKit 3.1. PSP 102.3 is backward compatible with PSP 102.2. Focus of this release is on the implementation of asymmetric models for both junction and overlap regions of the drain side.

November 2008 Release of PSP 103.0 (which includes JUNCAP 200.3) as part of SiMKit 3.2. PSP 103.0 is *not* fully backward compatible with PSP 102.3. The main changes are:

- Global, local and binning models are unified. When **SWGEO** = 1 (default) global model is used. When **SWGEO** = 0 local model is selected. The binning model is invoked if **SWGEO** is set to 2.
- Added non-uniform doping (NUD) model. The model can be invoked on by setting **SWNUD** = 1 or 2. When **SWNUD** = 1, a separate surface potential calculation is carried out and the NUD model does not affect the CV results. This avoids non-reciprocal capacitances. When **SWNUD** = 2, the extra surface potential calculation is skipped and this may result in non-reciprocal capacitances. Added related model parameters **GFACNUDO**, **GFACNUDL**, **GFACNUDEXP**, **GFACNUDW**, **GFACNUDLW**, **VSBNUDO** and **DVSBNUDO** to global, **GFACNUD**, **VSBNUD** and **DVSBNUD**

to local and **POGFACNUD**, **PLGFACNUD**, **PWGFACNUD**, **PLWGFACNUD**, **POVSBNUD** and **PODVSBNNUD** to binning models.

- Added V_{th} -adjustment model for CV. It can be turned on by setting **SWDELVTAC** = 1. Note that this requires extra computation of surface potentials. Added related model parameters **FACNEFFACO**, **FACNEFFACL**, **FACNEFFACW**, **FACNEFFACLW**, **DELVTACO**, **DELVTACL**, **DELVTACLEXP**, **DELVTACW** and **DELVTACLW** to global, **FACNEFFAC** and **DELVTAC** to local and **POFACNEFFAC**, **PLFACNEFFAC**, **PWFACNEFFAC**, **PLWFACNEFFAC**, **PODELVTAC**, **PLDELVTAC**, **PWDELVTAC** and **PLWDELVTAC** to binning model.
- Added external diffusion resistances to source and drain. Added instance parameters **NRS** and **NRD**; added model parameters **RSH** to global and binning, **RSE** and **RDE** to local model.
- Modified the geometrical scaling rules of following parameters: **VFB**, **STVFB**, **DPHIB**, **STBET** and **STTHESAT**.
- Modified the binning rule of **BETN**.
- Removed the effect of **FETA** from CV.
- Added local parameter values to OP-output.
- Some minor bug-fixes and implementation changes.

May 2009 Release of PSP 103.1 (which includes JUNCAP 200.3) as part of SiMKit 3.3. The main changes are:

- Added external sheet resistance **RSHD** for drain diffusion (used when **SWJUNASYM** = 1)
- Bug-fix and minor implementation change in NUD-model
- Minor bug fix in conditional for SP-calculation of overlap areas.
- Added noise source labeling (vA-code only)

December 2009 Release of PSP 103.1.1 (which includes JUNCAP 200.3) as part of SiMKit 3.4. The main changes are:

- Modified implementation of the asymmetrical junction model to improve simulation speed of verilog-A code.
- Modified implementation of the stand-alone JUNCAP2 model.
- Modified implementation of the MULT-scaling factor.
- Modified implementation of NUD model.
- Minor bug fixes.

July 2010 Release of PSP 103.1.2 β as part of SiMKit 3.5. The main changes are:

- Changes in the calculation of the surface-potential in the overlap regions and the calculation of the gate-current. These modifications lead to an 7% simulation speed increase, but leads to some small changes in the overlap-capacitance, gate-current, and GIDL-current w.r.t. the previous version.

December 2012 Release of PSP 103.2.0 (which includes JUNCAP 200.4) as part of SiMKit 4.0.1. The main changes are:

- Changes in the calculation of the surface potential in the overlap regions (see July 2010).
- Introduction of self heating. The self heating version of the model has a fifth terminal (dt) to represent the temperature increase. New parameters: **RTH**, **CTH**, **STRTH** (local model), **RTHO**, **CTHO**, **STRTHO** (global model and binning model).
- Some minor bug-fixes in the calculation of the OP-output.
- Several improvements in the noise-model implementation
 - Fixed sign of correlation coefficient (Verilog-A only).
 - Simplified implementation and better scaled noise amplitude at internal nodes (Verilog-A only).
 - Improved behavior when crossing $V_{ds} = 0$ at high-frequency.
- Scaled junction parameters added to OP-output.
- New parameter **PARAMCHK** to set level of clip warnings (SiMKit only).
- More efficient model evaluation when **MULT** = 0 (SiMKit only).

December 2013 Release of PSP 103.3.0 (which includes JUNCAP 200.4) as part of SiMKit 4.2. The main changes are:

- Addition of excess noise, which is important for sub-100-nm channel lengths. This addition is backwards compatible with PSP 103.2. New parameters: **FNTEXC** (local model), **FNTEXCL** (global model), and **POFNTEXC**, **PLFNTEXC**, **PWFNTEXC**, **PLWFNTEXC** (binning model).
- Minor bugfixes.

August 2016 Release of PSP 103.4 (which includes JUNCAP 200.5) as part of SiMKit 4.2. PSP 103.4 is backwards compatible with PSP 103.3. The main changes are:

- Addition of edge MOSFET for modeling of subthreshold hump effect. It can be turned on by setting **SWEDGE**=1. New parameters: **VFEDGE**, **STVFEDGE**, **DPHIBEDGE**, **NEFFEDGE**, **CTEDGE**, **BETNEGE**, **STBETEDGE**, **PSCEEDGE**, **PSCEBEDGE**, **PSCEEDGE**, **CFEDGE**, **CFEDGE**, **CFBEDGE**, **FNTEDGE**, **NFAEDGE**, **NFBEDGE**, **NFCEDGE**, **EFEDGE** (local model), **WEDGE**, **WEDGEW**, **VFEDGE**, **STVFEDGE**, **STVFEDGE**, **STVFEDGEW**, **STVFEDGE**, **DPHIBEDGE**, **DPHIBEDGE**, **DPHIBEDGELEXP**, **DPHIBEDGEW**, **DPHIBEDGE**, **NSUBEDGE**, **NSUBEDGE**, **NSUBEDGEW**, **NSUBEDGE**, **CTEDGE**, **CTEDGE**, **CTEDGELEXP**, **FBETEDGE**, **LPEDGE**, **BETEDGEW**, **STBETEDGE**, **STBETEDGE**, **STBETEDGEW**, **STBETEDGE**, **PSCEEDGE**, **PSCEEDGELEXP**, **PSCEEDGEW**, **PSCEBEDGE**, **PSCEBEDGE**, **CFEDGE**, **CFEDGELEXP**, **CFEDGEW**, **CFEDGE**, **CFBEDGE**, **FNTEDGE**, **NFAEDGE**, **NFBEDGE**, **NFCEDGE**, **EFEDGE** (global model), and **POVFEDGE**, **POSTVFEDGE**, **PLSTVFEDGE**, **PWSTVFEDGE**, **PLWSTVFEDGE**, **PODPHIBEDGE**, **PLDPHIBEDGE**, **PWDPHIBEDGE**, **PLWDPHIBEDGE**, **PONEFFEDGE**, **PLNEFFEDGE**, **PWNEFFEDGE**, **PLWNEFFEDGE**, **POCTEDGE**, **PLCTEDGE**, **PWCTEDGE**, **PLWCTEDGE**, **POBETEDGE**, **PLBETEDGE**, **PWBETEDGE**, **PLWBETEDGE**, **POSTBETEDGE**, **PLSTBETEDGE**, **PWSTBETEDGE**, **PLWSTBETEDGE**, **POPSCEEDGE**, **PLPSCEEDGE**, **PWPSCEEDGE**, **PLWPSCEEDGE**, **POPSCEBEDGE**, **POPSCEEDGE**, **POCFEDGE**, **PLCFEDGE**, **PWCFEDGE**, **PLWCFEDGE**, **POCFEDGE**, **POCFBEDGE**, **POFNTEGE**, **PONFAEDGE**, **PLNFAEDGE**, **PWNFAEDGE**, **PLWNFAEDGE**, **PONFBEDGE**, **PLNFBEDGE**, **PWNFBEDGE**, **PLWNFBEDGE**, **PONFCEDGE**, **PLNFCEDGE**, **PWNFCEDGE**, **PLWNFCEDGE**, **POEFEDGE** (binning model).

- New switch to active/disable the induced gate noise **SWIGN** (default value is 1 for backwards compatibility).
- New parameters for modeling of short channel effects on subthreshold slope:
 - Subthreshold slope degradation for short channel transistors: **PSCE** (local model), **PSCEL**, **PSCELEXP**, **PSCEW** (global model), and **POPSCE**, **PLPSCE**, **PWPSCE**, **PLWPSCE** (binning model).
 - Subthreshold slope dependence with drain voltage: **PSCED** (local model), **PSCEDO** (global model), and **POPSCED** (binning model).
 - Subthreshold slope dependence with bulk voltage: **PSCEB** (local model), **PSCEBO** (global model), and **POPSCEB** (binning model).
- New parameter of JUNCAP model: Coefficient for reverse breakdown current limitation **FREV**.
- Minor bugfixes.

April 2017 Release of PSP 103.5 (which includes JUNCAP 200.5). PSP 103.5 is backwards compatible with PSP 103.4. The main changes are:

- Addition of new mobility parameters for coulomb scattering effect: **THECS**, **STTHECS** (local model), **THECSO**, **STTHECSO** (global model), and **POTHECS**, **POSTTHECS** (binning model).
- Addition of new parameters for quadratic temperature dependence of flatband voltage: **ST2VFB** (local model), **ST2VFBO** (global model), and **POST2VFB** (binning model).

December 2017 Release of PSP 103.6 (which includes JUNCAP 200.5). PSP 103.6 is backwards compatible with PSP 103.5. The changes are:

- Induced gate noise: clipped value of `migid` using the correlation factor `c_igid`.
- Thermal noise of edge transistor: bug fix to avoid possible division by zero during the calculation of `redge`.
- Improvement of `gm/Id` in weak inversion: new model of interface states.
- Addition of new parameter **NSUBEDGELEXP**: exponent for channel length dependence of edge transistor substrate doping.
- Minimum values of calculated local parameters **NOV** and **NOVD** in global mode: now in lines with minimum values of local model parameters.

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.

June 2006 Documentation adapted to PSP 102.0 and some errors corrected.

October 2006 Documentation adapted to PSP 102.1 and some errors corrected.

October 2007 Documentation adapted to PSP 102.2 and some errors corrected.

April 2008 Documentation adapted to PSP 102.3 and some errors corrected.

November 2008 Documentation adapted to PSP 103.0 and some errors corrected.

June 2009 Documentation adapted to PSP 103.1 and some errors corrected.

December 2012 Documentation adapted to PSP 103.2.

December 2013 Documentation adapted to PSP 103.3 and some errors corrected.

August 2016 Documentation adapted to PSP 103.4.

April 2017 Documentation adapted to PSP 103.5.

December 2017 Documentation adapted to PSP 103.6

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Section 1

Introduction

1.1 Origin and purpose

The PSP model is a compact MOSFET model intended for analog, RF, and digital design. It is jointly developed by NXP Semiconductors and CEA-Leti. (From 2011 until 2015, it was jointly developed by NXP Semiconductors and Delft University of Technology. Until 2011, it was jointly developed by NXP Semiconductors and Arizona State University. The roots of PSP lie in both *MOS Model 11* (developed by NXP Semiconductors) and *SP* (developed at the Pennsylvania State University and later at Arizona 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. 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 PSP model web site: <http://www.cea.fr/cea-tech/leti/pspsupport> and the NXP Semiconductors web site: www.nxp.com/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 2.5.2. 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.

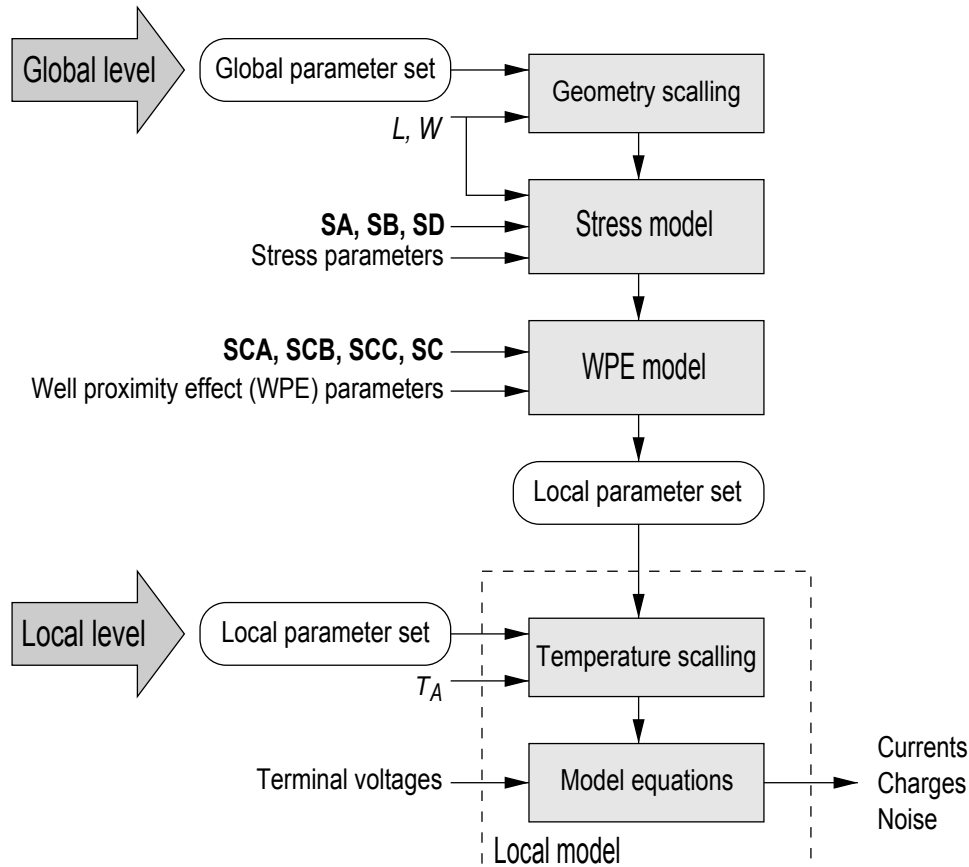


Figure 1.1: Simplified schematic overview of PSP's hierarchical structure.

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 2.5.2. Roughly speaking, this set contains all local parameters for a long/wide device 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 3.2). The geometrical 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 3.3) as an alternative to the geometrical (physics based) scaling rules. These binning rules come with their own set of parameters (see Section 2.5.2). 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 modifications of transistor properties due to stress and well proximity effect (WPE). In PSP, this is implemented by additional sets of transformation rules, which are optionally applied to the intermediate local parameter set generated at the global level. The parameters associated with the stress and WPE models 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 6.4.

1.3 Availability

The PSP model developers (CEA-Leti and NXP Semiconductors) distribute the PSP code in two formats:

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

The C-version is automatically generated from the Verilog-A version by the software package 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 6.5.

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 (NXP Semiconductors)
3. ADS (Agilent)

Some other circuit simulators vendors provide their own SiMKit adapter, such that simulations with models in SiMKit are possible.

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), stress and well proximity effect equations, the resulting local parameters are subjected to the clipping values as given in Section 2.5.2.

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

continued on next page...

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Symbol	Unit	Description
I_G^e	A	DC current into gate node
I_S^e	A	DC current into source node
I_B^e	A	DC current into bulk node
S_{fl}^e	A ² s	Spectral density of flicker noise current in the channel
$S_{fl,edge}^e$	A ² s	Spectral density of flicker noise current of edge transistor
S_{id}^e	A ² s	Spectral density of thermal noise current in the channel
$S_{id,edge}^e$	A ² s	Spectral density of thermal noise current of edge transistor
$S_{ig,S}^e$	A ² s	Spectral density of induced gate noise at source side
$S_{ig,D}^e$	A ² s	Spectral density of induced gate noise at drain side
S_{igs}^e	A ² s	Spectral density of gate current shot noise at source side
S_{igd}^e	A ² s	Spectral density of gate current shot noise at drain side
$S_{j,S}^e$	A ² s	Spectral density of source junction shot noise
$S_{j,D}^e$	A ² s	Spectral density of drain junction shot noise
S_{igid}^e	A ² s	Cross spectral density between S_{id}^e and (S_{igS}^e or S_{igD}^e)

Other circuit simulator variables

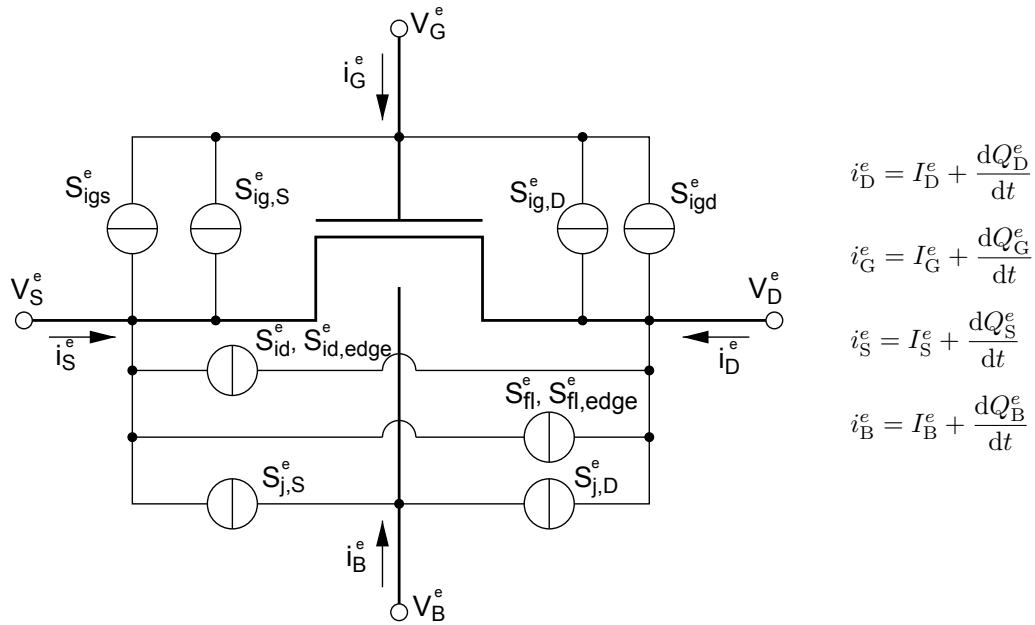
Next to the electrical variables described above, the quantities in the table below are also provided to the model by the circuit simulator.

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_0	F/m	$8.8541878176 \cdot 10^{-12}$	Permittivity of free space
7	$\epsilon_{r,Si}$	–	11.8	Relative permittivity of silicon
8	QM_N	$V m^{\frac{4}{3}} C^{-\frac{2}{3}}$	5.951993	Constant of quantum-mechanical behavior of electrons
9	QM_P	$V m^{\frac{4}{3}} C^{-\frac{2}{3}}$	7.448711	Constant of quantum-mechanical behavior of holes



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

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

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

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

Figure 2.1: Definition of external electrical quantities.

2.5 Model parameters

In this section all parameters of the PSP-model are described. The parameters for the intrinsic MOS model, the stress and well proximity effect models and the junction model are given in separate tables. The complete parameter list for each of the model entry levels is composed of several parts, as indicated in the table below.

Entry level	Sections
Global (geometrical scaling)	2.5.1 (instance parameters)
	2.5.2 (intrinsic MOS)
	2.5.3 (stress)
	2.5.4 (well proximity effect)
	2.5.5 (junctions)
	2.5.6 (parasitic resistances)
Binning	2.5.1 (instance parameters)
	2.5.2 (intrinsic MOS)
	2.5.3 (stress)
	2.5.4 (well proximity effect)
	2.5.5 (junctions)
	2.5.6 (parasitic resistances)
Local	2.5.1 (instance parameters)
	2.5.2 (intrinsic MOS)
	2.5.5 (junctions)
	2.5.6 (parasitic resistances)

2.5.1 Instance parameters

The instant parameters for global, local and binning models are listed in the table below. The last column of **Geo.** shows for which value of **SWGEO** the listed parameter is used. Note that, as explained in Section 6.4, the instance parameters for the JUNCAP2 model are used at the local level as well.

No.	Name	Unit	Default	Min.	Max.	Description	Geo.
0	<i>L</i>	m	10^{-6}	10^{-9}	—	Drawn channel length	1, 2
1	<i>W</i>	m	10^{-6}	10^{-9}	—	Drawn channel width (total width)	1, 2
2	ABSOURCE	m ²	10^{-12}	0	—	Source junction area	0, 1, 2
3	LSSOURCE	m	10^{-6}	0	—	STI-edge part of source junction perimeter	0, 1, 2
4	LGSOURCE	m	10^{-6}	0	—	Gate-edge part of source junction perimeter	0, 1, 2
5	ABDRAIN	m ²	10^{-12}	0	—	Drain junction area	0, 1, 2
6	LSDRAIN	m	10^{-6}	0	—	STI-edge part of drain junction perimeter	0, 1, 2
7	LGDRAIN	m	10^{-6}	0	—	Gate-edge part of drain junction perimeter	0, 1, 2
8	AS	m ²	10^{-12}	0	—	Source junction area (alternative spec.)	0, 1, 2
9	PS	m	10^{-6}	0	—	Source STI-edge perimeter (alternative spec.)	0, 1, 2
10	AD	m ²	10^{-12}	0	—	Drain junction area (alternative spec.)	0, 1, 2
11	PD	m	10^{-6}	0	—	Drain STI-edge perimeter (alternative spec.)	0, 1, 2
12	JW	m	$1 \cdot 10^{-6}$	0	—	Junction width	0
13	DELVTO	V	0	—	—	Threshold voltage shift parameter	0, 1, 2
14	FACTUO	—	1	0	—	Zero-field mobility pre-factor	0, 1, 2
15	DELVTOEDGE	V	0	—	—	Threshold voltage shift parameter of edge transistor	0, 1, 2
16	FACTUOEDGE	—	1	0	—	Zero-field mobility pre-factor of edge transistor	0, 1, 2
17	SA	m	0	—	—	Distance between OD-edge and poly at source side	1, 2
18	SB	m	0	—	—	Distance between OD-edge and poly at drain side	1, 2
19	SD	m	0	—	—	Distance between neighboring fingers	1, 2
20	SCA	—	0	0	—	Integral of the first distribution function for scattered well dopant	1, 2
21	SCB	—	0	0	—	Integral of the second distribution function for scattered well dopant	1, 2
22	SCC	—	0	0	—	Integral of the third distribution function for scattered well dopant	1, 2
23	SC	m	0	—	—	Distance between OD edge and nearest well edge	1, 2
24	NRS	—	0	—	—	Number of squares of source diffusion	1, 2

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No.	Name	Unit	Default	Min.	Max.	Description	Geo.
25	NRD	–	0	–	–	Number of squares of drain diffusion	1, 2
26	NGCON	–	1	1	2	Number of gate contacts	1, 2
27	XGW	m	10^{-7}	–	–	Distance from the gate contact to the channel edge	1, 2
28	NF	–	1	1	–	Number of fingers; internally rounded to the nearest integer	1, 2
29	MULT	–	1	0	–	Number of devices in parallel	0, 1, 2

Note that if both **SA** and **SB** are set to 0 the stress-equations are not computed. If **SCA**, **SCB**, **SCC** and **SC** are all set to 0 the well proximity effect 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.

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

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** = 2 or 3.

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

2.5.2 Intrinsic model

The model parameters for the intrinsic part of the MOSFET are listed in the table below. The last column—labeled ‘Geo.’—shows for which value of **SWGEO** the parameter is used. The convention used in this table is that, if a scaling rule exists for a local parameter its scaling (global and/or binning) parameters are grouped underneath. Note also some parameters do not have their local counterparts.

No.	Name	Unit	Default	Min.	Max.	Description	Geo.
0	LEVEL	–	103	–	–	Model selection parameter; see Sec. 6.1	0, 1, 2
1	TYPE	–	1	–1	1	Channel type parameter; 1 ↔ NMOS, –1 ↔ PMOS ¹	0, 1, 2
2	TR	°C	21	–273	–	Reference temperature	0, 1, 2
3	DTA	K	0	–	–	Temperature offset w.r.t. ambient circuit temperature	0, 1, 2
Switches							
4	PARAMCHK	–	0	–	–	Level of clip-warning info ²	0, 1, 2
5	SWGEO	–	1	0	2	Flag for geometrical model (0 ↔ local, 1 ↔ global, 2 ↔ binning)	0, 1, 2
6	SWIGATE	–	0	0	1	Flag for gate current (0 ↔ “off”)	0, 1, 2
7	SWIMPACT	–	0	0	1	Flag for impact ionization current (0 ↔ “off”)	0, 1, 2
8	SWGIDL	–	0	0	1	Flag for GIDL/GISL current (0 ↔ “off”)	0, 1, 2
9	SWJUNCAP	–	0	0	3	Flag for JUNCAP (0 ↔ “off”)	0, 1, 2
10	SWJUNASYM	–	0	–	–	Flag for asymmetric junctions (0 ↔ “off”)	0, 1, 2
11	SWNUD	–	0	0	2	Flag for NUD-effect (0 ↔ “off”)	0, 1, 2
12	SWEDGE	–	0	0	1	Flag for drain current of edge transistors (0 ↔ “off”)	0, 1, 2
13	SWDELVTAC	–	0	0	1	Flag for separate charge calculation (0 ↔ “off”)	0, 1, 2
14	QMC	–	1	0	–	Quantum-mechanical correction factor	0, 1, 2
Labels for binning set							
15	LMIN	m	0	–	–	Dummy parameter to label binning set	2
16	LMAX	m	1	–	–	Dummy parameter to label binning set	2
17	WMIN	m	0	–	–	Dummy parameter to label binning set	2
18	WMAX	m	1	–	–	Dummy parameter to label binning set	2
Process Parameters							

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¹See Section 6.3.1 for more information on usage of **TYPE** in various simulators.

²Only in SiMKit-version of PSP. See Section 6.5.4 for more information.

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No.	Name	Unit	Default	Min.	Max.	Description	Geo.
19	LVARO	m	0	—	—	Geometry independent difference between actual and programmed poly-silicon gate length	1, 2
20	LVARL	—	0	—	—	Length dependence of ΔL_{PS}	1, 2
21	LVARW	—	0	—	—	Width dependence of ΔL_{PS}	1, 2
22	LAP	m	0	—	—	Effective channel length reduction per side due to lateral diffusion of source/drain dopant ions	1, 2
23	WVARO	m	0	—	—	Geometry independent difference between actual and programmed field-oxide opening	1, 2
24	WVARL	—	0	—	—	Length dependence of ΔW_{OD}	1, 2
25	WVARW	—	0	—	—	Width dependence of ΔW_{OD}	1, 2
26	WOT	m	0	—	—	Effective reduction of channel width per side due to lateral diffusion of channel-stop dopant ions	1, 2
27	DLQ	m	0	—	—	Effective channel length offset for CV	1, 2
28	DWQ	m	0	—	—	Effective channel width offset for CV	1, 2
29	VFB	V	-1	—	—	Flat-band voltage at TR	0
30	VFBO	V	-1	—	—	Geometry-independent part	1
31	VFBL	V	0	—	—	Length dependence	1
32	VFBW	V	0	—	—	Width dependence	1
33	VFBLW	V	0	—	—	Area dependence	1
34	POVFB	V	-1	—	—	Geometry independent part	2
35	PLVFB	V	0	—	—	Length dependence	2
36	PWVFB	V	0	—	—	Width dependence	2
37	PLWVFB	V	0	—	—	Length times width dependence	2
38	STVFB	V/K	$5 \cdot 10^{-4}$	—	—	Temperature dependence of VFB	0
39	STVFBO	V/K	$5 \cdot 10^{-4}$	—	—	Geometry-independent part	1
40	STVFBL	V/K	0	—	—	Length dependence	1
41	STVFBW	V/K	0	—	—	Width dependence	1
42	STVFBLW	V/K	0	—	—	Area dependence	1
43	POSTVFB	V/K	$5 \cdot 10^{-4}$	—	—	Geometry independent part	2
44	PLSTVFB	V/K	0	—	—	Length dependence	2
45	PWSTVFB	V/K	0	—	—	Width dependence	2
46	PLWSTVFB	V/K	0	—	—	Length times width dependence	2
47	ST2VFB	K^{-1}	0	—	—	Quadratic temperature dependence of VFB	0
48	ST2VFBO	K^{-1}	0	—	—	Geometry-independent part	1

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No.	Name	Unit	Default	Min.	Max.	Description	Geo.
49	POST2VFB	K ⁻¹	0	–	–	Geometry independent part	2
50	TOX	m	2 · 10 ⁻⁹	10 ⁻¹⁰	–	Gate oxide thickness	0
51	TOXO	m	2 · 10 ⁻⁹	10 ⁻¹⁰	–	Gate oxide thickness	1
52	POTOX	m	2 · 10 ⁻⁹	–	–	Geometry independent part	2
53	EPSROX	–	3.9	1	–	Relative permittivity of gate dielectric	0
54	EPSROXO	–	3.9	1	–	Geometry independent part	1
55	POEPSROX	–	3.9	1	–	Geometry independent part	2
56	NEFF	m ⁻³	5 · 10 ²³	10 ²⁰	10 ²⁶	Substrate doping	0
57	NSUBO	m ⁻³	3 · 10 ²³	10 ²⁰	–	Geometry independent substrate doping	1
58	NSUBW	–	0	–	–	Width dependence of substrate doping due to segregation	1
59	WSEG	m	10 ⁻⁸	10 ⁻¹⁰	–	Characteristic length for segregation of substrate doping	1
60	NPCK	m ⁻³	10 ²⁴	0	–	Pocket doping level	1
61	NPCKW	–	0	–	–	Width dependence of NPCK due to segregation	1
62	WSEGP	m	10 ⁻⁸	10 ⁻¹⁰	–	Characteristic length for segregation of pocket doping	1
63	LPCK	m	10 ⁻⁸	10 ⁻¹⁰	–	Characteristic length for lateral doping profile	1
64	LPCKW	–	0	–	–	Width dependence of LPCK due to segregation	1
65	FOL1	–	0	–	–	First order length dependence of short channel body-effect	1
66	FOL2	–	0	–	–	Second order length dependence of short channel body-effect	1
67	PONEFF	m ⁻³	5 · 10 ²³	–	–	Geometry independent part	2
68	PLNEFF	m ⁻³	0	–	–	Length dependence	2
69	PWNEFF	m ⁻³	0	–	–	Width dependence	2
70	PLWNEFF	m ⁻³	0	–	–	Length times width dependence	2
71	FACNEFFAC	–	1	0	–	Pre-factor for effective substrate doping in separate charge calculation when SWDELVTAC = 1	0
72	FACNEFFACO	–	1	0	–	Geometry independent part	1
73	FACNEFFACL	–	0	–	–	Length dependence	1
74	FACNEFFACW	–	0	–	–	Width dependence	1
75	FACNEFFACLW	–	0	–	–	Area dependence	1
76	POFACNEFFAC	–	1	–	–	Geometry independent part	2

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No.	Name	Unit	Default	Min.	Max.	Description	Geo.
77	PLFACNEFFAC	–	0	–	–	Length dependence	2
78	PWFACNEFFAC	–	0	–	–	Width dependence	2
79	PLWFACNEFFAC	–	0	–	–	Area dependence	2
80	GFACNUD	–	1	0.01	–	Bodyfactor change due to NUD-effect	0
81	GFACNUDO	–	1	–	–	Geometry independent part	1
82	GFACNUDL	–	0	–	–	Length dependence	1
83	GFACNUDLEXP	–	1	–	–	Exponent for length dependence	1
84	GFACNUDW	–	0	–	–	Width dependence	1
85	GFACNUDLW	–	0	–	–	Area dependence	1
86	POGFACNUD	–	1	–	–	Geometry independent part	2
87	PLGFACNUD	–	0	–	–	Length dependence	2
88	PWGFACNUD	–	0	–	–	Width dependence	2
89	PLWGFACNUD	–	0	–	–	Area dependence	2
90	VSBNUD	V	0	0	–	Lower V_{SB} -value for NUD-effect	0
91	VSBNUDO	V	0	–	–	Geometry independent part	1
92	POVSBNUD	V	0	–	–	Geometry independent part	2
93	DVSBNUD	V	1	0.1	–	V_{SB} -range for NUD-effect	0
94	DVSBNUDO	V	1	–	–	Geometry independent part	1
95	PODVSBNUD	V	1	–	–	Geometry independent part	2
96	VNSUB	V	0	–	–	Effective doping bias-dependence parameter	0
97	VNSUBO	V	0	–	–	Geometry independent part	1
98	POVNSUB	V	0	–	–	Geometry independent part	2
99	NSLP	V	0.05	10^{-3}	–	Effective doping bias-dependence parameter	0
100	NSLPO	V	0.05	–	–	Geometry independent part	1
101	PONSLP	V	0.05	–	–	Geometry independent part	2
102	DNSUB	V^{-1}	0	0	1	Effective doping bias-dependence parameter	0
103	DNSUBO	V^{-1}	0	–	–	Geometry independent part	1
104	PODNSUB	V^{-1}	0	–	–	Geometry independent part	2
105	DPHIB	V	0	–	–	Offset of φ_B	0
106	DPHIBO	V	0	–	–	Geometry independent part	1
107	DPHIBL	V	0	–	–	Length dependence	1
108	DPHIBLEXP	–	1	–	–	Exponent for length dependence	1

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No.	Name	Unit	Default	Min.	Max.	Description	Geo.
109	DPHIBW	V	0	–	–	Width dependence	1
110	DPHIBLW	V	0	–	–	Area dependence	1
111	PODPHIB	V	0	–	–	Geometry independent part	2
112	PLDPHIB	V	0	–	–	Length dependence	2
113	PWDPHIB	V	0	–	–	Width dependence	2
114	PLWDPHIB	V	0	–	–	Length times width dependence	2
115	DELVTAC	V	0	–	–	Offset of φ_B in separate charge calculation when SWDELVTAC = 1	0
116	DELVTACO	V	0	–	–	Geometry independent part	1
117	DELVTACL	V	0	–	–	Length dependence	1
118	DELVTACLEXP	–	1	–	–	Exponent for length dependence	1
119	DELVTACW	V	0	–	–	Width dependence	1
120	DELVTACLW	V	0	–	–	Area dependence	1
121	PODELVTAC	V	0	–	–	Geometry independent part	2
122	PLDELVTAC	V	0	–	–	Length dependence	2
123	PWDELVTAC	V	0	–	–	Width dependence	2
124	PLWDELVTAC	V	0	–	–	Length times width dependence	2
125	NP	m^{-3}	10^{26}	0	–	Gate poly-silicon doping	0
126	NPO	m^{-3}	10^{26}	–	–	Geometry-independent part	1
127	NPL	–	0	–	–	Length dependence	1
128	PONP	m^{-3}	10^{26}	–	–	Geometry independent part	2
129	PLNP	m^{-3}	0	–	–	Length dependence	2
130	PWNP	m^{-3}	0	–	–	Width dependence	2
131	PLWNP	m^{-3}	0	–	–	Length times width dependence	2
132	TOXOV	m	$2 \cdot 10^{-9}$	10^{-10}	–	Overlap oxide thickness	0
133	TOXOVO	m	$2 \cdot 10^{-9}$	10^{-10}	–	Geometry independent part	1
134	POTOXOV	m	$2 \cdot 10^{-9}$	–	–	Geometry independent part	2
135	TOXOVD	m	$2 \cdot 10^{-9}$	10^{-10}	–	Overlap oxide thickness for drain side	0
136	TOXOVDO	m	$2 \cdot 10^{-9}$	10^{-10}	–	Geometry independent part	1
137	POTOXOVD	m	$2 \cdot 10^{-9}$	–	–	Geometry independent part	2
138	LOV	m	0	0	–	Overlap length for overlap capacitance	1
139	LOVD	m	0	0	–	Overlap length for gate/drain overlap capacitance	1
140	NOV	m^{-3}	$5 \cdot 10^{25}$	10^{20}	10^{27}	Effective doping of overlap region	0
141	NOVO	m^{-3}	$5 \cdot 10^{25}$	–	–	Geometry independent part	1

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No.	Name	Unit	Default	Min.	Max.	Description	Geo.
142	PONOV	m ⁻³	5 · 10 ²⁵	—	—	Geometry independent part	2
143	PLNOV	m ⁻³	0	—	—	Length dependence	2
144	PWNOV	m ⁻³	0	—	—	Width dependence	2
145	PLWNOV	m ⁻³	0	—	—	Length times width dependence	2
146	NOVD	m ⁻³	5 · 10 ²⁵	10 ²⁰	10 ²⁷	Effective doping of overlap region for drain side	0
147	NOVDO	m ⁻³	5 · 10 ²⁵	—	—	Geometry independent part	1
148	PONOV	m ⁻³	5 · 10 ²⁵	—	—	Geometry independent part	2
149	PLNOVD	m ⁻³	0	—	—	Length dependence	2
150	PWNOVD	m ⁻³	0	—	—	Width dependence	2
151	PLWNOVD	m ⁻³	0	—	—	Length times width dependence	2
Interface States Parameters							
152	CT	—	0	0	—	Interface states factor	0
153	CTO	—	0	—	—	Geometry-independent part	1
154	CTL	—	0	—	—	Length dependence	1
155	CTLEXP	—	1	—	—	Exponent for length dependence	1
156	CTW	—	0	—	—	Width dependence	1
157	CTLW	—	0	—	—	Area dependence	1
158	POCT	—	0	—	—	Geometry independent part	2
159	PLCT	—	0	—	—	Length dependence	2
160	PWCT	—	0	—	—	Width dependence	2
161	PLWCT	—	0	—	—	Length times width dependence	2
162	CTG	—	0	0	—	Gate voltage dependence of interface states factor	0
163	CTGO	—	0	—	—	Geometry-independent part	1
164	POCTG	—	0	—	—	Geometry independent part	2
165	CTB	—	0	—	—	Bulk voltage dependence of interface states factor	0
166	CTBO	—	0	—	—	Geometry-independent part	1
167	POCTB	—	0	—	—	Geometry independent part	2
168	STCT	—	1	—	—	Temperature dependence of CT	0
169	STCTO	—	1	—	—	Geometry-independent part	1
170	POSTCT	—	1	—	—	Geometry independent part	2
DIBL Parameters							
171	CF	—	0	0	—	DIBL parameter	0
172	CFL	—	0	—	—	Length dependence	1

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No.	Name	Unit	Default	Min.	Max.	Description	Geo.
173	CFLEXP	–	2	–	–	Exponent for length dependence	1
174	CFW	–	0	–	–	Width dependence	1
175	POCF	–	0	–	–	Geometry independent part	2
176	PLCF	–	0	–	–	Length dependence	2
177	PWCF	–	0	–	–	Width dependence	2
178	PLWCF	–	0	–	–	Length times width dependence	2
179	CFB	V ⁻¹	0	0	1	Back-bias dependence of CF	0
180	CFBO	V ⁻¹	0	–	–	Geometry independent part	1
181	POCFB	V ⁻¹	0	–	–	Geometry independent part	2
182	CFD	V ⁻¹	0	0	–	Drain voltage dependence of CF	0
183	CFDO	V ⁻¹	0	–	–	Geometry independent part	1
184	POCFD	V ⁻¹	0	–	–	Geometry independent part	2
Subthreshold Slope Parameters							
185	PSCE	–	0	0	–	Subthreshold slope coefficient for short channel transistor	0
186	PSCEL	–	0	–	–	Length dependence	1
187	PSCELEXP	–	2	–	–	Exponent for length dependence	1
188	PSCEW	–	0	–	–	Width dependence	1
189	POPSCE	–	0	–	–	Geometry independent part	2
190	PLPSCE	–	0	–	–	Length dependence	2
191	PWPSCE	–	0	–	–	Width dependence	2
192	PLWPSCE	–	0	–	–	Length times width dependence	2
193	PSCEB	V ⁻¹	0	0	1	Back-bias dependence of PSCE	0
194	PSCEBO	V ⁻¹	0	–	–	Geometry independent part	1
195	POPSCEB	V ⁻¹	0	–	–	Geometry independent part	2
196	PSCED	V ⁻¹	0	0	–	Drain voltage dependence of PSCE	0
197	PSCEDO	V ⁻¹	0	–	–	Geometry independent part	1
198	POPSCED	V ⁻¹	0	–	–	Geometry independent part	2
Mobility Parameters							
199	BETN	m ² /V/s	7 · 10 ⁻²	0	–	Product of channel aspect ratio and zero-field mobility at TR	0
200	UO	m ² /V/s	5 · 10 ⁻²	–	–	Zero-field mobility at TR	1
201	FBET1	–	0	–	–	Relative mobility decrease due to first lateral profile	1
202	FBET1W	–	0	–	–	Width dependence of FBET1	1
203	LP1	m	10 ⁻⁸	10 ⁻¹⁰	–	Mobility-related characteristic length of first lateral profile	1

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No.	Name	Unit	Default	Min.	Max.	Description	Geo.
204	LP1W	–	0	–	–	Width dependence of LP1	1
205	FBET2	–	0	–	–	Relative mobility decrease due to second lateral profile	1
206	LP2	m	10^{-8}	10^{-10}	–	Mobility-related characteristic length of second lateral profile	1
207	BETW1	–	0	–	–	First higher-order width scaling coefficient of BETN	1
208	BETW2	–	0	–	–	Second higher-order width scaling coefficient of BETN	1
209	WBET	m	10^{-9}	10^{-10}	–	Characteristic width for width scaling of BETN	1
210	POBETN	$m^2/V/s$	$7 \cdot 10^{-2}$	–	–	Geometry independent part	2
211	PLBETN	$m^2/V/s$	0	–	–	Length dependence	2
212	PWBETN	$m^2/V/s$	0	–	–	Width dependence	2
213	PLWBETN	$m^2/V/s$	0	–	–	Length times width dependence	2
214	STBET	–	1	–	–	Temperature dependence of BETN	0
215	STBETO	–	1	–	–	Geometry independent part	1
216	STBETL	–	0	–	–	Length dependence	1
217	STBETW	–	0	–	–	Width dependence	1
218	STBETLW	–	0	–	–	Area dependence	1
219	POSTBET	–	1	–	–	Geometry independent part	2
220	PLSTBET	–	0	–	–	Length dependence	2
221	PWSTBET	–	0	–	–	Width dependence	2
222	PLWSTBET	–	0	–	–	Length times width dependence	2
223	MUE	m/V	0.5	0	–	Mobility reduction coefficient at TR	0
224	MUEO	m/V	0.5	–	–	Geometry independent part	1
225	MUEW	–	0	–	–	Width dependence	1
226	POMUE	m/V	0.5	–	–	Geometry independent part	2
227	PLMUE	m/V	0	–	–	Length dependence	2
228	PWMUE	m/V	0	–	–	Width dependence	2
229	PLWMUE	m/V	0	–	–	Length times width dependence	2
230	STMUE	–	0	–	–	Temperature dependence of MUE	0
231	STMUEO	–	0	–	–	Geometry independent part	1
232	POSTMUE	–	0	–	–	Geometry independent part	2
233	THEMU	–	1.5	0	–	Mobility reduction exponent at TR	0
234	THEMUO	–	1.5	0	–	Geometry independent part	1
235	POTHEMU	–	1.5	–	–	Geometry independent part	2

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No.	Name	Unit	Default	Min.	Max.	Description	Geo.
236	STTHEMU	–	1.5	–	–	Temperature dependence of THEMU	0
237	STTHEMUO	–	1.5	–	–	Geometry independent part	1
238	POSTTHEMU	–	1.5	–	–	Geometry independent part	2
239	CS	–	0	0	–	Coulomb scattering parameter at TR	0
240	CSO	–	0	–	–	Geometry independent part	1
241	CSL	–	0	–	–	Length dependence	1
242	CSLEXP	–	1	–	–	Exponent for length dependence	1
243	CSW	–	0	–	–	Width dependence	1
244	CSLW	–	0	–	–	Area dependence	1
245	POCS	–	0	–	–	Geometry independent part	2
246	PLCS	–	0	–	–	Length dependence	2
247	PWCS	–	0	–	–	Width dependence	2
248	PLWCS	–	0	–	–	Length times width dependence	2
249	STCS	–	0	–	–	Temperature dependence of CS	0
250	STCSO	–	0	–	–	Geometry independent part	1
251	POSTCS	–	0	–	–	Geometry independent part	2
252	THECS	–	2	0	–	Coulomb scattering exponent at TR	0
253	THECSO	–	2	0	–	Geometry-independent part	1
254	POTHECS	–	2	0	–	Geometry independent part	2
255	STTHECS	–	0	–	–	Temperature dependence of THECS	0
256	STTHECSO	–	0	–	–	Geometry-independent part	1
257	POSTTHECS	–	0	–	–	Geometry independent part	2
258	XCOR	V^{-1}	0	0	–	Non-universality parameter	0
259	XCORO	V^{-1}	0	–	–	Geometry independent part	1
260	XCORL	–	0	–	–	Length dependence	1
261	XCORW	–	0	–	–	Width dependence	1
262	XCORLW	–	0	–	–	Area dependence	1
263	POXCOR	V^{-1}	0	–	–	Geometry independent part	2
264	PLXCOR	V^{-1}	0	–	–	Length dependence	2
265	PWXCOR	V^{-1}	0	–	–	Width dependence	2
266	PLWXCOR	V^{-1}	0	–	–	Length times width dependence	2
267	STXCOR	–	0	–	–	Temperature dependence of XCOR	0
268	STXCORO	–	0	–	–	Geometry independent part	1

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No.	Name	Unit	Default	Min.	Max.	Description	Geo.
269	POSTXCOR	–	0	–	–	Geometry independent part	2
270	FETA	–	1	0	–	Effective field parameter	0
271	FETAO	–	1	–	–	Geometry independent part	1
272	POFETA	–	1	–	–	Geometry independent part	2
Series Resistance Parameters							
273	RS	Ω	30	0	–	Source/drain series resistance at TR	0
274	RSW1	Ω	50	–	–	Source/drain series resistance for a channel width W_{EN}	1
275	RSW2	–	0	–	–	Higher-order width scaling	1
276	PORS	Ω	30	–	–	Geometry independent part	2
277	PLRS	Ω	0	–	–	Length dependence	2
278	PWRS	Ω	0	–	–	Width dependence	2
279	PLWRS	Ω	0	–	–	Length times width dependence	2
280	STRS	–	1	–	–	Temperature dependence of RS	0
281	STRSO	–	1	–	–	Geometry dependent part	1
282	POSTRS	–	1	–	–	Geometry independent part	2
283	RSB	V^{-1}	0	–0.5	1	Back-bias dependence of RS	0
284	RSBO	V^{-1}	0	–	–	Geometry independent part	1
285	PORSB	V^{-1}	0	–	–	Geometry independent part	2
286	RSG	V^{-1}	0	–0.5	–	Gate-bias dependence of RS	0
287	RSGO	V^{-1}	0	–	–	Geometry independent part	1
288	PORSG	V^{-1}	0	–	–	Geometry independent part	2
Velocity Saturation Parameters							
289	THESAT	V^{-1}	1	0	–	Velocity saturation parameter at TR	0
290	THESATO	V^{-1}	0	–	–	Geometry independent part	1
291	THESATL	V^{-1}	0.05	–	–	Length dependence	1
292	THESATLEXP	–	1	–	–	Exponent for length dependence	1
293	THESATW	–	0	–	–	Width dependence	1
294	THESATLW	–	0	–	–	Area dependence	1
295	POTHE SAT	V^{-1}	1	–	–	Geometry independent part	2
296	PLTHE SAT	V^{-1}	0	–	–	Length dependence	2
297	PWTHE SAT	V^{-1}	0	–	–	Width dependence	2
298	PLWTHE SAT	V^{-1}	0	–	–	Length times width dependence	2

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No.	Name	Unit	Default	Min.	Max.	Description	Geo.
299	STTHESAT	–	1	–	–	Temperature dependence of THESAT	0
300	STTHESATO	–	1	–	–	Geometry independent temperature dependence	1
301	STTHESATL	–	0	–	–	Length dependence	1
302	STTHESATW	–	0	–	–	Width dependence	1
303	STTHESATLW	–	0	–	–	Area dependence	1
304	POSTTHESAT	–	1	–	–	Geometry independent part	2
305	PLSTTHESAT	–	0	–	–	Length dependence	2
306	PWSTTHESAT	–	0	–	–	Width dependence	2
307	PLWSTTHESAT	–	0	–	–	Length times width dependence of temperature dependence	2
308	THESATB	V ⁻¹	0	–0.5	1	Back-bias dependence of velocity saturation	0
309	THESATBO	V ⁻¹	0	–	–	Geometry independent part	1
310	POTHEATB	V ⁻¹	0	–	–	Geometry independent part	2
311	PLTHEATB	V ⁻¹	0	–	–	Length dependence	2
312	PWTHEATB	V ⁻¹	0	–	–	Width dependence	2
313	PLWTHEATB	V ⁻¹	0	–	–	Length times width dependence	2
314	THESATG	V ⁻¹	0	–0.5	–	Gate-bias dependence of velocity saturation	0
315	THESATGO	V ⁻¹	0	–	–	Geometry independent part	1
316	POTHEATG	V ⁻¹	0	–	–	Geometry independent part	2
317	PLTHEATG	V ⁻¹	0	–	–	Length dependence	2
318	PWTHEATG	V ⁻¹	0	–	–	Width dependence	2
319	PLWTHEATG	V ⁻¹	0	–	–	Length times width dependence	2
Saturation Voltage Parameter							
320	AX	–	3	2	–	Linear/saturation transition factor	0
321	AXO	–	18	–	–	Geometry independent	1
322	AXL	–	0.4	0	–	Length dependence	1
323	POAX	–	3	–	–	Geometry independent part	2
324	PLAX	–	0	–	–	Length dependence	2
325	PWAX	–	0	–	–	Width dependence	2
326	PLWAX	–	0	–	–	Length times width dependence	2
Channel Length Modulation (CLM) Parameters							
327	ALP	–	0.01	0	–	CLM pre-factor	0
328	ALPL	–	5 · 10 ⁻⁴	–	–	Length dependence	1
329	ALPLEXP	–	1	–	–	Exponent for length dependence	1
330	ALPW	–	0	–	–	Width dependence	1

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No.	Name	Unit	Default	Min.	Max.	Description	Geo.
331	POALP	–	0.01	–	–	Geometry independent part	2
332	PLALP	–	0	–	–	Length dependence	2
333	PWALP	–	0	–	–	Width dependence	2
334	PLWALP	–	0	–	–	Length times width dependence	2
335	ALP1	V	0	0	–	CLM enhancement factor above threshold	0
336	ALP1L1	V	0	–	–	Length dependence	1
337	ALP1LEXP	–	0.5	–	–	Exponent for length dependence	1
338	ALP1L2	–	0	0	–	Second order length dependence	1
339	ALP1W	–	0	–	–	Width dependence	1
340	POALP1	V	0	–	–	Geometry independent part	2
341	PLALP1	V	0	–	–	Length dependence	2
342	PWALP1	V	0	–	–	Width dependence	2
343	PLWALP1	V	0	–	–	Length times width dependence	2
344	ALP2	V ⁻¹	0	0	–	CLM enhancement factor below threshold	0
345	ALP2L1	V	0	–	–	Length dependence	1
346	ALP2LEXP	–	0.5	–	–	Exponent for length dependence	1
347	ALP2L2	–	0	0	–	Second order length dependence	1
348	ALP2W	–	0	–	–	Width dependence	1
349	POALP2	V ⁻¹	0	–	–	Geometry independent part	2
350	PLALP2	V ⁻¹	0	–	–	Length dependence	2
351	PWALP2	V ⁻¹	0	–	–	Width dependence	2
352	PLWALP2	V ⁻¹	0	–	–	Length times width dependence	2
353	VP	V	0.05	10 ⁻¹⁰	–	CLM logarithmic dependence parameter	0
354	VPO	V	0.05	–	–	Geometry independent part	1
355	POVP	V	0.05	–	–	Geometry independent part	2
Impact Ionization (II) Parameters							
356	A1	–	1	0	–	Impact-ionization pre-factor	0
357	A1O	–	1	–	–	Geometry independent part	1
358	A1L	–	0	–	–	Length dependence	1
359	A1W	–	0	–	–	Width dependence	1
360	POA1	–	1	–	–	Geometry independent part	2
361	PLA1	–	0	–	–	Length dependence	2
362	PWA1	–	0	–	–	Width dependence	2
363	PLWA1	–	0	–	–	Length times width dependence	2
364	A2	V	10	0	–	Impact-ionization exponent at TR	0

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No.	Name	Unit	Default	Min.	Max.	Description	Geo.
365	A2O	V	10	–	–	Geometry independent part	1
366	POA2	V	10	–	–	Geometry independent part	2
367	STA2	V	0	–	–	Temperature dependence of A2	0
368	STA2O	V	0	–	–	Geometry independent part	1
369	POSTA2	V	0	–	–	Geometry independent part	2
370	A3	–	1	0	–	Saturation-voltage dependence of II	0
371	A3O	–	1	–	–	Geometry independent part	1
372	A3L	–	0	–	–	Length dependence	1
373	A3W	–	0	–	–	Width dependence	1
374	POA3	–	1	–	–	Geometry independent part	2
375	PLA3	–	0	–	–	Length dependence	2
376	PWA3	–	0	–	–	Width dependence	2
377	PLWA3	–	0	–	–	Length times width dependence	2
378	A4	$V^{-\frac{1}{2}}$	0	0	–	Back-bias dependence of II	0
379	A4O	$V^{-\frac{1}{2}}$	0	–	–	Geometry independent part	1
380	A4L	–	0	–	–	Length dependence	1
381	A4W	–	0	–	–	Width dependence	1
382	POA4	$V^{-\frac{1}{2}}$	0	–	–	Geometry independent part	2
383	PLA4	$V^{-\frac{1}{2}}$	0	–	–	Length dependence	2
384	PWA4	$V^{-\frac{1}{2}}$	0	–	–	Width dependence	2
385	PLWA4	$V^{-\frac{1}{2}}$	0	–	–	Length times width dependence	2
Gate Current Parameters							
386	GCO	–	0	–10	10	Gate tunnelling energy adjustment	0
387	GCOO	–	0	–	–	Geometry independent part	1
388	POGCO	–	0	–	–	Geometry independent part	2
389	IGINV	A	0	0	–	Gate channel current pre-factor	0
390	IGINVLW	A	0	–	–	Gate channel current pre-factor for a channel area of $W_{EN} \cdot L_{EN}$	1
391	POIGINV	A	0	–	–	Geometry independent part	2
392	PLIGINV	A	0	–	–	Length dependence	2
393	PWIGINV	A	0	–	–	Width dependence	2
394	PLWIGINV	A	0	–	–	Length times width dependence	2
395	IGOV	A	0	0	–	Gate overlap current pre-factor	0
396	IGOVW	A	0	–	–	Gate overlap current pre-factor for a channel width of W_{EN}	1

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No.	Name	Unit	Default	Min.	Max.	Description	Geo.
397	POIGOV	A	0	–	–	Geometry independent part	2
398	PLIGOV	A	0	–	–	Length dependence	2
399	PWIGOV	A	0	–	–	Width dependence	2
400	PLWIGOV	A	0	–	–	Length times width dependence	2
401	IGOVD	A	0	0	–	Gate overlap current pre-factor for drain side	0
402	IGOVDW	A	0	–	–	Gate overlap current pre-factor for a channel width of W_{EN} for drain side	1
403	POIGOVD	A	0	–	–	Geometry independent part	2
404	PLIGOVD	A	0	–	–	Length dependence	2
405	PWIGOVD	A	0	–	–	Width dependence	2
406	PLWIGOVD	A	0	–	–	Length times width dependence	2
407	STIG	–	2	–	–	Temperature dependence of gate current	0
408	STIGO	–	2	–	–	Geometry independent part	1
409	POSTIG	–	2	–	–	Geometry independent part	2
410	GC2	–	0.375	0	10	Gate current slope factor	0
411	GC2O	–	0.375	–	–	Geometry independent part	1
412	POGC2	–	$3.75 \cdot 10^{-1}$	–	–	Geometry independent part	2
413	GC3	–	0.063	–2	2	Gate current curvature factor	0
414	GC3O	–	0.063	–	–	Geometry independent part	1
415	POGC3	–	$6.3 \cdot 10^{-2}$	–	–	Geometry independent part	2
416	CHIB	V	3.1	1	–	Tunnelling barrier height	0
417	CHIBO	V	3.1	–	–	Geometry independent part	1
418	POCHIB	V	3.1	–	–	Geometry independent part	2
Gate-Induced Drain Leakage (GIDL) Parameters							
419	AGIDL	A/V^3	0	0	–	GIDL pre-factor	0
420	AGIDLW	A/V^3	0	–	–	Width dependence	1
421	POAGIDL	A/V^3	0	–	–	Geometry independent part	2
422	PLAGIDL	A/V^3	0	–	–	Length dependence	2
423	PWAGIDL	A/V^3	0	–	–	Width dependence	2
424	PLWAGIDL	A/V^3	0	–	–	Length times width dependence	2
425	AGIDLD	A/V^3	0	0	–	GIDL pre-factor for drain side	0
426	AGIDLDW	A/V^3	0	–	–	Width dependence	1

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No.	Name	Unit	Default	Min.	Max.	Description	Geo.
427	POAGIDLD	A/V ³	0	–	–	Geometry independent part	2
428	PLAGIDLD	A/V ³	0	–	–	Length dependence of	2
429	PWAGIDLD	A/V ³	0	–	–	Width dependence of	2
430	PLWAGIDLD	A/V ³	0	–	–	Length times width dependence	2
431	BGIDL	V	41	0	–	GIDL probability factor at TR	0
432	BGIDLO	V	41	–	–	Geometry independent part	1
433	POBGIDL	V	41	–	–	Geometry independent part	2
434	BGIDLD	V	41	0	–	GIDL probability factor at TR for drain side	0
435	BGIDLDO	V	41	–	–	Geometry independent part	1
436	POBGIDLD	V	41	–	–	Geometry independent part	2
437	STBGIDL	V/K	0	–	–	Temperature dependence of BGIDL	0
438	STBGIDLO	V/K	0	–	–	Geometry independent part	1
439	POSTBGIDL	V/K	0	–	–	Geometry independent part	2
440	STBGIDLD	V/K	0	–	–	Temperature dependence of BGIDL for drain side	0
441	STBGIDLDO	V/K	0	–	–	Geometry independent part	1
442	POSTBGIDLD	V/K	0	–	–	Geometry independent part	2
443	CGIDL	–	0	–	–	Back-bias dependence of GIDL	0
444	CGIDLO	–	0	–	–	Geometry independent part	1
445	POCGIDL	–	0	–	–	Geometry independent part	2
446	CGIDLD	–	0	–	–	Back-bias dependence of GIDL for drain side	0
447	CGIDLDO	–	0	–	–	Geometry independent part	1
448	POCGIDLD	–	0	–	–	Geometry independent part	2
Charge Model Parameters							
449	COX	F	10 ⁻¹⁴	0	–	Oxide capacitance for intrinsic channel	0
450	POCOX	F	10 ⁻¹⁴	–	–	Geometry independent part	2
451	PLCOX	F	0	–	–	Length dependence	2
452	PWCOX	F	0	–	–	Width dependence	2
453	PLWCOX	F	0	–	–	Length times width dependence	2
454	CGOV	F	10 ⁻¹⁵	0	–	Oxide capacitance for gate-drain/source overlap	0

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No.	Name	Unit	Default	Min.	Max.	Description	Geo.
455	POCGOV	F	10^{-15}	—	—	Geometry independent part	2
456	PLCGOV	F	0	—	—	Length dependence	2
457	PWCGOV	F	0	—	—	Width dependence	2
458	PLWCGOV	F	0	—	—	Length times width dependence	2
459	CGOVD	F	10^{-15}	0	—	Oxide capacitance for gate–drain/source overlap for drain side	0
460	POCGOVD	F	10^{-15}	—	—	Geometry independent part	2
461	PLCGOVD	F	0	—	—	Length dependence	2
462	PWCGOVD	F	0	—	—	Width dependence	2
463	PLWCGOVD	F	0	—	—	Length times width dependence	2
464	CGBOV	F	0	0	—	Oxide capacitance for gate–bulk overlap	0
465	CGBOVL	F	0	—	—	Oxide capacitance for gate–bulk overlap for a channel length of L_{EN}	1
466	POCGBOV	F	0	—	—	Geometry independent part	2
467	PLCGBOV	F	0	—	—	Length dependence	2
468	PWCGBOV	F	0	—	—	Width dependence	2
469	PLWCGBOV	F	0	—	—	Length times width dependence	2
470	CFR	F	0	0	—	Outer fringe capacitance	0
471	CFRW	F	0	—	—	Outer fringe capacitance for a channel width of W_{EN}	1
472	POCFR	F	0	—	—	Geometry independent part	2
473	PLCFR	F	0	—	—	Length dependence	2
474	PWCFR	F	0	—	—	Width dependence	2
475	PLWCFR	F	0	—	—	Length times width dependence	2
476	CFRD	F	0	0	—	Outer fringe capacitance for drain side	0
477	CFRDW	F	0	—	—	Outer fringe capacitance for a channel width of W_{EN} for drain side	1
478	POCFRD	F	0	—	—	Geometry independent part	2
479	PLCFRD	F	0	—	—	Length dependence	2
480	PWCFRD	F	0	—	—	Width dependence	2
481	PLWCFRD	F	0	—	—	Length times width dependence	2
Noise Model Parameters							
482	FNT	—	1	0	—	Thermal noise coefficient	0
483	FNTO	—	1	—	—	Geometry independent part	1

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No.	Name	Unit	Default	Min.	Max.	Description	Geo.
484	POFNT	–	1	–	–	Geometry independent part	2
485	FNTEXC	–	0	0	–	Excess noise coefficient	0
486	FNTEXCL	–	0	0	–	Length-dependence of excess noise	1
487	POFNTEXC	–	0	–	–	Geometry independent part	2
488	PLFNTEXC	–	0	–	–	Length dependence	2
489	PWFNTEXC	–	0	–	–	Width dependence	2
490	PLWFNTEXC	–	0	–	–	Length times width dependence	2
491	NFA	V^{-1}/m^4	$8 \cdot 10^{22}$	0	–	First coefficient of flicker noise	0
492	NFALW	V^{-1}/m^4	$8 \cdot 10^{22}$	–	–	First coefficient of flicker noise for a channel area of $W_{EN} \cdot L_{EN}$	1
493	PONFA	V^{-1}/m^4	$8 \cdot 10^{22}$	–	–	Geometry independent part	2
494	PLNFA	V^{-1}/m^4	0	–	–	Length dependence	2
495	PWNFA	V^{-1}/m^4	0	–	–	Width dependence	2
496	PLWNFA	V^{-1}/m^4	0	–	–	Length times width dependence	2
497	NFB	V^{-1}/m^2	$3 \cdot 10^7$	0	–	Second coefficient of flicker noise	0
498	NFBLW	V^{-1}/m^2	$3 \cdot 10^7$	–	–	Second coefficient of flicker noise for a channel area of $W_{EN} \cdot L_{EN}$	1
499	PONFB	V^{-1}/m^2	$3 \cdot 10^7$	–	–	Geometry independent part	2
500	PLNFB	V^{-1}/m^2	0	–	–	Length dependence	2
501	PWNFB	V^{-1}/m^2	0	–	–	Width dependence	2
502	PLWNFB	V^{-1}/m^2	0	–	–	Length times width dependence	2
503	NFC	V^{-1}	0	0	–	Third coefficient of flicker noise	0
504	NFCLW	V^{-1}	0	–	–	Third coefficient of flicker noise for a channel area of $W_{EN} \cdot L_{EN}$	1
505	PONFC	V^{-1}	0	–	–	Geometry independent part	2
506	PLNFC	V^{-1}	0	–	–	Length dependence	2
507	PWNFC	V^{-1}	0	–	–	Width dependence	2
508	PLWNFC	V^{-1}	0	–	–	Length times width dependence	2
509	EF	–	1	0	–	Flicker noise frequency exponent	0
510	EFO	–	1	–	–	Geometry independent part	1
511	POEF	–	1	–	–	Geometry independent part	2
512	LINTNOI	m	0	–	–	Length offset for flicker noise	1
513	ALPNOI	–	2	–	–	Exponent for length offset	1
Edge Transistor Model Parameters							
514	WEDGE	m	10^{-8}	0	–	Electrical width of edge transistor per side	1

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No.	Name	Unit	Default	Min.	Max.	Description	Geo.
515	WEDGEW	m	0	0	—	Main transistor width dependence of WEDGE	1
516	VFEDGE	V	−1	—	—	Flat band voltage of edge transistor at TR	0
517	VFEDGE0	V	−1	—	—	Geometry independent part	1
518	POVFEDGE	V	−1	—	—	Geometry independent part	2
519	STVFEDGE	V/K	$5 \cdot 10^{-4}$	—	—	Temperature dependence of VFEDGE	0
520	STVFEDGE0	V/K	$5 \cdot 10^{-4}$	—	—	Geometry independent part	1
521	STVFEDGE L	V/K	0	—	—	Length dependence	1
522	STVFEDGEW	V/K	0	—	—	Width dependence	1
523	STVFEDGE L W	V/K	0	—	—	Area dependence	1
524	POSTVFEDGE	V/K	$5 \cdot 10^{-4}$	—	—	Geometry independent part	2
525	PLSTVFEDGE	V/K	0	—	—	Length dependence	2
526	PWSTVFEDGE	V/K	0	—	—	Width dependence	2
527	PLWSTVFEDGE	V/K	0	—	—	Length times width dependence	2
528	DPHIBEDGE	V	0	—	—	Offset of φ_B for edge transistor	0
529	DPHIBEDGE0	V	0	—	—	Geometry independent part	1
530	DPHIBEDGE L	V	0	—	—	Length dependence	1
531	DPHIBEDGE L EXP	—	1	—	—	Exponent for length dependence	1
532	DPHIBEDGEW	—	0	—	—	Width dependence	1
533	DPHIBEDGE L W	—	0	—	—	Area dependence	1
534	PODPHIBEDGE	V	0	—	—	Geometry independent part	2
535	PLDPHIBEDGE	V	0	—	—	Length dependence	2
536	PWDPHIBEDGE	V	0	—	—	Width dependence	2
537	PLWDPHIBEDGE	V	0	—	—	Length times width dependence	2
538	NEFFEDGE	m^{-3}	$5 \cdot 10^{23}$	10^{20}	10^{26}	Effective substrate doping of edge transistor	0
539	NSUBEDGE0	m^{-3}	$5 \cdot 10^{23}$	10^{20}	—	Geometry independent substrate doping	1
540	NSUBEDGE L	—	0	—	—	Length dependence	1
541	NSUBEDGE L EXP	—	1	—	—	Exponent for length dependence	1
542	NSUBEDGEW	—	0	—	—	Width dependence of edge transistor substrate doping	1
543	NSUBEDGE L W	—	0	—	—	Area dependence	1
544	PONEFFEDGE	m^{-3}	$5 \cdot 10^{23}$	—	—	Geometry independent part	2
545	PLNEFFEDGE	m^{-3}	0	—	—	Length dependence	2
546	PWNEFFEDGE	m^{-3}	0	—	—	Width dependence	2
547	PLWNEFFEDGE	m^{-3}	0	—	—	Length times width dependence	2

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No.	Name	Unit	Default	Min.	Max.	Description	Geo.
548	CTEDGE	–	0	0	–	Interface states factor of edge transistor	0
549	CTEDGE0	–	0	–	–	Geometry-independent part	1
550	CTEDGEL	–	0	–	–	Length dependence	1
551	CTEDGELEXP	–	1	–	–	Exponent for length dependence	1
552	POCTEDGE	–	0	–	–	Geometry independent part	2
553	PLCTEDGE	–	0	–	–	Length dependence	2
554	PWCTEDGE	–	0	–	–	Width dependence	2
555	PLWCTEDGE	–	0	–	–	Length times width dependence	2
556	BETNEDGE	m ² /V/s	5 · 10 ⁻⁴	0	–	Product of channel aspect ratio and zero-field mobility of edge transistor at TR	0
557	FBETEDGE	–	0	–	–	Length dependence	1
558	LPEDGE	m	10 ⁻⁸	10 ⁻¹⁰	–	Exponent for length dependence	1
559	BETEDGEW	–	0	–	–	Width scaling coefficient	1
560	POBETNEDGE	m ² /V/s	5 · 10 ⁻⁴	–	–	Geometry independent part	2
561	PLBETNEDGE	m ² /V/s	0	–	–	Length dependence	2
562	PWBETNEDGE	m ² /V/s	0	–	–	Width dependence	2
563	PLWBETNEDGE	m ² /V/s	0	–	–	Length times width dependence	2
564	STBETEDGE	–	1	–	–	Temperature dependence of BETNEDGE	0
565	STBETEDGE0	–	1	–	–	Geometry independent part	1
566	STBETEDGEL	–	0	–	–	Length dependence	1
567	STBETEDGEW	–	0	–	–	Width dependence	1
568	STBETEDGELW	–	0	–	–	Area dependence	1
569	POSTBETEDGE	–	1	–	–	Geometry independent part	2
570	PLSTBETEDGE	–	0	–	–	Length dependence	2
571	PWSTBETEDGE	–	0	–	–	Width dependence	2
572	PLWSTBETEDGE	–	0	–	–	Length times width dependence	2
573	PSCEEDGE	–	0	0	–	Subthreshold slope coefficient for short channel edge transistor	0
574	PSCEEDGEL	–	0	–	–	Length dependence	1
575	PSCEEDGELEXP	–	2	–	–	Exponent for length dependence	1
576	PSCEEDGEW	–	0	–	–	Width dependence	1
577	POPSCEEDGE	–	0	–	–	Geometry independent part	2
578	PLPSCEEDGE	–	0	–	–	Length dependence	2
579	PWPSCEEDGE	–	0	–	–	Width dependence	2
580	PLWPSCEEDGE	–	0	–	–	Length times width dependence	2
581	PSCEBEDGE	V ⁻¹	0	0	1	Back-bias dependence of PSCEEDGE	0

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No.	Name	Unit	Default	Min.	Max.	Description	Geo.
582	PSCEBEDGEO	V ⁻¹	0	–	–	Geometry independent part	1
583	POPSCEBEDGE	V ⁻¹	0	–	–	Geometry independent part	2
584	PSCEDEDGE	V ⁻¹	0	0	–	Drain voltage dependence of PSCEEDGE	0
585	PSCEDEDGEO	V ⁻¹	0	–	–	Geometry independent part	1
586	POPSCEDEDGE	V ⁻¹	0	–	–	Geometry independent part	2
587	CFEDGE	–	0	0	–	DIBL parameter of edge transistor	0
588	CFEDGEL	–	0	–	–	Length dependence	1
589	CFEDGELEXP	–	2	–	–	Exponent for length dependence	1
590	CFEDGEW	–	0	–	–	Width dependence	1
591	POCFEDGE	–	0	–	–	Geometry independent part	2
592	PLCFEDGE	–	0	–	–	Length dependence	2
593	PWCFEDGE	–	0	–	–	Width dependence	2
594	PLWCFEDGE	–	0	–	–	Length times width dependence	2
595	CFBEDGE	V ⁻¹	0	0	1	Back-bias dependence of CFEDGE	0
596	CFBEDGEO	V ⁻¹	0	–	–	Geometry independent part	1
597	POCFBEDGE	V ⁻¹	0	–	–	Geometry independent part	2
598	CFDEDGE	V ⁻¹	0	0	–	Drain voltage dependence of CFEDGE	0
599	CFDEDGEO	V ⁻¹	0	–	–	Geometry independent part	1
600	POCFDEDGE	V ⁻¹	0	–	–	Geometry independent part	2
601	FNTEDGE	–	1	0	–	Thermal noise coefficient of edge transistor	0
602	FNTEDGEO	–	1	–	–	Geometry independent part	1
603	POFNTEDGE	–	1	–	–	Geometry independent part	2
604	NFAEDGE	V ⁻¹ /m ⁴	8 · 10 ²²	0	–	First coefficient of flicker noise of edge transistor	0
605	NFAEDGELW	V ⁻¹ /m ⁴	8 · 10 ²²	–	–	Area dependence	1
606	PONFAEDGE	V ⁻¹ /m ⁴	8 · 10 ²²	–	–	Geometry independent part	2
607	PLNFAEDGE	V ⁻¹ /m ⁴	0	–	–	Length dependence	2
608	PWNFAEDGE	V ⁻¹ /m ⁴	0	–	–	Width dependence	2
609	PLWNFAEDGE	V ⁻¹ /m ⁴	0	–	–	Length times width dependence	2
610	NFBEDGE	V ⁻¹ /m ²	3 · 10 ⁷	0	–	Second coefficient of flicker noise of edge transistor	0
611	NFBEDGELW	V ⁻¹ /m ²	3 · 10 ⁷	–	–	Area dependence	1

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No.	Name	Unit	Default	Min.	Max.	Description	Geo.
612	PONFBEDGE	V^{-1}/m^2	$3 \cdot 10^7$	–	–	Geometry independent part	2
613	PLNFBEDGE	V^{-1}/m^2	0	–	–	Length dependence	2
614	PWNFBEDGE	V^{-1}/m^2	0	–	–	Width dependence	2
615	PLWNFBEDGE	V^{-1}/m^2	0	–	–	Length times width dependence	2
616	NFCEDGE	V^{-1}	0	0	–	Third coefficient of flicker noise of edge transistor	0
617	NFCEDGELW	V^{-1}	0	–	–	Area dependence	1
618	PONFCEDGE	V^{-1}	0	–	–	Geometry independent part	2
619	PLNFCEDGE	V^{-1}	0	–	–	Length dependence	2
620	PWNFCEDGE	V^{-1}	0	–	–	Width dependence	2
621	PLWNFCEDGE	V^{-1}	0	–	–	Length times width dependence	2
622	EFEDGE	–	1	0	–	Flicker noise frequency exponent of edge transistor	0
623	EFEDGE0	–	1	–	–	Geometry independent part	1
624	POEFEDGE	–	1	–	–	Geometry independent part	2

2.5.3 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. Some trivial conversion of parameters BSIM→PSP is still necessary, see [2].

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

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

2.5.4 Parameters for well proximity effect model

The WPE model of BSIM4.5.0 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 parameter **K2WE** is not available in PSP. Except for some trivial conversion of parameters BSIM→PSP [2], WPE parameters from BSIM can be used directly in PSP. The WPE parameters have both geometrical and binning rules included as explained in Section 3.6.2. The last column—labeled ‘**Geo.**’—shows for which value of **SWGEO** the parameter is used.

No.	Name	Unit	Default	Min.	Max.	Description	Geo.
0	SCREF	m	$1 \cdot 10^{-6}$	0	—	Distance between OD-edge and well edge of a reference device	1, 2
1	WEB	—	0	—	—	Coefficient for SCB	1, 2
2	WEC	—	0	—	—	Coefficient for SCC	1, 2
3	KVTHOWEO	—	0	—	—	Geometry independent threshold shift parameter	1
4	KVTHOWEL	—	0	—	—	Length dependence	1
5	KVTHOWEW	—	0	—	—	Width dependence	1
6	KVTHOWELW	—	0	—	—	Area dependence	1
7	POKVTHOWE	—	0	—	—	Geometry independent part of threshold shift parameter	2
8	PLKVTHOWE	—	0	—	—	Length dependence	2
9	PWKVTHOWE	—	0	—	—	Width dependence	2
10	PLWKVTHOWE	—	0	—	—	Length times width dependence	2
11	KUOWEO	—	0	—	—	Geometry independent mobility degradation factor	1
12	KUOWEL	—	0	—	—	Length dependence	1
13	KUOWEW	—	0	—	—	Width dependence	1
14	KUOWELW	—	0	—	—	Area dependence	1
15	POKUOWE	—	0	—	—	Geometry independent part of mobility degradation factor	2
16	PLKUOWE	—	0	—	—	Length dependence	2
17	PWKUOWE	—	0	—	—	Width dependence	2
18	PLWKUOWE	—	0	—	—	Length times width dependence	2

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

The JUNCAP2 parameters are part of both the global and the local parameter sets. The last column of **Asym.** shows for which value of **SWJUNASYM** the listed parameter is enabled: i.e., when **SWJUNASYM** = 0, parameters No. 3-45 are used for both source-bulk and drain-bulk junctions and parameters No. 46-88 are ignored; when **SWJUNASYM** = 1, parameters No. 3-45 are used for source-bulk junction and No. 46-88 are used for drain-bulk junction; parameters No. 0-2 are used in both situations.

No.	Name	Unit	Default	Min.	Max.	Description	Asym.
0	TRJ	°C	21	T_{\min}	—	Reference temperature	0, 1
1	SWJUNEXP	—	0	0	1	Flag for JUNCAP2 Express; 0 ↔ full JUNCAP2 model, 1 ↔ Express model	0, 1
2	IMAX	A	10^3	10^{-12}	—	Maximum current up to which forward current behaves exponentially	0, 1
3	FREV	—	10^3	10^3	10^{10}	Coefficient for reverse breakdown current limitation	0, 1
Capacitance Parameters							
4	CJORBOT	F/m ²	10^{-3}	10^{-12}	—	Zero-bias capacitance per unit-of-area of bottom component for source-bulk junction	0, 1
5	CJORSTI	F/m	10^{-9}	10^{-18}	—	Zero-bias capacitance per unit-of-length of STI-edge component for source-bulk junction	0, 1
6	CJORGAT	F/m	10^{-9}	10^{-18}	—	Zero-bias capacitance per unit-of-length of gate-edge component for source-bulk junction	0, 1
7	VBIRBOT	V	1	$V_{\text{bi,low}}$	—	Built-in voltage at the reference temperature of bottom component for source-bulk junction	0, 1
8	VBIRSTI	V	1	$V_{\text{bi,low}}$	—	Built-in voltage at the reference temperature of STI-edge component for source-bulk junction	0, 1
9	VBIRGAT	V	1	$V_{\text{bi,low}}$	—	Built-in voltage at the reference temperature of gate-edge component for source-bulk junction	0, 1
10	PBOT	—	0.5	0.05	0.95	Grading coefficient of bottom component for source-bulk junction	0, 1
11	PSTI	—	0.5	0.05	0.95	Grading coefficient of STI-edge component for source-bulk junction	0, 1
12	PGAT	—	0.5	0.05	0.95	Grading coefficient of gate-edge component for source-bulk junction	0, 1

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No.	Name	Unit	Default	Min.	Max.	Description	Asym.
Ideal-current Parameters							
13	PHIGBOT	V	1.16	—	—	Zero-temperature bandgap voltage of bottom component for source-bulk junction	0, 1
14	PHIGSTI	V	1.16	—	—	Zero-temperature bandgap voltage of STI-edge component for source-bulk junction	0, 1
15	PHIGGAT	V	1.16	—	—	Zero-temperature bandgap voltage of gate-edge component for source-bulk junction	0, 1
16	IDSATRBOT	A/m ²	10 ⁻¹²	0	—	Saturation current density at the reference temperature of bottom component for source-bulk junction	0, 1
17	IDSATRSTI	A/m	10 ⁻¹⁸	0	—	Saturation current density at the reference temperature of STI-edge component for source-bulk junction	0, 1
18	IDSATRGAT	A/m	10 ⁻¹⁸	0	—	Saturation current density at the reference temperature of gate-edge component for source-bulk junction	0, 1
Shockley-Read-Hall Parameters							
19	CSRHBOT	A/m ³	10 ²	0	—	Shockley-Read-Hall prefactor of bottom component for source-bulk junction	0, 1
20	CSRHSTI	A/m ²	10 ⁻⁴	0	—	Shockley-Read-Hall prefactor of STI-edge component for source-bulk junction	0, 1
21	CSRHGAT	A/m ²	10 ⁻⁴	0	—	Shockley-Read-Hall prefactor of gate-edge component for source-bulk junction	0, 1
22	XJUNSTI	m	10 ⁻⁷	10 ⁻⁹	—	Junction depth of STI-edge component for source-bulk junction	0, 1
23	XJUNGAT	m	10 ⁻⁷	10 ⁻⁹	—	Junction depth of gate-edge component for source-bulk junction	0, 1
Trap-assisted Tunneling Parameters							
24	CTATBOT	A/m ³	10 ²	0	—	Trap-assisted tunneling prefactor of bottom component for source-bulk junction	0, 1
25	CTATSTI	A/m ²	10 ⁻⁴	0	—	Trap-assisted tunneling prefactor of STI-edge component for source-bulk junction	0, 1

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No.	Name	Unit	Default	Min.	Max.	Description	Asym.
26	CTATGAT	A/m ²	10 ⁻⁴	0	–	Trap-assisted tunneling prefactor of gate-edge component for source-bulk junction	0, 1
27	MEFFTATBOT	–	0.25	.01	–	Effective mass (in units of m_0) for trap-assisted tunneling of bottom component for source-bulk junction	0, 1
28	MEFFTATSTI	–	0.25	.01	–	Effective mass (in units of m_0) for trap-assisted tunneling of STI-edge component for source-bulk junction	0, 1
29	MEFFTATGAT	–	0.25	.01	–	Effective mass (in units of m_0) for trap-assisted tunneling of gate-edge component for source-bulk junction	0, 1
Band-to-band Tunneling Parameters							
30	CBBTBOT	AV ⁻³	10 ⁻¹²	0	–	Band-to-band tunneling prefactor of bottom component for source-bulk junction	0, 1
31	CBBTSTI	AV ⁻³ m	10 ⁻¹⁸	0	–	Band-to-band tunneling prefactor of STI-edge component for source-bulk junction	0, 1
32	CBBTGAT	AV ⁻³ m	10 ⁻¹⁸	0	–	Band-to-band tunneling prefactor of gate-edge component for source-bulk junction	0, 1
33	FBBTBOT	Vm ⁻¹	10 ⁹	–	–	Normalization field at the reference temperature for band-to-band tunneling of bottom component for source-bulk junction	0, 1
34	FBBTSTI	Vm ⁻¹	10 ⁹	–	–	Normalization field at the reference temperature for band-to-band tunneling of STI-edge component for source-bulk junction	0, 1
35	FBBTGAT	Vm ⁻¹	10 ⁹	–	–	Normalization field at the reference temperature for band-to-band tunneling of gate-edge component for source-bulk junction	0, 1
36	STFBTBOT	K ⁻¹	– 10 ⁻³	–	–	Temperature scaling parameter for band-to-band tunneling of bottom component for source-bulk junction	0, 1
37	STFBTSTI	K ⁻¹	– 10 ⁻³	–	–	Temperature scaling parameter for band-to-band tunneling of STI-edge component for source-bulk junction	0, 1

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No.	Name	Unit	Default	Min.	Max.	Description	Asym.
38	STFBBTGAT	K ⁻¹	– 10 ⁻³	–	–	Temperature scaling parameter for band-to-band tunneling of gate-edge component for source-bulk junction	0, 1
Avalanche and Breakdown Parameters							
39	VBRBOT	V	10	0.1	–	Breakdown voltage of bottom component for source-bulk junction	0, 1
40	VBRSTI	V	10	0.1	–	Breakdown voltage of STI-edge component for source-bulk junction	0, 1
41	VBRGAT	V	10	0.1	–	Breakdown voltage of gate-edge component for source-bulk junction	0, 1
42	PBRBOT	V	4	0.1	–	Breakdown onset tuning parameter of bottom component for source-bulk junction	0, 1
43	PBRSTI	V	4	0.1	–	Breakdown onset tuning parameter of STI-edge component for source-bulk junction	0, 1
44	PBRGAT	V	4	0.1	–	Breakdown onset tuning parameter of gate-edge component for source-bulk junction	0, 1
JUNCAP Express Parameters							
45	VJUNREF	V	2.5	0.5	–	Typical maximum source-bulk junction voltage; usually about $2 \cdot V_{\text{sup}}$	0, 1
46	FJUNQ	V	0.03	0	–	Fraction below which source-bulk junction capacitance components are neglected	0, 1
Capacitance Parameters							
47	CJORBOTD	F/m ²	10 ⁻³	10 ⁻¹²	–	Zero-bias capacitance per unit-of-area of bottom component for drain-bulk junction	1
48	CJORSTID	F/m	10 ⁻⁹	10 ⁻¹⁸	–	Zero-bias capacitance per unit-of-length of STI-edge component for drain-bulk junction	1
49	CJORGATD	F/m	10 ⁻⁹	10 ⁻¹⁸	–	Zero-bias capacitance per unit-of-length of gate-edge component for drain-bulk junction	1
50	VBIRBOTD	V	1	$V_{\text{bi,low}}$	–	Built-in voltage at the reference temperature of bottom component for drain-bulk junction	1
51	VBIRSTID	V	1	$V_{\text{bi,low}}$	–	Built-in voltage at the reference temperature of STI-edge component for drain-bulk junction	1

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No.	Name	Unit	Default	Min.	Max.	Description	Asym.
52	VBIRGATD	V	1	$V_{bi,low}$	—	Built-in voltage at the reference temperature of gate-edge component for drain-bulk junction	1
53	PBOTD	—	0.5	0.05	0.95	Grading coefficient of bottom component for drain-bulk junction	1
54	PSTID	—	0.5	0.05	0.95	Grading coefficient of STI-edge component for drain-bulk junction	1
55	PGATD	—	0.5	0.05	0.95	Grading coefficient of gate-edge component for drain-bulk junction	1
Ideal-current Parameters							
56	PHIGBOTD	V	1.16	—	—	Zero-temperature bandgap voltage of bottom component for drain-bulk junction	1
57	PHIGSTID	V	1.16	—	—	Zero-temperature bandgap voltage of STI-edge component for drain-bulk junction	1
58	PHIGGATD	V	1.16	—	—	Zero-temperature bandgap voltage of gate-edge component for drain-bulk junction	1
59	IDSATRBOTD	A/m ²	10 ⁻¹²	0	—	Saturation current density at the reference temperature of bottom component for drain-bulk junction	1
60	IDSATRSTID	A/m	10 ⁻¹⁸	0	—	Saturation current density at the reference temperature of STI-edge component for drain-bulk junction	1
61	IDSATRGATD	A/m	10 ⁻¹⁸	0	—	Saturation current density at the reference temperature of gate-edge component for drain-bulk junction	1
Shockley-Read-Hall Parameters							
62	CSRHBOTD	A/m ³	10 ²	0	—	Shockley-Read-Hall prefactor of bottom component for drain-bulk junction	1
63	CSRHSTID	A/m ²	10 ⁻⁴	0	—	Shockley-Read-Hall prefactor of STI-edge component for drain-bulk junction	1
64	CSRHGATD	A/m ²	10 ⁻⁴	0	—	Shockley-Read-Hall prefactor of gate-edge component for drain-bulk junction	1
65	XJUNSTID	m	10 ⁻⁷	10 ⁻⁹	—	Junction depth of STI-edge component for drain-bulk junction	1
66	XJUNGATD	m	10 ⁻⁷	10 ⁻⁹	—	Junction depth of gate-edge component for drain-bulk junction	1
Trap-assisted Tunneling Parameters							

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No.	Name	Unit	Default	Min.	Max.	Description	Asym.
67	CTATBOTD	A/m ³	10 ²	0	–	Trap-assisted tunneling prefactor of bottom component for drain-bulk junction	1
68	CTATSTID	A/m ²	10 ⁻⁴	0	–	Trap-assisted tunneling prefactor of STI-edge component for drain-bulk junction	1
69	CTATGATD	A/m ²	10 ⁻⁴	0	–	Trap-assisted tunneling prefactor of gate-edge component for drain-bulk junction	1
70	MEFFTATBOTD	–	0.25	.01	–	Effective mass (in units of m_0) for trap-assisted tunneling of bottom component for drain-bulk junction	1
71	MEFFTATSTID	–	0.25	.01	–	Effective mass (in units of m_0) for trap-assisted tunneling of STI-edge component for drain-bulk junction	1
72	MEFFTATGATD	–	0.25	.01	–	Effective mass (in units of m_0) for trap-assisted tunneling of gate-edge component for drain-bulk junction	1
Band-to-band Tunneling Parameters							
73	CBBTBOTD	AV ⁻³	10 ⁻¹²	0	–	Band-to-band tunneling prefactor of bottom component for drain-bulk junction	1
74	CBBTSTID	AV ⁻³ m	10 ⁻¹⁸	0	–	Band-to-band tunneling prefactor of STI-edge component for drain-bulk junction	1
75	CBBTGATD	AV ⁻³ m	10 ⁻¹⁸	0	–	Band-to-band tunneling prefactor of gate-edge component for drain-bulk junction	1
76	FBBTBOTD	Vm ⁻¹	10 ⁹	–	–	Normalization field at the reference temperature for band-to-band tunneling of bottom component for drain-bulk junction	1
77	FBBTSTID	Vm ⁻¹	10 ⁹	–	–	Normalization field at the reference temperature for band-to-band tunneling of STI-edge component for drain-bulk junction	1
78	FBBTGATD	Vm ⁻¹	10 ⁹	–	–	Normalization field at the reference temperature for band-to-band tunneling of gate-edge component for drain-bulk junction	1
79	STFBTBOTD	K ⁻¹	– 10 ⁻³	–	–	Temperature scaling parameter for band-to-band tunneling of bottom component for drain-bulk junction	1
80	STFBTSTID	K ⁻¹	– 10 ⁻³	–	–	Temperature scaling parameter for band-to-band tunneling of STI-edge component for drain-bulk junction	1

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No.	Name	Unit	Default	Min.	Max.	Description	Asym.
81	STFBBTGATD	K ⁻¹	– 10 ⁻³	–	–	Temperature scaling parameter for band-to-band tunneling of gate-edge component for drain-bulk junction	1
Avalanche and Breakdown Parameters							
82	VBRBOTD	V	10	0.1	–	Breakdown voltage of bottom component for drain-bulk junction	1
83	VBRSTID	V	10	0.1	–	Breakdown voltage of STI-edge component for drain-bulk junction	1
84	VBRGATD	V	10	0.1	–	Breakdown voltage of gate-edge component for drain-bulk junction	1
85	PBRBOTD	V	4	0.1	–	Breakdown onset tuning parameter of bottom component for drain-bulk junction	1
86	PBRSTID	V	4	0.1	–	Breakdown onset tuning parameter of STI-edge component for drain-bulk junction	1
87	PBRGATD	V	4	0.1	–	Breakdown onset tuning parameter of gate-edge component for drain-bulk junction	1
JUNCAP Express Parameters							
88	VJUNREFD	V	2.5	0.5	–	Typical maximum drain-bulk junction voltage; usually about $2 \cdot V_{\text{sup}}$	1
89	FJUNQD	V	0.03	0	–	Fraction below which drain-bulk junction capacitance components are neglected	1

2.5.6 Parameters for parasitic resistances

The parameters for parasitic resistances are listed in the table below. The last column—labeled ‘Geo.’—shows for which value of **SWGEO** the parameter is used.

No.	Name	Unit	Default	Min.	Max.	Description	Geo.
0	RG	Ω	0	0	–	Gate resistance R_{gate}	0
1	RGO	Ω	0	–	–	Gate resistance R_{gate}	1, 2
2	RINT	$\Omega \cdot m^2$	0	0	–	Contact resistance between silicide and ploy	1, 2
3	RVPOLY	$\Omega \cdot m^2$	0	0	–	Vertical poly resistance	1, 2
4	RSHG	Ω/\square	0	0	–	Gate electrode diffusion sheet resistance	1, 2
5	DLSIL	m	0	–	–	Silicide extension over the physical gate length	1, 2
6	RSE	Ω	0	0	–	External source resistance	0
7	RDE	Ω	0	0	–	External drain resistance	0
8	RSH	Ω/\square	0	–	–	Sheet resistance of source diffusion	1, 2
9	RSHD	Ω/\square	0	–	–	Sheet resistance of drain diffusion	1, 2
10	RBULK	Ω	0	0	–	Bulk resistance R_{bulk}	0
11	RBULKO	Ω	0	–	–	Bulk resistance R_{bulk}	1, 2
12	RWELL	Ω	0	0	–	Well resistance R_{well}	0
13	RWELLO	Ω	0	–	–	Well resistance R_{well}	1, 2
14	RJUNS	Ω	0	0	–	Source-side bulk resistance R_{juns}	0
15	RJUNSO	Ω	0	–	–	Source-side bulk resistance R_{juns}	1, 2
16	RJUND	Ω	0	0	–	Drain-side bulk resistance R_{jund}	0
17	RJUNDO	Ω	0	–	–	Drain-side bulk resistance R_{jund}	1, 2

2.5.7 Parameters for self heating

The parameters for self heating are listed below. They are only available in the self heating version of the model. The last column—labeled ‘Geo.’—shows for which value of **SWGEO** the parameter is used.

No.	Name	Unit	Default	Min.	Max.	Description	Geo.
0	RTH	K/W	0	0	–	Thermal resistance	0
1	RTHO	K/W	0	–	–	Geometry independent part	1, 2
2	RTHW1	K/W	0	–	–	Width dependence	1, 2
3	RTHW2	–	0	–	–	Offset in width dependence	1, 2
4	RTHLW	–	0	–	–	Length-correction to width dependence	1, 2
5	CTH	J/K	0	0	–	Thermal capacitance	0
6	CTHO	J/K	0	–	–	Geometry independent part	1, 2
7	CTHW1	J/K	0	–	–	Width dependence	1, 2
8	CTHW2	–	0	–	–	Offset in width dependence	1, 2
9	CTHLW	–	0	–	–	Length-correction to width dependence	1, 2
10	STRTH	–	0	–	–	Temperature sensitivity of RTH	0
11	STRTHO	–	0	–	–	Geometry independent part	1, 2

2.5.8 Parameters for NQS

The parameters for non-quasi-static effects are listed below. They are only available in the NQS-version of the model. The last column—labeled ‘**Geo.**’—shows for which value of **SWGEO** the parameter is used.

No.	Name	Unit	Default	Min.	Max.	Description	Geo.
0	SWNQS	–	0	0	9	Switch for NQS effects / number of collocation points	0, 1, 2
1	MUNQS	–	1	0	–	Relative mobility for NQS modeling	0
2	MUNQSO	–	1	–	–	Relative mobility for NQS modeling	1, 2

Section 3

Geometry dependence and Other effects

3.1 Introduction

The physical geometry scaling rules of PSP (Section 3.2) 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 3.3) 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.

Stress and well proximity effects are included in PSP. Use of the stress model (Section 3.5) and/or well proximity effect model (Section 3.6) leads to modification of some of the local parameters calculated from the geometrical or binning scaling rules.

3.2 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 2.5.2.
- The geometrical scaling equations are *only* calculated when **SWGEO** = 1.

Effective length and width

$$W_f = \frac{W}{\mathbf{NF}} \quad (3.1)$$

$$W_f = \frac{W}{\mathbf{NF}} \quad (3.2)$$

$$L_{\text{EN}} = 10^{-6} \quad (3.3)$$

$$W_{\text{EN}} = 10^{-6} \quad (3.4)$$

$$\Delta L_{\text{PS}} = \mathbf{LVARO} \cdot \left(1 + \mathbf{LVARL} \cdot \frac{L_{\text{EN}}}{L}\right) \cdot \left(1 + \mathbf{LVARW} \cdot \frac{W_{\text{EN}}}{W_f}\right) \quad (3.5)$$

$$\Delta W_{\text{OD}} = \mathbf{WVARO} \cdot \left(1 + \mathbf{WVARL} \cdot \frac{L_{\text{EN}}}{L}\right) \cdot \left(1 + \mathbf{WVARW} \cdot \frac{W_{\text{EN}}}{W_f}\right) \quad (3.6)$$

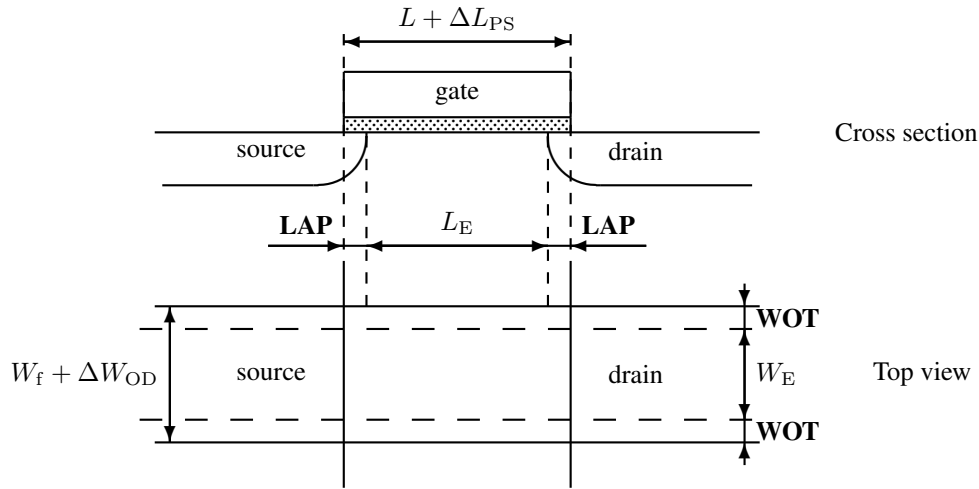


Figure 3.1: Specification of the dimensions of a MOS transistor

$$L_E = L - \Delta L = L + \Delta L_{PS} - 2 \cdot \mathbf{LAP} \quad (3.7)$$

$$W_E = W_f - \Delta W = W_f + \Delta W_{OD} - 2 \cdot \mathbf{WOT} \quad (3.8)$$

$$L_{E,CV} = L + \Delta L_{PS} - 2 \cdot \mathbf{LAP} + \mathbf{DLQ} \quad (3.9)$$

$$W_{E,CV} = W_f + \Delta W_{OD} - 2 \cdot \mathbf{WOT} + \mathbf{DWQ} \quad (3.10)$$

$$L_{G,CV} = L + \Delta L_{PS} + \mathbf{DLQ} \quad (3.11)$$

$$W_{G,CV} = W_f + \Delta W_{OD} + \mathbf{DWQ} \quad (3.12)$$

Note: If the calculated L_E , W_E , $L_{E,CV}$, $W_{E,CV}$, $L_{G,CV}$, or $W_{G,CV}$ is smaller than 1 nm (10^{-9} m), the value is clipped to this lower bound of 1 nm.

Process Parameters

$$\mathbf{VFB} = \mathbf{VFBO} + \mathbf{VFBL} \cdot \frac{L_{EN}}{L_E} + \mathbf{VFBW} \cdot \frac{W_{EN}}{W_E} + \mathbf{VFBWLW} \cdot \frac{W_{EN} \cdot L_{EN}}{W_E \cdot L_E} \quad (3.13)$$

$$\mathbf{STVFB} = \mathbf{STVFBO} + \mathbf{STVFBL} \cdot \frac{L_{EN}}{L_E} + \mathbf{STVFBW} \cdot \frac{W_{EN}}{W_E} + \mathbf{STVFBWLW} \cdot \frac{W_{EN} \cdot L_{EN}}{W_E \cdot L_E} \quad (3.14)$$

$$\mathbf{ST2VFB} = \mathbf{ST2VFBO} \quad (3.15)$$

$$\mathbf{TOX} = \mathbf{TOXO} \quad (3.16)$$

$$\mathbf{EPSROX} = \mathbf{EPSROXO} \quad (3.17)$$

$$N_{\text{sub0,eff}} = \mathbf{NSUBO} \cdot \text{MAX} \left(\left[1 + \mathbf{NSUBW} \cdot \frac{W_{\text{EN}}}{W_{\text{E}}} \cdot \ln \left(1 + \frac{W_{\text{E}}}{\mathbf{WSEGP}} \right) \right], 10^{-3} \right) \quad (3.18)$$

$$N_{\text{pck,eff}} = \mathbf{NPCK} \cdot \text{MAX} \left(\left[1 + \mathbf{NPCKW} \cdot \frac{W_{\text{EN}}}{W_{\text{E}}} \cdot \ln \left(1 + \frac{W_{\text{E}}}{\mathbf{WSEGP}} \right) \right], 10^{-3} \right) \quad (3.19)$$

$$L_{\text{pck,eff}} = \mathbf{LPCK} \cdot \text{MAX} \left(\left[1 + \mathbf{LPCKW} \cdot \frac{W_{\text{EN}}}{W_{\text{E}}} \cdot \ln \left(1 + \frac{W_{\text{E}}}{\mathbf{WSEGP}} \right) \right], 10^{-3} \right) \quad (3.20)$$

$$a = 7.5 \cdot 10^{10} \quad (3.21)$$

$$b = \sqrt{N_{\text{sub0,eff}} + 0.5 \cdot N_{\text{pck,eff}}} - \sqrt{N_{\text{sub0,eff}}} \quad (3.22)$$

$$N_{\text{sub}} = \begin{cases} N_{\text{sub0,eff}} + N_{\text{pck,eff}} \cdot \left[2 - \frac{L_{\text{E}}}{L_{\text{pck,eff}}} \right] & \text{for } L_{\text{E}} < L_{\text{pck,eff}} \\ N_{\text{sub0,eff}} + N_{\text{pck,eff}} \cdot \frac{L_{\text{pck,eff}}}{L_{\text{E}}} & \text{for } L_{\text{pck,eff}} \leq L_{\text{E}} \leq 2 \cdot L_{\text{pck,eff}} \\ \left[\sqrt{N_{\text{sub0,eff}}} + a \cdot \ln \left(1 + 2 \cdot \frac{L_{\text{pck,eff}}}{L_{\text{E}}} \cdot \left[\exp \left(\frac{b}{a} \right) - 1 \right] \right) \right]^2 & \text{for } L_{\text{E}} > 2 \cdot L_{\text{pck,eff}} \end{cases} \quad (3.23)$$

$$\mathbf{NEFF} = N_{\text{sub}} \cdot \left(1 - \mathbf{FOL1} \cdot \frac{L_{\text{EN}}}{L_{\text{E}}} - \mathbf{FOL2} \cdot \left[\frac{L_{\text{EN}}}{L_{\text{E}}} \right]^2 \right) \quad (3.24)$$

$$\begin{aligned} \mathbf{FACNEFFAC} &= \mathbf{FACNEFFACO} + \mathbf{FACNEFFACL} \cdot \frac{L_{\text{EN}}}{L_{\text{E}}} \\ &+ \mathbf{FACNEFFACW} \cdot \frac{W_{\text{EN}}}{W_{\text{E}}} + \mathbf{FACNEFFACLW} \cdot \frac{L_{\text{EN}} \cdot W_{\text{EN}}}{L_{\text{E}} \cdot W_{\text{E}}} \end{aligned} \quad (3.25)$$

$$\begin{aligned} \mathbf{GFACNUD} &= \mathbf{GFACNUDO} + \mathbf{GFACNUDL} \cdot \left[\frac{L_{\text{EN}}}{L_{\text{E}}} \right]^{\mathbf{GFACNUDEXP}} \\ &+ \mathbf{GFACNUDW} \cdot \frac{W_{\text{EN}}}{W_{\text{E}}} + \mathbf{GFACNUDLW} \cdot \frac{L_{\text{EN}} \cdot W_{\text{EN}}}{L_{\text{E}} \cdot W_{\text{E}}} \end{aligned} \quad (3.26)$$

$$\mathbf{VSBNUD} = \mathbf{VSBNUDO} \quad (3.27)$$

$$\mathbf{DVSBNUD} = \mathbf{DVSBNUDO} \quad (3.28)$$

$$\mathbf{VNSUB} = \mathbf{VNSUBO} \quad (3.29)$$

$$\mathbf{NSLP} = \mathbf{NSLPO} \quad (3.30)$$

$$\mathbf{DNSUB} = \mathbf{DNSUBO} \quad (3.31)$$

$$\begin{aligned} \mathbf{DPHIB} = \mathbf{DPHIBO} + \mathbf{DPHIBL} \cdot \left[\frac{L_{EN}}{L_E} \right]^{\mathbf{DPHIBLEXP}} \\ + \mathbf{DPHIBW} \cdot \frac{W_{EN}}{W_E} + \mathbf{DPHIBLW} \cdot \frac{W_{EN} \cdot L_{EN}}{W_E \cdot L_E} \end{aligned} \quad (3.32)$$

$$\begin{aligned} \mathbf{DELVTAC} = \mathbf{DELVTACO} + \mathbf{DELVTACL} \cdot \left[\frac{L_{EN}}{L_E} \right]^{\mathbf{DELVTACLEXP}} \\ + \mathbf{DELVTACW} \cdot \frac{W_{EN}}{W_E} + \mathbf{DELVTACLW} \cdot \frac{W_{EN} \cdot L_{EN}}{W_E \cdot L_E} \end{aligned} \quad (3.33)$$

$$\mathbf{NP} = \mathbf{NPO} \cdot \text{MAX} \left(10^{-6}, 1 + \mathbf{NPL} \cdot \frac{L_{EN}}{L_E} \right) \quad (3.34)$$

$$\mathbf{TOXOV} = \mathbf{TOXOVO} \quad (3.35)$$

$$\mathbf{TOXOVD} = \mathbf{TOXOVDO} \quad (3.36)$$

$$\mathbf{NOV} = \mathbf{NOVO} \quad (3.37)$$

$$\mathbf{NOVD} = \mathbf{NOVDO} \quad (3.38)$$

Interface States Parameters

$$\begin{aligned} \mathbf{CT} = \left(\mathbf{CTO} + \mathbf{CTL} \cdot \left[\frac{L_{EN}}{L_E} \right]^{\mathbf{CTLEXP}} \right) \cdot \left(1 + \mathbf{CTW} \cdot \frac{W_{EN}}{W_E} \right) \\ \cdot \left(1 + \mathbf{CTLW} \cdot \frac{W_{EN} \cdot L_{EN}}{W_E \cdot L_E} \right) \end{aligned} \quad (3.39)$$

$$\mathbf{CTG} = \mathbf{STGO} \quad (3.40)$$

$$\mathbf{CTB} = \mathbf{CTBO} \quad (3.41)$$

$$\mathbf{STCT} = \mathbf{STCTO} \quad (3.42)$$

DIBL Parameters

$$\mathbf{CF} = \mathbf{CFL} \cdot \left[\frac{L_{EN}}{L_E} \right]^{\mathbf{CFLEXP}} \cdot \left(1 + \mathbf{CFW} \cdot \frac{W_{EN}}{W_E} \right) \quad (3.43)$$

$$\mathbf{CFB} = \mathbf{CFBO} \quad (3.44)$$

$$\mathbf{CFD} = \mathbf{CFDO} \quad (3.45)$$

Subthreshold Slope Parameters

$$\mathbf{PSCE} = \mathbf{PSCEL} \cdot \left[\frac{L_{EN}}{L_E} \right]^{\mathbf{PSCELEXP}} \cdot \left(1 + \mathbf{PSCEW} \cdot \frac{W_{EN}}{W_E} \right) \quad (3.46)$$

$$\mathbf{PSCEB} = \mathbf{PSCEBO} \quad (3.47)$$

$$\mathbf{PSCED} = \mathbf{PSCEDO} \quad (3.48)$$

Mobility Parameters

$$F_{\beta 1, \text{eff}} = \mathbf{FBET1} \cdot \left(1 + \mathbf{FBET1W} \cdot \frac{W_{\text{EN}}}{W_{\text{E}}} \right) \quad (3.49)$$

$$L_{\text{P1,eff}} = \mathbf{LP1} \cdot \text{MAX} \left(\left[1 + \mathbf{LP1W} \cdot \frac{W_{\text{EN}}}{W_{\text{E}}} \right], 10^{-3} \right) \quad (3.50)$$

$$G_{\text{P,E}} = 1 + F_{\beta 1, \text{eff}} \cdot \frac{L_{\text{P1,eff}}}{L_{\text{E}}} \cdot \left[1 - \exp \left(-\frac{L_{\text{E}}}{L_{\text{P1,eff}}} \right) \right] \\ + \mathbf{FBET2} \cdot \frac{\mathbf{LP2}}{L_{\text{E}}} \cdot \left[1 - \exp \left(-\frac{L_{\text{E}}}{\mathbf{LP2}} \right) \right] \quad (3.51)$$

$$G_{\text{W,E}} = 1 + \mathbf{BETW1} \cdot \frac{W_{\text{EN}}}{W_{\text{E}}} + \mathbf{BETW2} \cdot \frac{W_{\text{EN}}}{W_{\text{E}}} \cdot \ln \left(1 + \frac{W_{\text{E}}}{\mathbf{WBET}} \right) \quad (3.52)$$

$$\mathbf{BETN} = \frac{\mathbf{UO}}{G_{\text{P,E}}} \cdot \frac{W_{\text{E}}}{L_{\text{E}}} \cdot G_{\text{W,E}} \quad (3.53)$$

$$\mathbf{STBET} = \mathbf{STBETO} + \mathbf{STBETL} \cdot \frac{L_{\text{EN}}}{L_{\text{E}}} + \mathbf{STBETW} \cdot \frac{W_{\text{EN}}}{W_{\text{E}}} + \mathbf{STBETLW} \cdot \frac{W_{\text{EN}} \cdot L_{\text{EN}}}{W_{\text{E}} \cdot L_{\text{E}}} \quad (3.54)$$

$$\mathbf{MUE} = \mathbf{MUEO} \cdot \left[1 + \mathbf{MUEW} \cdot \frac{W_{\text{EN}}}{W_{\text{E}}} \right] \quad (3.55)$$

$$\mathbf{STMUE} = \mathbf{STMUEO} \quad (3.56)$$

$$\mathbf{THEMU} = \mathbf{THEMUO} \quad (3.57)$$

$$\mathbf{STTHEMU} = \mathbf{STTHEMUO} \quad (3.58)$$

$$\mathbf{CS} = \left(\mathbf{CSO} + \mathbf{CSL} \cdot \left[\frac{L_{\text{EN}}}{L_{\text{E}}} \right]^{\mathbf{CSLEXP}} \right) \cdot \left(1 + \mathbf{CSW} \cdot \frac{W_{\text{EN}}}{W_{\text{E}}} \right) \\ \cdot \left(1 + \mathbf{CSLW} \cdot \frac{W_{\text{EN}} \cdot L_{\text{EN}}}{W_{\text{E}} \cdot L_{\text{E}}} \right) \quad (3.59)$$

$$\mathbf{STCS} = \mathbf{STCSO} \quad (3.60)$$

$$\mathbf{THECS} = \mathbf{THECSO} \quad (3.61)$$

$$\mathbf{STTHECS} = \mathbf{STTHECSO} \quad (3.62)$$

$$\mathbf{XCOR} = \mathbf{XCORO} \cdot \left(1 + \mathbf{XCORL} \cdot \frac{L_{\text{EN}}}{L_{\text{E}}} \right) \cdot \left(1 + \mathbf{XCORW} \cdot \frac{W_{\text{EN}}}{W_{\text{E}}} \right) \\ \cdot \left(1 + \mathbf{XCORLW} \cdot \frac{W_{\text{EN}} \cdot L_{\text{EN}}}{W_{\text{E}} \cdot L_{\text{E}}} \right) \quad (3.63)$$

$$\mathbf{STXCOR} = \mathbf{STXCORO} \quad (3.64)$$

$$\mathbf{FETA} = \mathbf{FETAO} \quad (3.65)$$

Series Resistance Parameters

$$\mathbf{RS} = \mathbf{RSW1} \cdot \frac{W_{EN}}{W_E} \cdot \left[1 + \mathbf{RSW2} \cdot \frac{W_{EN}}{W_E} \right] \quad (3.66)$$

$$\mathbf{STRS} = \mathbf{STRSO} \quad (3.67)$$

$$\mathbf{RSB} = \mathbf{RSBO} \quad (3.68)$$

$$\mathbf{RSG} = \mathbf{RSGO} \quad (3.69)$$

Velocity Saturation Parameters

$$\begin{aligned} \mathbf{THESAT} = & \left(\mathbf{THESATO} + \mathbf{THESATL} \cdot \frac{G_{W,E}}{G_{P,E}} \cdot \left[\frac{L_{EN}}{L_E} \right]^{\mathbf{THESATLEXP}} \right) \\ & \cdot \left(1 + \mathbf{THESATW} \cdot \frac{W_{EN}}{W_E} \right) \cdot \left(1 + \mathbf{THESATLW} \cdot \frac{W_{EN} \cdot L_{EN}}{W_E \cdot L_E} \right) \end{aligned} \quad (3.70)$$

$$\begin{aligned} \mathbf{STTHESAT} = & \mathbf{STTHESATO} + \mathbf{STTHESATL} \cdot \frac{L_{EN}}{L_E} \\ & + \mathbf{STTHESATW} \cdot \frac{W_{EN}}{W_E} + \mathbf{STTHESATLW} \cdot \frac{W_{EN} \cdot L_{EN}}{W_E \cdot L_E} \end{aligned} \quad (3.71)$$

$$\mathbf{THESATB} = \mathbf{THESATBO} \quad (3.72)$$

$$\mathbf{THESATG} = \mathbf{THESATGO} \quad (3.73)$$

Saturation Voltage Parameter

$$\mathbf{AX} = \frac{\mathbf{AXO}}{1 + \mathbf{AXL} \cdot \frac{L_{EN}}{L_E}} \quad (3.74)$$

Channel Length Modulation (CLM) Parameters

$$\mathbf{ALP} = \mathbf{ALPL} \cdot \left[\frac{L_{EN}}{L_E} \right]^{\mathbf{ALPLEXP}} \cdot \left(1 + \mathbf{ALPW} \cdot \frac{W_{EN}}{W_E} \right) \quad (3.75)$$

$$\mathbf{ALP1} = \frac{\mathbf{ALP1L1} \cdot \left[\frac{L_{EN}}{L_E} \right]^{\mathbf{ALP1LEXP}}}{1 + \mathbf{ALP1L2} \cdot \left[\frac{L_{EN}}{L_E} \right]^{\mathbf{ALP1LEXP}+1}} \cdot \left(1 + \mathbf{ALP1W} \cdot \frac{W_{EN}}{W_E} \right) \quad (3.76)$$

$$\mathbf{ALP2} = \frac{\mathbf{ALP2L1} \cdot \left[\frac{L_{EN}}{L_E} \right]^{\mathbf{ALP2LEXP}}}{1 + \mathbf{ALP2L2} \cdot \left[\frac{L_{EN}}{L_E} \right]^{\mathbf{ALP2LEXP}+1}} \cdot \left(1 + \mathbf{ALP2W} \cdot \frac{W_{EN}}{W_E} \right) \quad (3.77)$$

$$\mathbf{VP} = \mathbf{VPO} \quad (3.78)$$

Impact Ionization (II) Parameters

$$\mathbf{A1} = \mathbf{A1O} \cdot \left(1 + \mathbf{A1L} \cdot \frac{L_{EN}}{L_E}\right) \cdot \left(1 + \mathbf{A1W} \cdot \frac{W_{EN}}{W_E}\right) \quad (3.79)$$

$$\mathbf{A2} = \mathbf{A2O} \quad (3.80)$$

$$\mathbf{STA2} = \mathbf{STA2O} \quad (3.81)$$

$$\mathbf{A3} = \mathbf{A3O} \cdot \left(1 + \mathbf{A3L} \cdot \frac{L_{EN}}{L_E}\right) \cdot \left(1 + \mathbf{A3W} \cdot \frac{W_{EN}}{W_E}\right) \quad (3.82)$$

$$\mathbf{A4} = \mathbf{A4O} \cdot \left(1 + \mathbf{A4L} \cdot \frac{L_{EN}}{L_E}\right) \cdot \left(1 + \mathbf{A4W} \cdot \frac{W_{EN}}{W_E}\right) \quad (3.83)$$

Gate Current Parameters

$$\mathbf{GCO} = \mathbf{GCOO} \quad (3.84)$$

$$\mathbf{IGINV} = \mathbf{IGINVLW} \cdot \frac{W_E \cdot L_E}{W_{EN} \cdot L_{EN}} \quad (3.85)$$

$$\mathbf{IGOV} = \mathbf{IGOVW} \cdot \frac{W_E \cdot \mathbf{LOV}}{W_{EN} \cdot L_{EN}} \quad (3.86)$$

$$\mathbf{IGOVD} = \mathbf{IGOVDW} \cdot \frac{W_E \cdot \mathbf{LOVD}}{W_{EN} \cdot L_{EN}} \quad (3.87)$$

$$\mathbf{STIG} = \mathbf{STIGO} \quad (3.88)$$

$$\mathbf{GC2} = \mathbf{GC2O} \quad (3.89)$$

$$\mathbf{GC3} = \mathbf{GC3O} \quad (3.90)$$

$$\mathbf{CHIB} = \mathbf{CHIBO} \quad (3.91)$$

Gate-Induced Drain Leakage (GIDL) Parameters

$$\mathbf{AGIDL} = \mathbf{AGIDLW} \cdot \frac{W_E \cdot \mathbf{LOV}}{W_{EN} \cdot L_{EN}} \quad (3.92)$$

$$\mathbf{AGIDL D} = \mathbf{AGIDL DW} \cdot \frac{W_E \cdot \mathbf{LOVD}}{W_{EN} \cdot L_{EN}} \quad (3.93)$$

$$\mathbf{BGIDL} = \mathbf{BGIDLO} \quad (3.94)$$

$$\mathbf{BGIDL D} = \mathbf{BGIDL DO} \quad (3.95)$$

$$\mathbf{STBGIDL} = \mathbf{STBGIDLO} \quad (3.96)$$

$$\mathbf{STBGIDL D} = \mathbf{STBGIDL DO} \quad (3.97)$$

$$\mathbf{CGIDL} = \mathbf{CGIDLO} \quad (3.98)$$

$$\mathbf{CGIDL D} = \mathbf{CGIDL DO} \quad (3.99)$$

Charge Model Parameters

$$\epsilon_{\text{ox}} = \epsilon_0 \cdot \mathbf{EPSROX} \quad (3.100)$$

$$\mathbf{COX} = \epsilon_{\text{ox}} \cdot \frac{W_{\text{E,CV}} \cdot L_{\text{E,CV}}}{\mathbf{TOX}} \quad (3.101)$$

$$\mathbf{CGOV} = \epsilon_{\text{ox}} \cdot \frac{W_{\text{E,CV}} \cdot \mathbf{LOV}}{\mathbf{TOXOV}} \quad (3.102)$$

$$\mathbf{CGOVD} = \epsilon_{\text{ox}} \cdot \frac{W_{\text{E,CV}} \cdot \mathbf{LOVD}}{\mathbf{TOXOVD}} \quad (3.103)$$

$$\mathbf{CGBOV} = \mathbf{CGBOVL} \cdot \frac{L_{\text{G,CV}}}{L_{\text{EN}}} \quad (3.104)$$

$$\mathbf{CFR} = \mathbf{CFRW} \cdot \frac{W_{\text{G,CV}}}{W_{\text{EN}}} \quad (3.105)$$

$$\mathbf{CFRD} = \mathbf{CFRDW} \cdot \frac{W_{\text{G,CV}}}{W_{\text{EN}}} \quad (3.106)$$

Thermal Noise Model Parameters

Note that the equation below makes use of the value of **BETN** calculated in Eq. (3.53). Because **BETN** is roughly proportional to $W_{\text{E}}/L_{\text{E}}$, the resulting **FNTEXC** is roughly proportional to $1/L_{\text{E}}^2$. In addition, it will inherit some minor L - and W -dependence from **BETN**.

$$\mathbf{FNTEXC} = \mathbf{FNTEXCL} \cdot \mathbf{BETN}^2 \cdot \left[\frac{W_{\text{EN}}}{W_{\text{E}}} \right]^2 \quad (3.107)$$

Flicker Noise Model Parameters

$$L_{\text{noi}} = \text{MAX} \left(1 - \frac{2 \cdot \mathbf{LINTNOI}}{L_{\text{E}}}, 10^{-3} \right) \quad (3.108)$$

$$L_{\text{red}} = \frac{1}{L_{\text{noi}}^{\mathbf{ALPNOI}}} \quad (3.109)$$

$$\mathbf{NFA} = L_{\text{red}} \cdot \mathbf{NFALW} \cdot \frac{W_{\text{EN}} \cdot L_{\text{EN}}}{W_{\text{E}} \cdot L_{\text{E}}} \quad (3.110)$$

$$\mathbf{NFB} = L_{\text{red}} \cdot \mathbf{NFBLW} \cdot \frac{W_{\text{EN}} \cdot L_{\text{EN}}}{W_{\text{E}} \cdot L_{\text{E}}} \quad (3.111)$$

$$\mathbf{NFC} = L_{\text{red}} \cdot \mathbf{NFCLW} \cdot \frac{W_{\text{EN}} \cdot L_{\text{EN}}}{W_{\text{E}} \cdot L_{\text{E}}} \quad (3.112)$$

$$\mathbf{EF} = \mathbf{EFO} \quad (3.113)$$

Edge transistor parameters

$$W_{\text{E,edge}} = 2 \cdot \mathbf{WEDGE} + \mathbf{WEDGEW} \cdot W_{\text{E}} \quad (3.114)$$

$$\mathbf{VFBEDGE} = \mathbf{VFBEDGEO} \quad (3.115)$$

$$\begin{aligned} \text{STVFBEDGE} &= \text{STVFBEDGEO} + \text{STVFBEDGEL} \cdot \frac{L_{\text{EN}}}{L_{\text{E}}} \\ &+ \text{STVFBEDGEW} \cdot \frac{W_{\text{EN}}}{W_{\text{E}}} + \text{STVFBEDGELW} \cdot \frac{W_{\text{EN}} \cdot L_{\text{EN}}}{W_{\text{E}} \cdot L_{\text{E}}} \end{aligned} \quad (3.116)$$

$$\begin{aligned} \text{DPHIBEDGE} &= \text{DPHIBEDGEO} + \text{DPHIBEDGEL} \cdot \left[\frac{L_{\text{EN}}}{L_{\text{E}}} \right]^{\text{DPHIBEDGELEXP}} \\ &+ \text{DPHIBEDGEW} \cdot \frac{W_{\text{EN}}}{W_{\text{E}}} + \text{DPHIBEDGELW} \cdot \frac{W_{\text{EN}} \cdot L_{\text{EN}}}{W_{\text{E}} \cdot L_{\text{E}}} \end{aligned} \quad (3.117)$$

$$\begin{aligned} \text{NEFFEDGE} &= \text{NSUBEDGEO} \cdot \left(1 + \text{NSUBEDGEL} \cdot \left[\frac{L_{\text{EN}}}{L_{\text{E}}} \right]^{\text{NSUBEDGELEXP}} \right) \\ &\cdot \left(1 + \text{NSUBEDGEW} \cdot \frac{W_{\text{EN}}}{W_{\text{E}}} \right) \cdot \left(1 + \text{NSUBEDGELW} \cdot \frac{W_{\text{EN}} \cdot L_{\text{EN}}}{W_{\text{E}} \cdot L_{\text{E}}} \right) \end{aligned} \quad (3.118)$$

$$\text{CTEDGE} = \left(\text{CTEDGEO} + \text{CTEDGEL} \cdot \left[\frac{L_{\text{EN}}}{L_{\text{E}}} \right]^{\text{CTEDGELEXP}} \right) \quad (3.119)$$

$$G_{\text{PE,edge}} = 1 + \text{FBETEDGE} \cdot \frac{\text{LPEDGE}}{L_{\text{E}}} \cdot \left[1 - \exp\left(-\frac{L_{\text{E}}}{\text{LPEDGE}}\right) \right] \quad (3.120)$$

$$\text{BETNEDGE} = \frac{\text{UO}}{G_{\text{PE,edge}}} \cdot \frac{W_{\text{E,edge}}}{L_{\text{E}}} \cdot \left(1 + \text{BETEDGEW} \cdot \frac{W_{\text{EN}}}{W_{\text{E}}} \right) \quad (3.121)$$

$$\begin{aligned} \text{STBETEDGE} &= \text{STBETEDGEO} + \text{STBETEDGEL} \cdot \frac{L_{\text{EN}}}{L_{\text{E}}} \\ &+ \text{STBETEDGEW} \cdot \frac{W_{\text{EN}}}{W_{\text{E}}} + \text{STBETEDGELW} \cdot \frac{W_{\text{EN}} \cdot L_{\text{EN}}}{W_{\text{E}} \cdot L_{\text{E}}} \end{aligned} \quad (3.122)$$

$$\text{PSCEEDGE} = \text{PSCEEDGEL} \cdot \left[\frac{L_{\text{EN}}}{L_{\text{E}}} \right]^{\text{PSCEEDGELEXP}} \cdot \left(1 + \text{PSCEEDGEW} \cdot \frac{W_{\text{EN}}}{W_{\text{E}}} \right) \quad (3.123)$$

$$\text{PSCEBEDGE} = \text{PSCEBEDGEO} \quad (3.124)$$

$$\text{PSCEDEDGE} = \text{PSCEDEDGEO} \quad (3.125)$$

$$\text{CFEDGE} = \text{CFEDGEL} \cdot \left[\frac{L_{\text{EN}}}{L_{\text{E}}} \right]^{\text{CFEDGELEXP}} \cdot \left(1 + \text{CFEDGEW} \cdot \frac{W_{\text{EN}}}{W_{\text{E}}} \right) \quad (3.126)$$

$$\text{CFDEDGE} = \text{CFDEDGEO} \quad (3.127)$$

$$\text{CFBEDGE} = \text{CFBEDGEO} \quad (3.128)$$

$$\text{FNTEDGE} = \text{FNTEDGEO} \quad (3.129)$$

$$\text{NFAEDGE} = \text{NFAEDGELW} \cdot \frac{W_{\text{EN}} \cdot L_{\text{EN}}}{W_{\text{E,edge}} \cdot L_{\text{E}}} \quad (3.130)$$

$$\mathbf{NFBEDGE} = \mathbf{NFBEDGELW} \cdot \frac{W_{\text{EN}} \cdot L_{\text{EN}}}{W_{\text{E,edge}} \cdot L_{\text{E}}} \quad (3.131)$$

$$\mathbf{NFCEDGE} = \mathbf{NFCEDGELW} \cdot \frac{W_{\text{EN}} \cdot L_{\text{EN}}}{W_{\text{E,edge}} \cdot L_{\text{E}}} \quad (3.132)$$

$$\mathbf{EFEDGE} = \mathbf{EFEDGEO} \quad (3.133)$$

WPE parameters

$$\begin{aligned} K_{\text{vthowe}} = \mathbf{KVTHOWEO} + \mathbf{KVTHOWEL} \cdot \frac{L_{\text{EN}}}{L_{\text{E}}} + \mathbf{KVTHOWEW} \cdot \frac{W_{\text{EN}}}{W_{\text{E}}} \\ + \mathbf{KVTHOWELW} \cdot \frac{L_{\text{EN}} \cdot W_{\text{EN}}}{L_{\text{E}} \cdot W_{\text{E}}} \end{aligned} \quad (3.134)$$

$$\begin{aligned} K_{\text{uowe}} = \mathbf{KUOWEO} + \mathbf{KUOWEL} \cdot \frac{L_{\text{EN}}}{L_{\text{E}}} + \mathbf{KUOWEW} \cdot \frac{W_{\text{EN}}}{W_{\text{E}}} \\ + \mathbf{KUOWELW} \cdot \frac{L_{\text{EN}} \cdot W_{\text{EN}}}{L_{\text{E}} \cdot W_{\text{E}}} \end{aligned} \quad (3.135)$$

Self heating parameters

$$\mathbf{RTH} = \mathbf{RTHO} + \frac{\mathbf{RTHW1}}{\mathbf{RTHW2} + \frac{W_{\text{E}}}{W_{\text{EN}}} \cdot \left[1 + \mathbf{RTHLW} \cdot \frac{L_{\text{E}}}{L_{\text{EN}}} \right]} \quad (3.136)$$

$$\mathbf{CTH} = \mathbf{CTHO} + \mathbf{CTHW1} \cdot \left\{ \mathbf{CTHW2} + \frac{W_{\text{E}}}{W_{\text{EN}}} \cdot \left[1 + \mathbf{CTHLW} \cdot \frac{L_{\text{E}}}{L_{\text{EN}}} \right] \right\} \quad (3.137)$$

$$\mathbf{STRTH} = \mathbf{STRTHO} \quad (3.138)$$

NQS parameters

$$\mathbf{MUNQS} = \mathbf{MUNQSO} \quad (3.139)$$

3.3 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 one 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 3.2 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.

Note: The binning equations are *only* calculated when **SWGEO** = 2.

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 , $1/L_E$, W_E , and $1/W_E$ (examples below are for a fictitious parameter **YYY**):

1. Type I

$$\mathbf{YYY} = \mathbf{POYYY} + \mathbf{PLYYY} \cdot \frac{L_{EN}}{L_E} + \mathbf{PWYYY} \cdot \frac{W_{EN}}{W_E} + \mathbf{PLWYYY} \cdot \frac{L_{EN} \cdot W_{EN}}{L_E \cdot W_E} \quad (3.140)$$

2. Type II

$$\mathbf{YYY} = \mathbf{POYYY} + \mathbf{PLYYY} \cdot \frac{L_E}{L_{EN}} + \mathbf{PWYYY} \cdot \frac{W_E}{W_{EN}} + \mathbf{PLWYYY} \cdot \frac{L_E \cdot W_E}{L_{EN} \cdot W_{EN}} \quad (3.141)$$

3. Type III

$$\mathbf{YYY} = \mathbf{POYYY} + \mathbf{PLYYY} \cdot \frac{L_{EN}}{L_E} + \mathbf{PWYYY} \cdot \frac{W_E}{W_{EN}} + \mathbf{PLWYYY} \cdot \frac{W_E \cdot L_{EN}}{W_{EN} \cdot L_E} \quad (3.142)$$

4. Type IV (no binning)

$$\mathbf{YYY} = \mathbf{POYYY} \quad (3.143)$$

In Table 3.2 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 applications of the stress equations in Section 3.5 and well proximity equations in Section 3.6), clipping is applied according to Section 2.5.2.

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	VFB	yes	type I	43	RS	yes	type I
1	STVFB	yes	type I	44	STRS	no	no
2	ST2VFB	no	no	45	RSB	no	no
3	TOX	no	no	46	RSG	no	no
4	EPSROX	no	no	47	THESAT	yes	type I
5	NEFF	yes	type I	48	STTHESAT	yes	type I
6	FACNEFFAC	yes	type I	49	THESATB	no	type I
7	GFACNUD	yes	type I	50	THESATG	no	type I
8	VSBNUD	no	no	51	AX	yes	type I
9	DVSBNUD	no	no	52	ALP	yes	type I
10	VNSUB	no	no	53	ALP1	yes	type I
11	NSLP	no	no	54	ALP2	yes	type I
12	DNSUB	no	no	55	VP	no	no
13	DPHIB	yes	type I	56	A1	yes	type I
14	DELVTAC	yes	type I	57	A2	no	no
15	NP	yes	type I	58	STA2	no	no
16	TOXOV	no	no	59	A3	yes	type I
17	TOXOVD	no	no	60	A4	yes	type I
18	NOV	no	type I	61	GCO	no	no
19	NOVD	no	type I	62	IGINV	yes	type II
20	CT	yes	type I	63	IGOV	yes	type III
21	CTG	no	no	64	IGOVD	yes	type III
22	CTB	no	no	65	STIG	no	no
23	STCT	no	no	66	GC2	no	no
24	CF	yes	type I	67	GC3	no	no
25	CFB	no	no	68	CHIB	no	no
26	CFD	no	no	69	AGIDL	yes	type III
27	PSCE	yes	type I	70	AGIDLD	yes	type III
28	PSCEB	no	no	71	BGIDL	no	no
29	PSCED	no	no	72	BGIDLD	no	no
30	BETN	yes	type I	73	STBGIDL	no	no
31	STBET	yes	type I	74	STBGIDLD	no	no
32	MUE	yes	type I	75	CGIDL	no	no
33	STMUE	no	no	76	CGIDL	no	no
34	THEMU	no	no	77	CGIDLD	no	no
35	STTHEMU	no	no	78	COX	yes	type II
36	CS	yes	type I	79	CGOV	yes	type III
37	STCS	no	no	80	CGOVD	yes	type III
38	THECS	no	no	81	CGBOV	yes	type II
39	STTHECS	no	no	82	CFR	yes	type III
40	XCOR	yes	type I	83	CFRD	yes	type III
41	STXCOR	no	no	84	FNT	no	no
42	FETA	no	no	85	FNTEXC	yes	type I

Table 3.2: 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
86	NFA	yes	type I	98	PSCEEDGE	yes	type I
87	NFB	yes	type I	99	PSCEBEDGE	no	no
88	NFC	yes	type I	100	PSCEDEEDGE	no	no
89	EF	no	no	101	CFEDGE	yes	type I
90	DTA	no	no	102	CFDEEDGE	no	no
91	VFBEEDGE	no	no	103	CFBEEDGE	no	no
92	STVFBEDGE	yes	type I	104	FNTEDGE	no	no
93	DPHIBEEDGE	yes	type I	105	NFAEDGE	yes	type I
94	NEFFEDGE	yes	type I	106	NFBEDGE	yes	type I
95	CTEDGE	yes	type I	107	NFCEDGE	yes	type I
96	BETNEEDGE	yes	type I	108	EFEDGE	no	no
97	STBETEDGE	yes	type I				

Effective length and width

$$L_{EN} = 10^{-6} \quad (3.144)$$

$$W_{EN} = 10^{-6} \quad (3.145)$$

$$\Delta L_{PS} = \mathbf{LVARO} \cdot \left(1 + \mathbf{LVARL} \cdot \frac{L_{EN}}{L} \right) \quad (3.146)$$

$$\Delta W_{OD} = \mathbf{WVARO} \cdot \left(1 + \mathbf{WVARW} \cdot \frac{W_{EN}}{W_f} \right) \quad (3.147)$$

$$L_E = L - \Delta L = L + \Delta L_{PS} - 2 \cdot \mathbf{LAP} \quad (3.148)$$

$$W_E = W_f - \Delta W = W_f + \Delta W_{OD} - 2 \cdot \mathbf{WOT} \quad (3.149)$$

$$L_{E,CV} = L + \Delta L_{PS} - 2 \cdot \mathbf{LAP} + \mathbf{DLQ} \quad (3.150)$$

$$W_{E,CV} = W_f + \Delta W_{OD} - 2 \cdot \mathbf{WOT} + \mathbf{DWQ} \quad (3.151)$$

$$L_{G,CV} = L + \Delta L_{PS} + \mathbf{DLQ} \quad (3.152)$$

$$W_{G,CV} = W_f + \Delta W_{OD} + \mathbf{DWQ} \quad (3.153)$$

Note: If the calculated L_E , W_E , $L_{E,CV}$, $W_{E,CV}$, $L_{G,CV}$, or $W_{G,CV}$ is smaller than 1 nm (10^{-9} m), the value is clipped to this lower bound of 1 nm.

Process Parameters

$$\mathbf{VFB} = \mathbf{POVFB} + \mathbf{PLVFB} \cdot \frac{L_{EN}}{L_E} + \mathbf{PWVFB} \cdot \frac{W_{EN}}{W_E} + \mathbf{PLWVFB} \cdot \frac{L_{EN} \cdot W_{EN}}{L_E \cdot W_E} \quad (3.154)$$

$$\begin{aligned} \text{STVFB} = \text{POSTVFB} + \text{PLSTVFB} \cdot \frac{L_{\text{EN}}}{L_{\text{E}}} \\ + \text{PWSTVFB} \cdot \frac{W_{\text{EN}}}{W_{\text{E}}} + \text{PLWSTVFB} \cdot \frac{L_{\text{EN}} \cdot W_{\text{EN}}}{L_{\text{E}} \cdot W_{\text{E}}} \end{aligned} \quad (3.155)$$

$$\text{ST2VFB} = \text{POST2VFB} \quad (3.156)$$

$$\text{TOX} = \text{POTOX} \quad (3.157)$$

$$\text{EPSROX} = \text{POEPSROX} \quad (3.158)$$

$$\text{NEFF} = \text{PONEFF} + \text{PLNEFF} \cdot \frac{L_{\text{EN}}}{L_{\text{E}}} + \text{PWNEFF} \cdot \frac{W_{\text{EN}}}{W_{\text{E}}} + \text{PLWNEFF} \cdot \frac{L_{\text{EN}} \cdot W_{\text{EN}}}{L_{\text{E}} \cdot W_{\text{E}}} \quad (3.159)$$

$$\begin{aligned} \text{FACNEFFAC} = \text{POFACNEFFAC} + \text{PLFACNEFFAC} \cdot \frac{L_{\text{EN}}}{L_{\text{E}}} \\ + \text{PWFACNEFFAC} \cdot \frac{W_{\text{EN}}}{W_{\text{E}}} + \text{PLWFACNEFFAC} \cdot \frac{L_{\text{EN}} \cdot W_{\text{EN}}}{L_{\text{E}} \cdot W_{\text{E}}} \end{aligned} \quad (3.160)$$

$$\begin{aligned} \text{GFACNUD} = \text{POGFACNUD} + \text{PLGFACNUD} \cdot \frac{L_{\text{EN}}}{L_{\text{E}}} \\ + \text{PWGFACNUD} \cdot \frac{W_{\text{EN}}}{W_{\text{E}}} + \text{PLWGFACNUD} \cdot \frac{L_{\text{EN}} \cdot W_{\text{EN}}}{L_{\text{E}} \cdot W_{\text{E}}} \end{aligned} \quad (3.161)$$

$$\text{VSBNUD} = \text{POVSBNUD} \quad (3.162)$$

$$\text{DVSBNUD} = \text{PODVSBNUD} \quad (3.163)$$

$$\text{VNSUB} = \text{POVNSUB} \quad (3.164)$$

$$\text{NSLP} = \text{PONS LP} \quad (3.165)$$

$$\text{DNSUB} = \text{PODNSUB} \quad (3.166)$$

$$\begin{aligned} \text{DPHIB} = \text{PODPHIB} + \text{PLDPHIB} \cdot \frac{L_{\text{EN}}}{L_{\text{E}}} \\ + \text{PDPHIB} \cdot \frac{W_{\text{EN}}}{W_{\text{E}}} + \text{PLDPHIB} \cdot \frac{L_{\text{EN}} \cdot W_{\text{EN}}}{L_{\text{E}} \cdot W_{\text{E}}} \end{aligned} \quad (3.167)$$

$$\begin{aligned} \text{DELVTAC} = \text{PODELVTAC} + \text{PLDELVTAC} \cdot \frac{L_{\text{EN}}}{L_{\text{E}}} \\ + \text{PWDELVTAC} \cdot \frac{W_{\text{EN}}}{W_{\text{E}}} + \text{PLWDELVTAC} \cdot \frac{L_{\text{EN}} \cdot W_{\text{EN}}}{L_{\text{E}} \cdot W_{\text{E}}} \end{aligned} \quad (3.168)$$

$$\text{NP} = \text{PONP} + \text{PLNP} \cdot \frac{L_{\text{EN}}}{L_{\text{E}}} + \text{PWNP} \cdot \frac{W_{\text{EN}}}{W_{\text{E}}} + \text{PLWNP} \cdot \frac{L_{\text{EN}} \cdot W_{\text{EN}}}{L_{\text{E}} \cdot W_{\text{E}}} \quad (3.169)$$

$$\text{TOXOV} = \text{POTOXOV} \quad (3.170)$$

$$\mathbf{TOXOVD} = \mathbf{POTOXOVD} \quad (3.171)$$

$$\mathbf{NOV} = \mathbf{PONOV} + \mathbf{PLNOV} \cdot \frac{L_{EN}}{L_E} + \mathbf{PWNOV} \cdot \frac{W_{EN}}{W_E} + \mathbf{PLWNOV} \cdot \frac{L_{EN} \cdot W_{EN}}{L_E \cdot W_E} \quad (3.172)$$

$$\mathbf{NOVD} = \mathbf{PONOVD} + \mathbf{PLNOVD} \cdot \frac{L_{EN}}{L_E} + \mathbf{PWNOVD} \cdot \frac{W_{EN}}{W_E} + \mathbf{PLWNOVD} \cdot \frac{L_{EN} \cdot W_{EN}}{L_E \cdot W_E} \quad (3.173)$$

Interface States Parameters

$$\mathbf{CT} = \mathbf{POCT} + \mathbf{PLCT} \cdot \frac{L_{EN}}{L_E} + \mathbf{PWCT} \cdot \frac{W_{EN}}{W_E} + \mathbf{PLWCT} \cdot \frac{L_{EN} \cdot W_{EN}}{L_E \cdot W_E} \quad (3.174)$$

$$\mathbf{CTG} = \mathbf{POCTG} \quad (3.175)$$

$$\mathbf{CTB} = \mathbf{POCTB} \quad (3.176)$$

$$\mathbf{STCT} = \mathbf{POSTCT} \quad (3.177)$$

DIBL Parameters

$$\mathbf{CF} = \mathbf{POCF} + \mathbf{PLCF} \cdot \frac{L_{EN}}{L_E} + \mathbf{PWCF} \cdot \frac{W_{EN}}{W_E} + \mathbf{PLWCF} \cdot \frac{L_{EN} \cdot W_{EN}}{L_E \cdot W_E} \quad (3.178)$$

$$\mathbf{CFB} = \mathbf{POCFB} \quad (3.179)$$

$$\mathbf{CFD} = \mathbf{POCFD} \quad (3.180)$$

Subthreshold Slope Parameters

$$\mathbf{PSCE} = \mathbf{POPSCE} + \mathbf{PLPSCE} \cdot \frac{L_{EN}}{L_E} + \mathbf{PWPSCE} \cdot \frac{W_{EN}}{W_E} + \mathbf{PLWPSCE} \cdot \frac{L_{EN} \cdot W_{EN}}{L_E \cdot W_E} \quad (3.181)$$

$$\mathbf{PSCEB} = \mathbf{POPSCEB} \quad (3.182)$$

$$\mathbf{PSCED} = \mathbf{POPSCED} \quad (3.183)$$

Mobility Parameters

$$\mathbf{BETN} = \frac{W_E}{L_E} \cdot \left(\mathbf{POBETN} + \mathbf{PLBETN} \cdot \frac{L_{EN}}{L_E} + \mathbf{PWBETN} \cdot \frac{W_{EN}}{W_E} + \mathbf{PLWBETN} \cdot \frac{L_{EN} \cdot W_{EN}}{L_E \cdot W_E} \right) \quad (3.184)$$

(See Section 7.6.1 for an explanation of this binning rule.)

$$\mathbf{STBET} = \mathbf{POSTBET} + \mathbf{PLSTBET} \cdot \frac{L_{EN}}{L_E} + \mathbf{PWSTBET} \cdot \frac{W_{EN}}{W_E} + \mathbf{PLWSTBET} \cdot \frac{L_{EN} \cdot W_{EN}}{L_E \cdot W_E} \quad (3.185)$$

$$\mathbf{MUE} = \mathbf{POMUE} + \mathbf{PLMUE} \cdot \frac{L_{EN}}{L_E} + \mathbf{PWMUE} \cdot \frac{W_{EN}}{W_E} + \mathbf{PLWMUE} \cdot \frac{L_{EN} \cdot W_{EN}}{L_E \cdot W_E} \quad (3.186)$$

$$\mathbf{STMUE} = \mathbf{POSTMUE} \quad (3.187)$$

$$\mathbf{THEMU} = \mathbf{POTHEMU} \quad (3.188)$$

$$\mathbf{STTHEMU} = \mathbf{POSTTHEMU} \quad (3.189)$$

$$\mathbf{CS} = \mathbf{POCS} + \mathbf{PLCS} \cdot \frac{L_{EN}}{L_E} + \mathbf{PWCS} \cdot \frac{W_{EN}}{W_E} + \mathbf{PLWCS} \cdot \frac{L_{EN} \cdot W_{EN}}{L_E \cdot W_E} \quad (3.190)$$

$$\mathbf{STCS} = \mathbf{POSTCS} \quad (3.191)$$

$$\mathbf{THECS} = \mathbf{POTHECS} \quad (3.192)$$

$$\mathbf{STTHECS} = \mathbf{POSTTHECS} \quad (3.193)$$

$$\mathbf{XCOR} = \mathbf{POXCOR} + \mathbf{PLXCOR} \cdot \frac{L_{EN}}{L_E} + \mathbf{PWXCOR} \cdot \frac{W_{EN}}{W_E} + \mathbf{PLWXCOR} \cdot \frac{L_{EN} \cdot W_{EN}}{L_E \cdot W_E} \quad (3.194)$$

$$\mathbf{STXCOR} = \mathbf{POSTXCOR} \quad (3.195)$$

$$\mathbf{FETA} = \mathbf{POFETA} \quad (3.196)$$

Series Resistance Parameters

$$\mathbf{RS} = \mathbf{PORS} + \mathbf{PLRS} \cdot \frac{L_{EN}}{L_E} + \mathbf{PWRS} \cdot \frac{W_{EN}}{W_E} + \mathbf{PLWRS} \cdot \frac{L_{EN} \cdot W_{EN}}{L_E \cdot W_E} \quad (3.197)$$

$$\mathbf{STRS} = \mathbf{POSTRS} \quad (3.198)$$

$$\mathbf{RSB} = \mathbf{PORSB} \quad (3.199)$$

$$\mathbf{RSG} = \mathbf{PORSG} \quad (3.200)$$

Velocity Saturation Parameters

$$\begin{aligned} \mathbf{THESAT} = \mathbf{POTHEAT} + \mathbf{PLTHESAT} \cdot \frac{L_{EN}}{L_E} \\ + \mathbf{PWTHESAT} \cdot \frac{W_{EN}}{W_E} + \mathbf{PLWTHESAT} \cdot \frac{L_{EN} \cdot W_{EN}}{L_E \cdot W_E} \end{aligned} \quad (3.201)$$

$$\begin{aligned} \mathbf{STTHESAT} = \mathbf{POSTTHESAT} + \mathbf{PLSTTHESAT} \cdot \frac{L_{EN}}{L_E} \\ + \mathbf{PWSTTHESAT} \cdot \frac{W_{EN}}{W_E} + \mathbf{PLWSTTHESAT} \cdot \frac{L_{EN} \cdot W_{EN}}{L_E \cdot W_E} \end{aligned} \quad (3.202)$$

$$\begin{aligned} \mathbf{THESATB} = \mathbf{POTHEATB} + \mathbf{PLTHESATB} \cdot \frac{L_{EN}}{L_E} \\ + \mathbf{PWTHESATB} \cdot \frac{W_{EN}}{W_E} + \mathbf{PLWTHESATB} \cdot \frac{L_{EN} \cdot W_{EN}}{L_E \cdot W_E} \end{aligned} \quad (3.203)$$

$$\begin{aligned} \text{THESATG} = & \text{POTHESATG} + \text{PLTHESATG} \cdot \frac{L_{\text{EN}}}{L_{\text{E}}} \\ & + \text{PWTHESATG} \cdot \frac{W_{\text{EN}}}{W_{\text{E}}} + \text{PLWTHESATG} \cdot \frac{L_{\text{EN}} \cdot W_{\text{EN}}}{L_{\text{E}} \cdot W_{\text{E}}} \end{aligned} \quad (3.204)$$

Saturation Voltage Parameters

$$\text{AX} = \text{POAX} + \text{PLAX} \cdot \frac{L_{\text{EN}}}{L_{\text{E}}} + \text{PWAX} \cdot \frac{W_{\text{EN}}}{W_{\text{E}}} + \text{PLWAX} \cdot \frac{L_{\text{EN}} \cdot W_{\text{EN}}}{L_{\text{E}} \cdot W_{\text{E}}} \quad (3.205)$$

Channel Length Modulation (CLM) Parameters

$$\text{ALP} = \text{POALP} + \text{PLALP} \cdot \frac{L_{\text{EN}}}{L_{\text{E}}} + \text{PWALP} \cdot \frac{W_{\text{EN}}}{W_{\text{E}}} + \text{PLWALP} \cdot \frac{L_{\text{EN}} \cdot W_{\text{EN}}}{L_{\text{E}} \cdot W_{\text{E}}} \quad (3.206)$$

$$\text{ALP1} = \text{POALP1} + \text{PLALP1} \cdot \frac{L_{\text{EN}}}{L_{\text{E}}} + \text{PWALP1} \cdot \frac{W_{\text{EN}}}{W_{\text{E}}} + \text{PLWALP1} \cdot \frac{L_{\text{EN}} \cdot W_{\text{EN}}}{L_{\text{E}} \cdot W_{\text{E}}} \quad (3.207)$$

$$\text{ALP2} = \text{POALP2} + \text{PLALP2} \cdot \frac{L_{\text{EN}}}{L_{\text{E}}} + \text{PWALP2} \cdot \frac{W_{\text{EN}}}{W_{\text{E}}} + \text{PLWALP2} \cdot \frac{L_{\text{EN}} \cdot W_{\text{EN}}}{L_{\text{E}} \cdot W_{\text{E}}} \quad (3.208)$$

$$\text{VP} = \text{POVP} \quad (3.209)$$

Impact Ionization (II) Parameters

$$\text{A1} = \text{POA1} + \text{PLA1} \cdot \frac{L_{\text{EN}}}{L_{\text{E}}} + \text{PWA1} \cdot \frac{W_{\text{EN}}}{W_{\text{E}}} + \text{PLWA1} \cdot \frac{L_{\text{EN}} \cdot W_{\text{EN}}}{L_{\text{E}} \cdot W_{\text{E}}} \quad (3.210)$$

$$\text{A2} = \text{POA2} \quad (3.211)$$

$$\text{STA2} = \text{POSTA2} \quad (3.212)$$

$$\text{A3} = \text{POA3} + \text{PLA3} \cdot \frac{L_{\text{EN}}}{L_{\text{E}}} + \text{PWA3} \cdot \frac{W_{\text{EN}}}{W_{\text{E}}} + \text{PLWA3} \cdot \frac{L_{\text{EN}} \cdot W_{\text{EN}}}{L_{\text{E}} \cdot W_{\text{E}}} \quad (3.213)$$

$$\text{A4} = \text{POA4} + \text{PLA4} \cdot \frac{L_{\text{EN}}}{L_{\text{E}}} + \text{PWA4} \cdot \frac{W_{\text{EN}}}{W_{\text{E}}} + \text{PLWA4} \cdot \frac{L_{\text{EN}} \cdot W_{\text{EN}}}{L_{\text{E}} \cdot W_{\text{E}}} \quad (3.214)$$

Gate Current Parameters

$$\text{GCO} = \text{POGCO} \quad (3.215)$$

$$\begin{aligned} \text{IGINV} = & \text{POIGINV} + \text{PLIGINV} \cdot \frac{L_{\text{E}}}{L_{\text{EN}}} \\ & + \text{PWIGINV} \cdot \frac{W_{\text{E}}}{W_{\text{EN}}} + \text{PLWIGINV} \cdot \frac{L_{\text{E}} \cdot W_{\text{E}}}{L_{\text{EN}} \cdot W_{\text{EN}}} \end{aligned} \quad (3.216)$$

$$\text{IGOV} = \text{POIGOV} + \text{PLIGOV} \cdot \frac{L_{\text{EN}}}{L_{\text{E}}} + \text{PWIGOV} \cdot \frac{W_{\text{E}}}{W_{\text{EN}}} + \text{PLWIGOV} \cdot \frac{W_{\text{E}} \cdot L_{\text{EN}}}{W_{\text{EN}} \cdot L_{\text{E}}} \quad (3.217)$$

$$\begin{aligned} \mathbf{IGOVD} = \mathbf{POIGOVD} + \mathbf{PLIGOVD} \cdot \frac{L_{EN}}{L_E} \\ + \mathbf{PWIGOVD} \cdot \frac{W_E}{W_{EN}} + \mathbf{PLWIGOVD} \cdot \frac{W_E \cdot L_{EN}}{W_{EN} \cdot L_E} \end{aligned} \quad (3.218)$$

$$\mathbf{STIG} = \mathbf{POSTIG} \quad (3.219)$$

$$\mathbf{GC2} = \mathbf{POGC2} \quad (3.220)$$

$$\mathbf{GC3} = \mathbf{POGC3} \quad (3.221)$$

$$\mathbf{CHIB} = \mathbf{POCHIB} \quad (3.222)$$

Gate-Induced Drain Leakage (GIDL) Parameters

$$\begin{aligned} \mathbf{AGIDL} = \mathbf{POAGIDL} + \mathbf{PLAGIDL} \cdot \frac{L_{EN}}{L_E} \\ + \mathbf{PWAGIDL} \cdot \frac{W_E}{W_{EN}} + \mathbf{PLWAGIDL} \cdot \frac{W_E \cdot L_{EN}}{W_{EN} \cdot L_E} \end{aligned} \quad (3.223)$$

$$\begin{aligned} \mathbf{AGIDLD} = \mathbf{POAGIDLD} + \mathbf{PLAGIDLD} \cdot \frac{L_{EN}}{L_E} \\ + \mathbf{PWAGIDLD} \cdot \frac{W_E}{W_{EN}} + \mathbf{PLWAGIDLD} \cdot \frac{W_E \cdot L_{EN}}{W_{EN} \cdot L_E} \end{aligned} \quad (3.224)$$

$$\mathbf{BGIDL} = \mathbf{POBGIDL} \quad (3.225)$$

$$\mathbf{BGIDLD} = \mathbf{POBGIDLD} \quad (3.226)$$

$$\mathbf{STBGIDL} = \mathbf{POSTBGIDL} \quad (3.227)$$

$$\mathbf{STBGIDLD} = \mathbf{POSTBGIDLD} \quad (3.228)$$

$$\mathbf{CGIDL} = \mathbf{POCGIDL} \quad (3.229)$$

$$\mathbf{CGIDLD} = \mathbf{POCGIDLD} \quad (3.230)$$

Charge Model Parameters

$$\mathbf{COX} = \mathbf{POCOX} + \mathbf{PLCOX} \cdot \frac{L_{E,CV}}{L_{EN}} + \mathbf{PWCOX} \cdot \frac{W_{E,CV}}{W_{EN}} + \mathbf{PLWCOX} \cdot \frac{L_{E,CV} \cdot W_{E,CV}}{L_{EN} \cdot W_{EN}} \quad (3.231)$$

$$\begin{aligned} \mathbf{CGOV} = \mathbf{POCGOV} + \mathbf{PLCGOV} \cdot \frac{L_{EN}}{L_{E,CV}} \\ + \mathbf{PWCGOV} \cdot \frac{W_{E,CV}}{W_{EN}} + \mathbf{PLWCGOV} \cdot \frac{W_{E,CV} \cdot L_{EN}}{W_{EN} \cdot L_{E,CV}} \end{aligned} \quad (3.232)$$

$$\begin{aligned} \text{CGOVD} = & \text{POCGOVD} + \text{PLCGOVD} \cdot \frac{L_{\text{EN}}}{L_{\text{E,CV}}} \\ & + \text{PWC GOVD} \cdot \frac{W_{\text{E,CV}}}{W_{\text{EN}}} + \text{PLWCGOVD} \cdot \frac{W_{\text{E,CV}} \cdot L_{\text{EN}}}{W_{\text{EN}} \cdot L_{\text{E,CV}}} \end{aligned} \quad (3.233)$$

$$\begin{aligned} \text{CGBOV} = & \text{POCGBOV} + \text{PLCGBOV} \cdot \frac{L_{\text{G,CV}}}{L_{\text{EN}}} \\ & + \text{PWC GBOV} \cdot \frac{W_{\text{G,CV}}}{W_{\text{EN}}} + \text{PLWCGBOV} \cdot \frac{L_{\text{G,CV}} \cdot W_{\text{G,CV}}}{L_{\text{EN}} \cdot W_{\text{EN}}} \end{aligned} \quad (3.234)$$

$$\text{CFR} = \text{POCFR} + \text{PLCFR} \cdot \frac{L_{\text{EN}}}{L_{\text{G,CV}}} + \text{PWC FR} \cdot \frac{W_{\text{G,CV}}}{W_{\text{EN}}} + \text{PLWCFR} \cdot \frac{W_{\text{G,CV}} \cdot L_{\text{EN}}}{W_{\text{EN}} \cdot L_{\text{G,CV}}} \quad (3.235)$$

$$\text{CFRD} = \text{POCFRD} + \text{PLCFRD} \cdot \frac{L_{\text{EN}}}{L_{\text{G,CV}}} + \text{PWC FRD} \cdot \frac{W_{\text{G,CV}}}{W_{\text{EN}}} + \text{PLWCFRD} \cdot \frac{W_{\text{G,CV}} \cdot L_{\text{EN}}}{W_{\text{EN}} \cdot L_{\text{G,CV}}} \quad (3.236)$$

Thermal Noise Model Parameters

$$\text{FNT} = \text{POFNT} \quad (3.237)$$

$$\begin{aligned} \text{FNTEXC} = & \left[\frac{L_{\text{EN}}}{L_{\text{E}}} \right]^2 \cdot \left(\text{POFNTEXC} + \text{PLFNTEXC} \cdot \frac{L_{\text{EN}}}{L_{\text{E}}} \right. \\ & \left. + \text{PWFNTEXC} \cdot \frac{W_{\text{EN}}}{W_{\text{E}}} + \text{PLWFNTEXC} \cdot \frac{L_{\text{EN}} \cdot W_{\text{EN}}}{L_{\text{E}} \cdot W_{\text{E}}} \right) \end{aligned} \quad (3.238)$$

Flicker Noise Model Parameters

$$\text{NFA} = \text{PONFA} + \text{PLNFA} \cdot \frac{L_{\text{EN}}}{L_{\text{E}}} + \text{PWNFA} \cdot \frac{W_{\text{EN}}}{W_{\text{E}}} + \text{PLWNFA} \cdot \frac{L_{\text{EN}} \cdot W_{\text{EN}}}{L_{\text{E}} \cdot W_{\text{E}}} \quad (3.239)$$

$$\text{NFB} = \text{PONFB} + \text{PLNFB} \cdot \frac{L_{\text{EN}}}{L_{\text{E}}} + \text{PWNFB} \cdot \frac{W_{\text{EN}}}{W_{\text{E}}} + \text{PLWNFB} \cdot \frac{L_{\text{EN}} \cdot W_{\text{EN}}}{L_{\text{E}} \cdot W_{\text{E}}} \quad (3.240)$$

$$\text{NFC} = \text{PONFC} + \text{PLNFC} \cdot \frac{L_{\text{EN}}}{L_{\text{E}}} + \text{PWNFC} \cdot \frac{W_{\text{EN}}}{W_{\text{E}}} + \text{PLWNFC} \cdot \frac{L_{\text{EN}} \cdot W_{\text{EN}}}{L_{\text{E}} \cdot W_{\text{E}}} \quad (3.241)$$

$$\text{EF} = \text{POEF} \quad (3.242)$$

Edge transistor parameters

$$\text{VFBEDGE} = \text{POVFBEDGE} \quad (3.243)$$

$$\begin{aligned} \text{STVFBEDGE} = & \text{POSTVFBEDGE} + \text{PLSTVFBEDGE} \cdot \frac{L_{\text{EN}}}{L_{\text{E}}} \\ & + \text{PWSTVFBEDGE} \cdot \frac{W_{\text{EN}}}{W_{\text{E}}} + \text{PLWSTVFBEDGE} \cdot \frac{L_{\text{EN}} \cdot W_{\text{EN}}}{L_{\text{E}} \cdot W_{\text{E}}} \end{aligned} \quad (3.244)$$

$$\begin{aligned} \mathbf{DPHIBEDGE} &= \mathbf{PODPHIBEDGE} + \mathbf{PLDPHIBEDGE} \cdot \frac{L_{EN}}{L_E} \\ &+ \mathbf{PWDPHIBEDGE} \cdot \frac{W_{EN}}{W_E} + \mathbf{PLWDPHIBEDGE} \cdot \frac{L_{EN} \cdot W_{EN}}{L_E \cdot W_E} \end{aligned} \quad (3.245)$$

$$\begin{aligned} \mathbf{NEFFEDGE} &= \mathbf{PONEFFEDGE} + \mathbf{PLNEFFEDGE} \cdot \frac{L_{EN}}{L_E} \\ &+ \mathbf{PWNEFFEDGE} \cdot \frac{W_{EN}}{W_E} + \mathbf{PLWNEFFEDGE} \cdot \frac{L_{EN} \cdot W_{EN}}{L_E \cdot W_E} \end{aligned} \quad (3.246)$$

$$\begin{aligned} \mathbf{CTEDGE} &= \mathbf{POCTEDGE} + \mathbf{PLCTEDGE} \cdot \frac{L_{EN}}{L_E} \\ &+ \mathbf{PWCTEDGE} \cdot \frac{W_{EN}}{W_E} + \mathbf{PLWCTEDGE} \cdot \frac{L_{EN} \cdot W_{EN}}{L_E \cdot W_E} \end{aligned} \quad (3.247)$$

$$\begin{aligned} \mathbf{BETNEDGE} &= \frac{L_{EN}}{L_E} \cdot \left(\mathbf{POBETNEDGE} + \mathbf{PLBETNEDGE} \cdot \frac{L_{EN}}{L_E} \right. \\ &\left. + \mathbf{PWBETNEDGE} \cdot \frac{W_{EN}}{W_E} + \mathbf{PLWBETNEDGE} \cdot \frac{L_{EN} \cdot W_{EN}}{L_E \cdot W_E} \right) \end{aligned} \quad (3.248)$$

$$\begin{aligned} \mathbf{STBETEDGE} &= \mathbf{POSTBETEDGE} + \mathbf{PLSTBETEDGE} \cdot \frac{L_{EN}}{L_E} \\ &+ \mathbf{PWSTBETEDGE} \cdot \frac{W_{EN}}{W_E} + \mathbf{PLWSTBETEDGE} \cdot \frac{L_{EN} \cdot W_{EN}}{L_E \cdot W_E} \end{aligned} \quad (3.249)$$

$$\begin{aligned} \mathbf{PSCEEDGE} &= \mathbf{POPSCEEDGE} + \mathbf{PLPSCEEDGE} \cdot \frac{L_{EN}}{L_E} \\ &+ \mathbf{PWPSCEEDGE} \cdot \frac{W_{EN}}{W_E} + \mathbf{PLWPSCEEDGE} \cdot \frac{L_{EN} \cdot W_{EN}}{L_E \cdot W_E} \end{aligned} \quad (3.250)$$

$$\mathbf{PSCEBEDGE} = \mathbf{POPSCEBEDGE} \quad (3.251)$$

$$\mathbf{PSCEDEEDGE} = \mathbf{POPSCEDEEDGE} \quad (3.252)$$

$$\begin{aligned} \mathbf{CFEDGE} &= \mathbf{POCFEDGE} + \mathbf{PLCFEDGE} \cdot \frac{L_{EN}}{L_E} \\ &+ \mathbf{PWCFFEDGE} \cdot \frac{W_{EN}}{W_E} + \mathbf{PLWCFEDGE} \cdot \frac{L_{EN} \cdot W_{EN}}{L_E \cdot W_E} \end{aligned} \quad (3.253)$$

$$\mathbf{CFDEEDGE} = \mathbf{POCFDEEDGE} \quad (3.254)$$

$$\mathbf{CFBEDGE} = \mathbf{POCFBEDGE} \quad (3.255)$$

$$\mathbf{FNTEEDGE} = \mathbf{POFNTEEDGE} \quad (3.256)$$

$$\begin{aligned} \mathbf{NFAEDGE} = \mathbf{PONFAEDGE} + \mathbf{PLNFAEDGE} \cdot \frac{L_{EN}}{L_E} \\ + \mathbf{PWNFAEDGE} \cdot \frac{W_{EN}}{W_E} + \mathbf{PLWNFAEDGE} \cdot \frac{L_{EN} \cdot W_{EN}}{L_E \cdot W_E} \end{aligned} \quad (3.257)$$

$$\begin{aligned} \mathbf{NFBEDGE} = \mathbf{PONFBEDGE} + \mathbf{PLNFBEDGE} \cdot \frac{L_{EN}}{L_E} \\ + \mathbf{PWNFBEDGE} \cdot \frac{W_{EN}}{W_E} + \mathbf{PLWNFBEDGE} \cdot \frac{L_{EN} \cdot W_{EN}}{L_E \cdot W_E} \end{aligned} \quad (3.258)$$

$$\begin{aligned} \mathbf{NFCEDGE} = \mathbf{PONFCEDGE} + \mathbf{PLNFCEDGE} \cdot \frac{L_{EN}}{L_E} \\ + \mathbf{PWNFCEDGE} \cdot \frac{W_{EN}}{W_E} + \mathbf{PLWNFCEDGE} \cdot \frac{L_{EN} \cdot W_{EN}}{L_E \cdot W_E} \end{aligned} \quad (3.259)$$

$$\mathbf{EFEDGE} = \mathbf{POEFEDGE} \quad (3.260)$$

WPE parameters

$$\begin{aligned} K_{\text{vthowe}} = \mathbf{POKVTHOWE} + \mathbf{PLKVTHOWE} \cdot \frac{L_{EN}}{L_E} + \mathbf{PWKVTHOWE} \cdot \frac{W_{EN}}{W_E} \\ + \mathbf{PLWKVTHOWE} \cdot \frac{L_{EN} \cdot W_{EN}}{L_E \cdot W_E} \end{aligned} \quad (3.261)$$

$$\begin{aligned} K_{\text{uowe}} = \mathbf{POKUOWE} + \mathbf{PLKUOWE} \cdot \frac{L_{EN}}{L_E} + \mathbf{PWKUOWE} \cdot \frac{W_{EN}}{W_E} \\ + \mathbf{PLWKUOWE} \cdot \frac{L_{EN} \cdot W_{EN}}{L_E \cdot W_E} \end{aligned} \quad (3.262)$$

Self heating parameters

(Also for **SWGEO** = 2, the geometrical scaling rules are used.)

$$\mathbf{RTH} = \mathbf{RTHO} + \frac{\mathbf{RTHW1}}{\mathbf{RTHW2} + \frac{W_E}{W_{EN}} \cdot \left[1 + \mathbf{RTHLW} \cdot \frac{L_E}{L_{EN}} \right]} \quad (3.263)$$

$$\mathbf{CTH} = \mathbf{CTHO} + \mathbf{CTHW1} \cdot \left\{ \mathbf{CTHW2} + \frac{W_E}{W_{EN}} \cdot \left[1 + \mathbf{CTHLW} \cdot \frac{L_E}{L_{EN}} \right] \right\} \quad (3.264)$$

$$\mathbf{STRTH} = \mathbf{STRTHO} \quad (3.265)$$

NQS parameters

(Also for **SWGEO** = 2, the geometrical scaling rules are used.)

$$\mathbf{MUNQS} = \mathbf{MUNQSO} \quad (3.266)$$

3.4 Parasitic resistances

PSP model contains a network of parasitic elements: a gate resistance, two diffusion resistances for source and drain, 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 in Fig. 3.2. At this moment, only the gate resistance is scaled with geometry (facilitating the implementation of multi-finger devices).

Note: The resistance equations are calculated when **SWGEO** = 1 or 2.

$$L_f = L + \Delta L_{PS} \tag{3.267}$$

$$L_{sil,f} = L_f + \mathbf{DLSIL} \tag{3.268}$$

$$W_{E,f} = W_f + \Delta W_{OD} \tag{3.269}$$

$$X_{GWE} = \mathbf{XGW} - 0.5 \cdot \Delta W_{OD} \tag{3.270}$$

$$\mathbf{RG} = \mathbf{RGO} + \frac{1}{\mathbf{NF}} \cdot \left[\frac{\mathbf{RSHG} \cdot \left(\frac{W_{E,f}}{3 \cdot \mathbf{NGCON}} + X_{GWE} \right)}{\mathbf{NGCON} \cdot L_{sil,f}} + \frac{\mathbf{RINT} + \mathbf{RVPOLY}}{W_{E,f} \cdot L_f} \right] \tag{3.271}$$

$$\mathbf{RSE} = \mathbf{NRS} \cdot \mathbf{RSH} \tag{3.272}$$

$$\mathbf{RDE} = \mathbf{NRD} \cdot \mathbf{RSHD} \tag{3.273}$$

$$\mathbf{RBULK} = \mathbf{RBULKO} \tag{3.274}$$

$$\mathbf{RWELL} = \mathbf{RWELLO} \tag{3.275}$$

$$\mathbf{RJUNS} = \mathbf{RJUNSO} \tag{3.276}$$

$$\mathbf{RJUND} = \mathbf{RJUNDO} \tag{3.277}$$

Note: The values of L_f , $L_{sil,f}$, $W_{E,f}$ and X_{GWE} are clipped to a minimum value of 1 nm. The calculated local parameters are subject to the boundaries specified in Section 2.5.6.

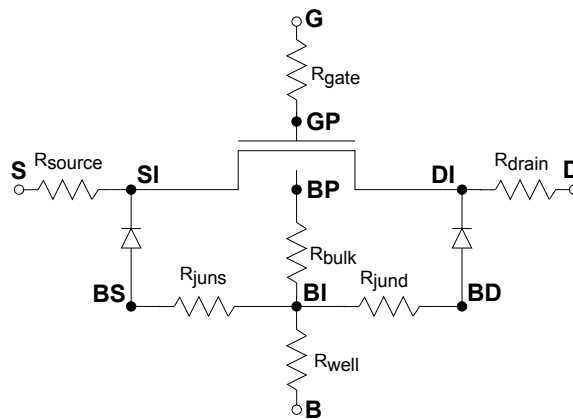


Figure 3.2: Parasitics circuit

3.5 Stress effects

The stress model of BSIM4.4.0 [3] 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. Some trivial conversion of parameters BSIM→PSP is still necessary, see [2].

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

Calculation of **SA** and **SB** for irregular layouts is given in Section B.1.

Note:

- After modification of the local parameters by the stress equations, clipping is applied according to Section 2.5.2.
- If both **SA** and **SB** are set to 0, the stress-equations are *not* computed.
- The stress equations are calculated when **SWGEO** = 1 or 2.

3.5.1 Layout effects for multi-finger devices

For multi-finger devices, effective values **SA_{eff}** and **SB_{eff}** for the instance parameters are calculated (see Fig. 3.3).

$$\frac{1}{\mathbf{SA}_{\text{eff}} + 0.5 \cdot L} = \frac{1}{\mathbf{NF}} \cdot \sum_{i=0}^{\mathbf{NF}-1} \frac{1}{\mathbf{SA} + 0.5 \cdot L + i \cdot (\mathbf{SD} + L)} \quad (3.278)$$

$$\frac{1}{\mathbf{SB}_{\text{eff}} + 0.5 \cdot L} = \frac{1}{\mathbf{NF}} \cdot \sum_{i=0}^{\mathbf{NF}-1} \frac{1}{\mathbf{SB} + 0.5 \cdot L + i \cdot (\mathbf{SD} + L)} \quad (3.279)$$

3.5.2 Layout effects for regular shapes

$$R_A = \frac{1}{\mathbf{SA}_{\text{eff}} + 0.5 \cdot L} \quad (3.280)$$

$$R_B = \frac{1}{\mathbf{SB}_{\text{eff}} + 0.5 \cdot L} \quad (3.281)$$

$$R_{A,\text{ref}} = \frac{1}{\mathbf{SAREF} + 0.5 \cdot L} \quad (3.282)$$

$$R_{B,\text{ref}} = \frac{1}{\mathbf{SBREF} + 0.5 \cdot L} \quad (3.283)$$

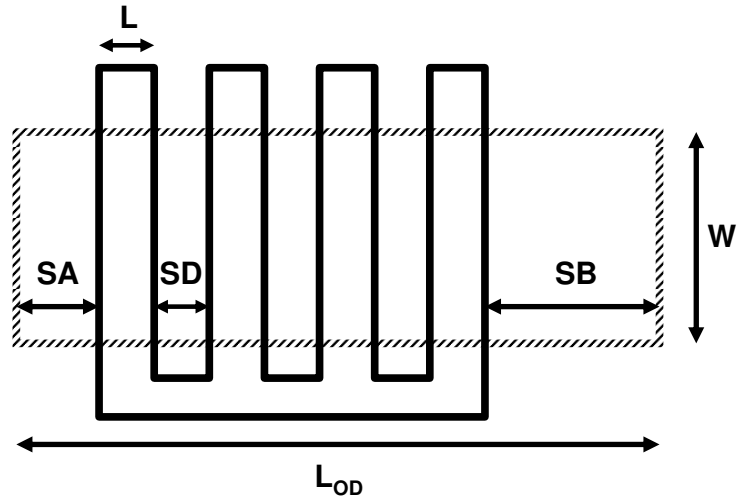


Figure 3.3: A typical layout of multi-finger devices with an additional instance parameters SD .

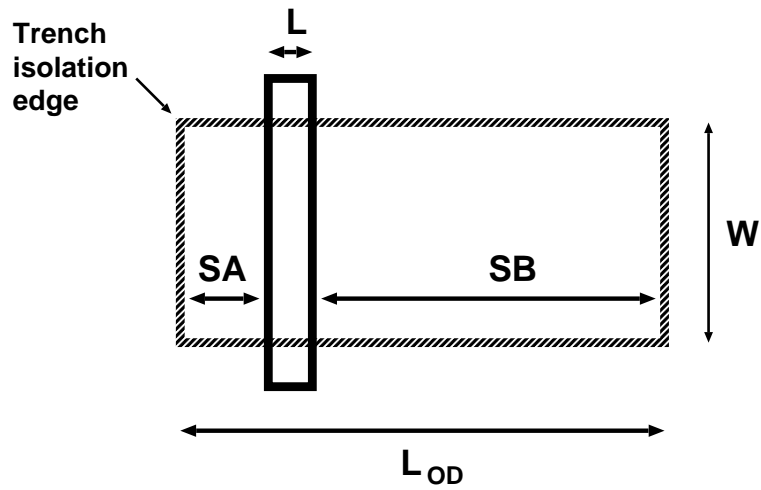


Figure 3.4: Typical layout of a MOSFET. Note that $L_{OD} = SA + SB + L$, where OD is the active region definition.

3.5.3 Parameter modifications

Mobility-related equations

$$K_{u0} = \left(1 + \frac{\mathbf{LKUO}}{(L + \Delta L_{PS})^{\mathbf{LLODKUO}}} + \frac{\mathbf{WKUO}}{(W_f + \Delta W_{OD} + \mathbf{WLOD})^{\mathbf{WLODKUO}}} \right. \\ \left. + \frac{\mathbf{PKUO}}{(L + \Delta L_{PS})^{\mathbf{LLODKUO}} \cdot (W_f + \Delta W_{OD} + \mathbf{WLOD})^{\mathbf{WLODKUO}}} \right) \cdot \left[1 + \mathbf{TKUO} \cdot \left(\frac{T_{KA}}{T_{KR}} - 1 \right) \right] \quad (3.284)$$

$$\rho_\beta = \frac{\mathbf{KUO}}{K_{u0}} \cdot (R_A + R_B) \quad (3.285)$$

$$\rho_{\beta,\text{ref}} = \frac{\mathbf{KUO}}{K_{u0}} \cdot (R_{A,\text{ref}} + R_{B,\text{ref}}) \quad (3.286)$$

$$\mathbf{BETN} = \frac{1 + \rho_\beta}{1 + \rho_{\beta,\text{ref}}} \cdot \mathbf{BETN}_{\text{ref}} \quad (3.287)$$

$$\mathbf{THESAT} = \frac{1 + \rho_\beta}{1 + \rho_{\beta,\text{ref}}} \cdot \frac{1 + \mathbf{KVSAT} \cdot \rho_{\beta,\text{ref}}}{1 + \mathbf{KVSAT} \cdot \rho_\beta} \cdot \mathbf{THESAT}_{\text{ref}} \quad (3.288)$$

$$\mathbf{BETNEDGE} = \frac{1 + \rho_\beta}{1 + \rho_{\beta,\text{ref}}} \cdot \mathbf{BETNEDGE}_{\text{ref}} \quad (3.289)$$

Threshold-voltage-related equations

$$K_{\text{vth0}} = 1 + \frac{\mathbf{LKVTHO}}{(L + \Delta L_{PS})^{\mathbf{LLODVTH}}} + \frac{\mathbf{WKVTHO}}{(W_f + \Delta W_{OD} + \mathbf{WLOD})^{\mathbf{WLODVTH}}} \\ + \frac{\mathbf{PKVTHO}}{(L + \Delta L_{PS})^{\mathbf{LLODVTH}} \cdot (W_f + \Delta W_{OD} + \mathbf{WLOD})^{\mathbf{WLODVTH}}} \quad (3.290)$$

$$\Delta R = R_A + R_B - R_{A,\text{ref}} - R_{B,\text{ref}} \quad (3.291)$$

$$\mathbf{VFB} = \mathbf{VFB}_{\text{ref}} + \mathbf{KVTHO} \cdot \frac{\Delta R}{K_{\text{vth0}}} \quad (3.292)$$

$$\mathbf{CF} = \mathbf{CF}_{\text{ref}} + \mathbf{STETAO} \cdot \frac{\Delta R}{K_{\text{vth0}}^{\mathbf{LODETAO}}} \quad (3.293)$$

$$\mathbf{VFBEDGE} = \mathbf{VFBEDGE}_{\text{ref}} + \mathbf{KVTHO} \cdot \frac{\Delta R}{K_{\text{vth0}}} \quad (3.294)$$

$$\mathbf{CFEDGE} = \mathbf{CFEDGE}_{\text{ref}} + \mathbf{STETAO} \cdot \frac{\Delta R}{K_{\text{vth0}}^{\mathbf{LODETAO}}} \quad (3.295)$$

3.6 Well proximity effects

The well proximity effect (WPE) model from BSIM4.5.0 [4, 5, 6] has been adopted in PSP with two changes relative to BSIM4.5.0: (1) in the original BSIM parameter names all zeros have been replaced by ‘O’s in order to comply with PSP naming convention and (2) the BSIM parameter *K2WE* is not available in PSP. Except for some trivial conversion of parameters BSIM→PSP [2], WPE parameters from BSIM can be used directly in PSP.

The local PSP parameters affected by the WPE equations are **VFB**, **BETN**, **VFEDGE** and **BETNEDGE**

How to calculate **SCA**, **SCB**, and **SCC** is shown in Section B.2.

Note:

- After modification of the local parameters by the WPE equations, clipping is applied according to Section 2.5.2.
- If **SCA**, **SCB**, **SCC** and **SC** are all set to 0, the WPE equations are *not* computed.
- The WPE equations are calculated when **SWGEO** = 1 or 2.

3.6.1 Parameters for pre-layout simulation

If **SCA** = **SCB** = **SCC** = 0 and **SC** > 0, **SCA**, **SCB**, and **SCC** will be computed from **SC** according to Eqs. (B.9)–(B.11), as shown below. Here, **SC** should be taken as the distance to the nearest well edge (see Fig. 3.5). If any of the parameters **SCA**, **SCB**, or **SCC** is positive, all three values as supplied will be used and **SC** will be ignored.

If **SCA** = **SCB** = **SCC** = 0 and **SC** > 0

$$SCA = \frac{SCREF^2}{W_f} \cdot \left(\frac{1}{SC} - \frac{1}{SC + W_f} \right) \tag{3.296}$$

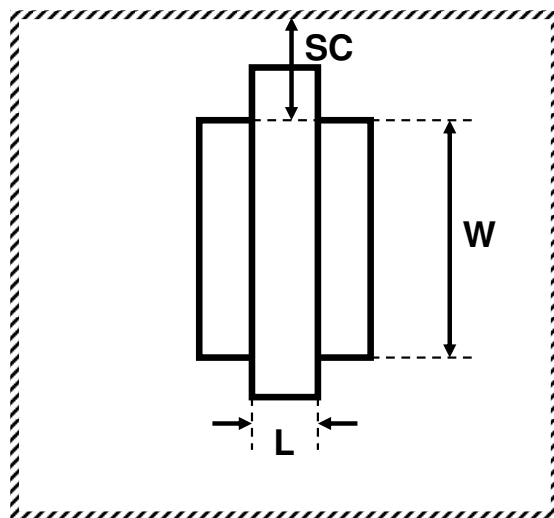


Figure 3.5: A layout of MOS devices for pre-layout simulation using estimated value for **SC**.

$$\begin{aligned} \mathbf{SCB} = \frac{1}{W_f \cdot \mathbf{SCREF}} \cdot & \left[\frac{\mathbf{SCREF}}{10} \cdot \mathbf{SC} \cdot \exp\left(-10 \cdot \frac{\mathbf{SC}}{\mathbf{SCREF}}\right) + \frac{\mathbf{SCREF}^2}{100} \cdot \exp\left(-10 \cdot \frac{\mathbf{SC}}{\mathbf{SCREF}}\right) \right. \\ & - \frac{\mathbf{SCREF}}{10} \cdot (\mathbf{SC} + W_f) \cdot \exp\left(-10 \cdot \frac{\mathbf{SC} + W_f}{\mathbf{SCREF}}\right) \\ & \left. - \frac{\mathbf{SCREF}^2}{100} \cdot \exp\left(-10 \cdot \frac{\mathbf{SC} + W_f}{\mathbf{SCREF}}\right) \right] \quad (3.297) \end{aligned}$$

$$\begin{aligned} \mathbf{SCC} = \frac{1}{W_f \cdot \mathbf{SCREF}} \cdot & \left[\frac{\mathbf{SCREF}}{20} \cdot \mathbf{SC} \cdot \exp\left(-20 \cdot \frac{\mathbf{SC}}{\mathbf{SCREF}}\right) + \frac{\mathbf{SCREF}^2}{400} \cdot \exp\left(-20 \cdot \frac{\mathbf{SC}}{\mathbf{SCREF}}\right) \right. \\ & - \frac{\mathbf{SCREF}}{20} \cdot (\mathbf{SC} + W_f) \cdot \exp\left(-20 \cdot \frac{\mathbf{SC} + W_f}{\mathbf{SCREF}}\right) \\ & \left. - \frac{\mathbf{SCREF}^2}{400} \cdot \exp\left(-20 \cdot \frac{\mathbf{SC} + W_f}{\mathbf{SCREF}}\right) \right] \quad (3.298) \end{aligned}$$

3.6.2 Calculation of parameter modifications

The calculation of K_{vthowe} and K_{uowe} is given in Section 3.2 (global model) or 3.3 (binning model).

$$\mathbf{VFB} = \mathbf{VFB}_{\text{ref}} + K_{\text{vthowe}} \cdot (\mathbf{SCA} + \mathbf{WEB} \cdot \mathbf{SCB} + \mathbf{WEC} \cdot \mathbf{SCC}) \quad (3.299)$$

$$\mathbf{BETN} = \mathbf{BETN}_{\text{ref}} \cdot [1 + K_{\text{uowe}} \cdot (\mathbf{SCA} + \mathbf{WEB} \cdot \mathbf{SCB} + \mathbf{WEC} \cdot \mathbf{SCC})] \quad (3.300)$$

$$\mathbf{VFBEDGE} = \mathbf{VFBEDGE}_{\text{ref}} + K_{\text{vthowe}} \cdot (\mathbf{SCA} + \mathbf{WEB} \cdot \mathbf{SCB} + \mathbf{WEC} \cdot \mathbf{SCC}) \quad (3.301)$$

$$\mathbf{BETNEDGE} = \mathbf{BETNEDGE}_{\text{ref}} \cdot [1 + K_{\text{uowe}} \cdot (\mathbf{SCA} + \mathbf{WEB} \cdot \mathbf{SCB} + \mathbf{WEC} \cdot \mathbf{SCC})] \quad (3.302)$$

3.7 Asymmetric junctions

From PSP 102.3 onwards, asymmetric junction can be modeled in PSP. This includes asymmetric source-bulk and drain-bulk junctions, GIDL/GISL, overlap gate currents, overlap capacitances and outer fringe capacitances. The asymmetric junction model can be switched on by means of the parameter **SWJUNASYM**. Note that if **SWJUNASYM** = 1, the new parameters for the drain side are used all together. Those whose values are not explicitly specified in the model card are set to their default value, *not* to their counterparts for the source side. In other words, it is not possible to activate the parameters for the drain side on a one-by-one basis. The physical scaling and binning rules to calculate the related local parameters for the drain side are given in Section 3.2 and 3.3.

If **SWJUNASYM** = 0, the related parameters for the drain side are ignored. Effectively, the following assignments are applied before evaluation of the calculations described in Section 4.

If **SWJUNASYM** = 0:

$$\mathbf{TOXOVD} = \mathbf{TOXOV} \quad (3.303)$$

$$\mathbf{NOVD} = \mathbf{NOV} \quad (3.304)$$

$$\mathbf{AGIDLD} = \mathbf{AGIDL} \quad (3.305)$$

$$\mathbf{BGIDLD} = \mathbf{BGIDL} \quad (3.306)$$

$$\mathbf{STBGIDLD} = \mathbf{STBGIDL} \quad (3.307)$$

$$\mathbf{CGIDLD} = \mathbf{CGIDL} \quad (3.308)$$

$$\mathbf{IGOVD} = \mathbf{IGOV} \quad (3.309)$$

$$\mathbf{CGOVD} = \mathbf{CGOV} \quad (3.310)$$

$$\mathbf{CFRD} = \mathbf{CFR} \quad (3.311)$$

$$\mathbf{RSHD} = \mathbf{RSH} \quad (3.312)$$

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

$$T_{KR} = T_0 + \mathbf{TR} \quad (4.1)$$

$$T_{KA} = T_0 + T_A + \mathbf{DTA} \quad (4.2)$$

$$T_{KD} = T_{KA} + V_{dt} \quad (4.3)$$

$$\Delta T = T_{KD} - T_{KR} \quad (4.4)$$

$$\Delta T_A = T_{KA} - T_{KR} \quad (4.5)$$

$$\phi_T = \frac{k_B \cdot T_{KD}}{q} \quad (4.6)$$

$$\phi_{T_A} = \frac{k_B \cdot T_{KA}}{q} \quad (4.7)$$

Local process parameters

$$V_{FB} = \mathbf{VFB} + \mathbf{STVFB} \cdot \Delta T \cdot (1 + \mathbf{ST2VFB} \cdot \Delta T) + \mathbf{DELVTO} \quad (4.8)$$

$$E_g/q = 1.179 - 9.025 \cdot 10^{-5} \cdot T_{KD} - 3.05 \cdot 10^{-7} \cdot T_{KD}^2 \quad (4.9)$$

$$r_T = (1.045 + 4.5 \cdot 10^{-4} \cdot T_{KD}) \cdot (0.523 + 1.4 \cdot 10^{-3} \cdot T_{KD} - 1.48 \cdot 10^{-6} \cdot T_{KD}^2) \quad (4.10)$$

$$n_i = 2.5 \cdot 10^{25} \cdot r_T^{3/4} \cdot (T_{KD}/300)^{3/2} \cdot \exp\left(-\frac{E_g/q}{2 \cdot \phi_T}\right) \quad (4.11)$$

$$\phi_{B,dc}^{cl} = \mathbf{MAX}(\mathbf{DPHIB} + 2 \cdot \phi_T \cdot \ln[\mathbf{NEFF}/n_i], 0.05) \quad (4.12)$$

$$N_{\text{eff,ac}} = \text{MIN}[\text{MAX}(\mathbf{FACNEFFAC} \cdot \mathbf{NEFF}, 10^{20}), 10^{26}] \quad (4.13)$$

$$\phi_{\text{B,ac}}^{\text{cl}} = \text{MAX}(\mathbf{DPHIB} + \mathbf{DELVTAC} + 2 \cdot \phi_{\text{T}} \cdot \ln [N_{\text{eff,ac}}/n_i], 0.05) \quad (4.14)$$

$$\epsilon_{\text{ox}} = \mathbf{EPSROX} \cdot \epsilon_0 \quad (4.15)$$

$$C_{\text{ox}} = \epsilon_{\text{ox}}/\mathbf{TOX} \quad (4.16)$$

$$\epsilon_{\text{Si}} = \epsilon_{\text{r,Si}} \cdot \epsilon_0 \quad (4.17)$$

$$\gamma_{0,\text{dc}} = \sqrt{2 \cdot q \cdot \epsilon_{\text{Si}} \cdot \mathbf{NEFF}}/C_{\text{ox}} \quad (4.18)$$

$$\gamma_{0,\text{ac}} = \sqrt{2 \cdot q \cdot \epsilon_{\text{Si}} \cdot N_{\text{eff,ac}}}/C_{\text{ox}} \quad (4.19)$$

$$G_{0,\text{dc}}^{\text{cl}} = \gamma_{0,\text{dc}}/\sqrt{\phi_{\text{T}}} \quad (4.20)$$

$$G_{0,\text{ac}}^{\text{cl}} = \gamma_{0,\text{ac}}/\sqrt{\phi_{\text{T}}} \quad (4.21)$$

Interface states parameter

$$C_{\text{T}} = \mathbf{CT} \cdot (T_{\text{KR}}/T_{\text{KD}})^{\mathbf{STCT}} \quad (4.22)$$

$$C_{\text{TG}} = \mathbf{CTG} \cdot (T_{\text{KD}}/T_{\text{KR}}) \quad (4.23)$$

Polysilicon depletion parameter

$$k_{\text{P}} = \begin{cases} \text{if } \mathbf{NP} = 0 & \left\{ \begin{array}{l} k_{\text{P}} = 0 \end{array} \right. \\ \text{if } \mathbf{NP} > 0 & \left\{ \begin{array}{l} \mathbf{NP}_1 = \text{MAX}(\mathbf{NP}, 8 \cdot 10^7/\mathbf{TOX}^2) \\ \mathbf{NP}_2 = \text{MAX}(\mathbf{NP}_1, 5 \cdot 10^{24}) \\ k_{\text{P}} = 2 \cdot \phi_{\text{T}} \cdot C_{\text{ox}}^2/(q \cdot \epsilon_{\text{Si}} \cdot \mathbf{NP}_2) \end{array} \right. \end{cases} \quad (4.24)$$

Quantum-mechanical correction parameters

$$q_{\text{lim}} = 10 \cdot \phi_{\text{T}} \quad (4.25)$$

$$q_{\text{q}} = \begin{cases} 0.4 \cdot \mathbf{QMC} \cdot QM_{\text{N}} \cdot C_{\text{ox}}^{2/3} & \text{for NMOS} \\ 0.4 \cdot \mathbf{QMC} \cdot QM_{\text{P}} \cdot C_{\text{ox}}^{2/3} & \text{for PMOS} \end{cases} \quad (4.26)$$

$$q_{\text{b0,dc}} = \gamma_{0,\text{dc}} \cdot \sqrt{\phi_{\text{B,dc}}^{\text{cl}}} \quad (4.27)$$

$$q_{\text{b0,ac}} = \gamma_{0,\text{ac}} \cdot \sqrt{\phi_{\text{B,ac}}^{\text{cl}}} \quad (4.28)$$

$$\phi_{\text{B,dc}} = \phi_{\text{B,dc}}^{\text{cl}} + 0.75 \cdot q_{\text{q}} \cdot q_{\text{b0,dc}}^{2/3} \quad (4.29)$$

$$\phi_{\text{B,ac}} = \phi_{\text{B,ac}}^{\text{cl}} + 0.75 \cdot q_{\text{q}} \cdot q_{\text{b0,ac}}^{2/3} \quad (4.30)$$

$$\mathbf{G}_{0,\text{dc}} = G_{0,\text{dc}}^{\text{cl}} \cdot \left(1 + q_{\text{q}} \cdot q_{\text{b0,dc}}^{-1/3}\right) \quad (4.31)$$

$$\mathbf{G}_{0,\text{ac}} = G_{0,\text{ac}}^{\text{cl}} \cdot \left(1 + q_{\text{q}} \cdot q_{\text{b0,ac}}^{-1/3}\right) \quad (4.32)$$

V_{SB} -clipping parameters

$$\phi_{X,dc} = 0.95 \cdot \phi_{B,dc} \quad (4.33)$$

$$\phi_{X,ac} = 0.95 \cdot \phi_{B,ac} \quad (4.34)$$

$$a_{\phi,dc} = 2.5 \cdot 10^{-3} \cdot \phi_{B,dc}^2 \quad (4.35)$$

$$a_{\phi,ac} = 2.5 \cdot 10^{-3} \cdot \phi_{B,ac}^2 \quad (4.36)$$

$$b_{\phi,dc} = 2.5 \cdot 10^{-3} \cdot \phi_{B,dc}^2 \quad (4.37)$$

$$b_{\phi,ac} = 2.5 \cdot 10^{-3} \cdot \phi_{B,ac}^2 \quad (4.38)$$

$$\phi_{X,dc}^* = \text{MINA} \left(\phi_{X,dc} - 0.5 \cdot \sqrt{b_{\phi,dc}}, 0, a_{\phi,dc} \right) \quad (4.39)$$

$$\phi_{X,ac}^* = \text{MINA} \left(\phi_{X,ac} - 0.5 \cdot \sqrt{b_{\phi,ac}}, 0, a_{\phi,ac} \right) \quad (4.40)$$

NUD parameters

$$u_{s1} = \sqrt{\text{VSBNUD} + \phi_{B,dc}} - \sqrt{\phi_{B,dc}} \quad (4.41)$$

$$u_{s21} = \sqrt{\text{DVSBNUD} + \phi_{B,dc}} - \sqrt{\phi_{B,dc}} - u_{s1} \quad (4.42)$$

Local process parameters in gate overlap regions

$$\gamma_{ov} = \sqrt{2 \cdot q \cdot \epsilon_{Si} \cdot \text{NOV} \cdot \text{TOXOV}} / \epsilon_{ox} \quad (4.43)$$

$$\gamma_{dov} = \sqrt{2 \cdot q \cdot \epsilon_{Si} \cdot \text{NOVD} \cdot \text{TOXOVD}} / \epsilon_{ox} \quad (4.44)$$

$$G_{ov} = \gamma_{ov} / \sqrt{\phi_T} \quad (4.45)$$

$$G_{dov} = \gamma_{dov} / \sqrt{\phi_T} \quad (4.46)$$

$$\epsilon_{ov} = 3.1 \cdot G_{ov} + 8.5 \quad (4.47)$$

$$a_{ov} = \begin{cases} 64/G_{ov} & \text{for } 1/G_{ov} < 0.06 \\ 22/G_{ov} + 3 & \text{for } 0.06 \leq 1/G_{ov} \leq 0.45 \\ -7.2/G_{ov} + 15.5 & \text{for } 0.45 < 1/G_{ov} \leq 1.6 \\ G_{ov} & \text{for } 1/G_{ov} > 1.6 \end{cases} \quad (4.48)$$

$$\delta_{ov} = \frac{\epsilon_{ov}}{2} + \frac{G_{ov}^2}{2} - G_{ov} \cdot \sqrt{\frac{\epsilon_{ov}}{2} + \frac{G_{ov}^2}{4} + a_{ov}} \quad (4.49)$$

$$\epsilon_{dov} = 3.1 \cdot G_{dov} + 8.5 \quad (4.50)$$

$$a_{\text{dov}} = \begin{cases} 64/G_{\text{dov}} & \text{for } 1/G_{\text{dov}} < 0.06 \\ 22/G_{\text{dov}} + 3 & \text{for } 0.06 \leq 1/G_{\text{dov}} \leq 0.45 \\ -7.2/G_{\text{dov}} + 15.5 & \text{for } 0.45 < 1/G_{\text{dov}} \leq 1.6 \\ G_{\text{dov}} & \text{for } 1/G_{\text{dov}} > 1.6 \end{cases} \quad (4.51)$$

$$\delta_{\text{dov}} = \frac{\varepsilon_{\text{dov}}}{2} + \frac{G_{\text{dov}}^2}{2} - G_{\text{dov}} \cdot \sqrt{\frac{\varepsilon_{\text{dov}}}{2} + \frac{G_{\text{dov}}^2}{4} + a_{\text{dov}}} \quad (4.52)$$

Mobility parameters

$$\beta = \text{FACTUO} \cdot \text{BETN} \cdot C_{\text{ox}} \cdot (T_{\text{KR}}/T_{\text{KD}})^{\text{STBET}} \quad (4.53)$$

$$\theta_{\mu} = \text{THEMU} \cdot (T_{\text{KR}}/T_{\text{KD}})^{\text{STTHEMU}} \quad (4.54)$$

$$\mu_{\text{E}} = \text{MUE} \cdot (T_{\text{KR}}/T_{\text{KD}})^{\text{STMUE}} \quad (4.55)$$

$$X_{\text{cor}} = \text{XCOR} \cdot (T_{\text{KR}}/T_{\text{KD}})^{\text{STXCOR}} \quad (4.56)$$

$$C_{\text{S}} = \text{CS} \cdot (T_{\text{KR}}/T_{\text{KD}})^{\text{STCS}} \quad (4.57)$$

$$\theta_{\text{cs}} = \text{THECS} \cdot (T_{\text{KR}}/T_{\text{KD}})^{\text{STTHECS}} \quad (4.58)$$

$$E_{\text{eff0}} = 10^{-8} \cdot C_{\text{ox}}/\epsilon_{\text{Si}} \quad (4.59)$$

$$\eta_{\mu} = \begin{cases} 1/2 \cdot \text{FETA} & \text{for NMOS} \\ 1/3 \cdot \text{FETA} & \text{for PMOS} \end{cases} \quad (4.60)$$

$$\eta_{\mu,\text{ac}} = \begin{cases} 1/2 & \text{for NMOS} \\ 1/3 & \text{for PMOS} \end{cases} \quad (4.61)$$

Series resistance parameter

$$R_{\text{s}} = \text{RS} \cdot (T_{\text{KR}}/T_{\text{KD}})^{\text{STRS}} \quad (4.62)$$

$$\theta_{\text{R}} = 2 \cdot \beta \cdot R_{\text{s}} \quad (4.63)$$

Velocity saturation parameter

$$\theta_{\text{sat}} = \text{THESAT} \cdot (T_{\text{KR}}/T_{\text{KD}})^{\text{STTHESAT}} \quad (4.64)$$

Gate current parameters

$$I_{\text{GINV}} = \text{IGINV} \cdot (T_{\text{KA}}/T_{\text{KR}})^{\text{STIG}} \quad (4.65)$$

$$I_{\text{GOV}} = \text{IGOV} \cdot (T_{\text{KA}}/T_{\text{KR}})^{\text{STIG}} \quad (4.66)$$

$$I_{GOVD} = IGOVD \cdot (T_{KA}/T_{KR})^{STIG} \quad (4.67)$$

$$B = \frac{4}{3} \cdot \frac{TOX}{\hbar} \cdot \sqrt{2 \cdot q \cdot m_0 \cdot CHIB} = 6.830909 \cdot 10^9 \cdot TOX \cdot \sqrt{CHIB} \quad (4.68)$$

$$B_{ov} = B \cdot TOXOV/TOX \quad (4.69)$$

$$B_{ovd} = B \cdot TOXOVD/TOX \quad (4.70)$$

$$GC_Q = \begin{cases} -0.99 \cdot \frac{GC2}{2 \cdot GC3} & \text{for } GC3 < 0 \\ 0 & \text{for } GC3 \geq 0 \end{cases} \quad (4.71)$$

$$\alpha_b = \frac{E_g/q + \phi_{B,dc}}{2} \quad (4.72)$$

Gate-induced drain leakage parameters

$$A_{GIDL} = AGIDL \cdot \left(\frac{2 \cdot 10^{-9}}{TOXOV} \right)^2 \quad (4.73)$$

$$A_{GIDLd} = AGIDLd \cdot \left(\frac{2 \cdot 10^{-9}}{TOXOVD} \right)^2 \quad (4.74)$$

$$B_{GIDL} = BGIDL \cdot \text{MAX}([1 + STBGIDL \cdot \Delta T_A], 0) \cdot \left(\frac{TOXOV}{2 \cdot 10^{-9}} \right) \quad (4.75)$$

$$B_{GIDLd} = BGIDLd \cdot \text{MAX}([1 + STBGIDLd \cdot \Delta T_A], 0) \cdot \left(\frac{TOXOVD}{2 \cdot 10^{-9}} \right) \quad (4.76)$$

Noise parameter

$$N_T = FNT \cdot 4 \cdot k_B \cdot T_{KD} \quad (4.77)$$

Edge transistor parameters

$$V_{FB,edge} = VFBEDGE + STVFBEDGE \cdot \Delta T + DELVTOEDGE \quad (4.78)$$

$$\beta_{edge} = FACTUOEDGE \cdot BETNEDGE \cdot C_{ox} \cdot (T_{KR}/T_{KD})^{STBETEDGE} \quad (4.79)$$

$$\phi_{T0,edge}^* = \phi_T \cdot \left(1 + CTEDGE \cdot \frac{T_{KR}}{T_{KD}} \right) \quad (4.80)$$

$$\phi_{B,edge} = \text{MAX}(\text{DPHIBEDGE} + 2 \cdot \phi_{T0,edge}^* \cdot \ln[\text{NEFFEDGE}/n_i], 0.05) \quad (4.81)$$

$$\gamma_{edge} = \sqrt{2 \cdot q \cdot \epsilon_{Si} \cdot \text{NEFFEDGE}}/C_{ox} \quad (4.82)$$

$$G_{edge} = \gamma_{edge}/\sqrt{\phi_T} \quad (4.83)$$

$$\phi_{X,edge} = 0.95 \cdot \phi_{B,edge} \quad (4.84)$$

$$a_{\phi,\text{edge}} = 2.5 \cdot 10^{-3} \cdot \phi_{\text{B,edge}}^2 \quad (4.85)$$

$$b_{\phi,\text{edge}} = 2.5 \cdot 10^{-3} \cdot \phi_{\text{B,edge}}^2 \quad (4.86)$$

$$\phi_{\text{X,edge}}^* = \text{MINA} \left(\phi_{\text{X,edge}} - \frac{\sqrt{b_{\phi,\text{edge}}}}{2}, 0, a_{\phi,\text{edge}} \right) \quad (4.87)$$

$$N_{\text{T,edge}} = \text{FNTEEDGE} \cdot 4 \cdot k_{\text{B}} \cdot T_{\text{KD}} \quad (4.88)$$

Impact-ionization parameter

$$a_2 = \text{A2} \cdot (T_{\text{KD}}/T_{\text{KR}})^{\text{STA2}} \quad (4.89)$$

Self heating

$$R_{\text{TH}} = \text{RTH} \cdot \left(\frac{T_{\text{KA}}}{T_{\text{KR}}} \right)^{\text{STRTH}} \quad (4.90)$$

Additional internal parameters

$$x_1 = 1.25 \quad (4.91)$$

4.2 Current Model

In this section, the current model equations of the PSP-model are given. Use is made of the applied terminal bias values V_{GS} , V_{DS} and V_{SB} , the local parameters listed in Section 2.5.2 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 $\text{MINA}(\cdot)$, $\text{MAXA}(\cdot)$, $\chi(\cdot)$ and $\sigma_{1,2}(\cdot)$ can be found in Appendix A.

Depending on the value of the parameters **SWNUD** and **SWDELVTAC**, the surface potential (at source- and drain-side of the channel) and associated computations, i.e., Eqs. (4.103)–(4.202), may be evaluated twice: once for the dc-characteristics and a second time for the ac-characteristics of the model. Details are given below.

4.2.1 Conditioning of Terminal Voltages

$$V_{\text{dsx}} = \frac{V_{\text{DS}}^2}{\sqrt{V_{\text{DS}}^2 + 0.01} + 0.1} \quad (4.92)$$

$$\phi_{\text{V,dc}} = \text{MINA}(V_{\text{SB}}, V_{\text{SB}} + V_{\text{DS}}, \mathbf{b}_{\phi,\text{dc}}) + \phi_{\mathbf{X},\text{dc}} \quad (4.93)$$

$$\phi_{\text{V,ac}} = \text{MINA}(V_{\text{SB}}, V_{\text{SB}} + V_{\text{DS}}, \mathbf{b}_{\phi,\text{ac}}) + \phi_{\mathbf{X},\text{ac}} \quad (4.94)$$

$$V_{\text{SB,dc}}^* = V_{\text{SB}} - \text{MINA}(\phi_{\text{V,dc}}, 0, \mathbf{a}_{\phi,\text{dc}}) + \phi_{\mathbf{X},\text{dc}}^* \quad (4.95)$$

$$V_{\text{SB,ac}}^* = V_{\text{SB}} - \text{MINA}(\phi_{\text{V,ac}}, 0, \mathbf{a}_{\phi,\text{ac}}) + \phi_{\mathbf{X},\text{ac}}^* \quad (4.96)$$

Nonuniform doping effect. Eqs. (4.97)–(4.102) are only evaluated when **SWNUD** \neq 0 and **GFACNUD** \neq 1:

$$V_{\text{mB}} = V_{\text{SB}}^* + 0.5 \cdot (V_{\text{DS}} - V_{\text{dsx}}) \quad (4.97)$$

$$u_{\text{s}} = \sqrt{V_{\text{mB}} + \phi_{\mathbf{B}}} - \sqrt{\phi_{\mathbf{B}}} \quad (4.98)$$

$$p = 2 \cdot \frac{u_{\text{s}} - \mathbf{u}_{\text{s1}}}{\mathbf{u}_{\text{s21}}} - 1 \quad (4.99)$$

$$u_{\text{s,nud}} = u_{\text{s}} - 0.25 \cdot (1 - \mathbf{GFACNUD}) \cdot \mathbf{u}_{\text{s21}} \cdot \left\{ p + \sqrt{p^2 + [\ln(2)]^2} \right\} \quad (4.100)$$

$$V_{\text{mB,nud}} = \left(u_{\text{s,nud}} + 2 \cdot \sqrt{\phi_{\mathbf{B}}} \right) \cdot u_{\text{s,nud}} \quad (4.101)$$

$$V_{\text{SB,dc}}^* = V_{\text{mB,nud}} - 0.5 \cdot (V_{\text{DS}} - V_{\text{dsx}}) \quad (4.102)$$

The surface potential (at source- and drain-side of the channel) and associated computations, i.e., Eqs. (4.103)–(4.202), are evaluated using $V_{\text{SB}}^* = V_{\text{SB,dc}}^*$, $\phi_{\mathbf{B}} = \phi_{\mathbf{B},\text{dc}}$, and $\mathbf{G}_0 = \mathbf{G}_{0,\text{dc}}$.

If **SWNUD** = 1 or **SWDELVTAC** = 1, Eqs. (4.103)–(4.202) are evaluated a second time using $V_{\text{SB}}^* = V_{\text{SB,ac}}^*$, $\phi_{\mathbf{B}} = \phi_{\mathbf{B},\text{ac}}$, and $\mathbf{G}_0 = \mathbf{G}_{0,\text{ac}}$.

$$V_{\text{DB}}^* = V_{\text{DS}} + V_{\text{SB}}^* \quad (4.103)$$

$$V_{\text{sbx}} = V_{\text{SB}}^* + \frac{V_{\text{DS}} - V_{\text{dsx}}}{2} \quad (4.104)$$

4.2.2 Short Channel effects

Drain-induced barrier lowering:

$$V_{ds}^* = \begin{cases} V_{dsx} & \text{for } \mathbf{CFD} < 10^{-10} \\ 2 \cdot (\sqrt{1.0 + \mathbf{CFD} \cdot V_{dsx}} - 1) / \mathbf{CFD} & \text{for } \mathbf{CFD} \geq 10^{-10} \end{cases} \quad (4.105)$$

$$\Delta V_G = \mathbf{CF} \cdot V_{dsx}^* \cdot (1 + \mathbf{CFB} \cdot V_{sbx}) \quad (4.106)$$

$$V_{GB}^* = V_{GS} + V_{SB}^* + \Delta V_G - V_{FB} \quad (4.107)$$

Subthreshold slope degradation induced by short channel effects:

$$n_{SCE} = 1 + \mathbf{PSCE} \cdot (1 + \mathbf{PSCED} \cdot V_{dsx}) \cdot (1 + \mathbf{PSCEB} \cdot V_{sbx}) \quad (4.108)$$

4.2.3 Bias-Dependent Body Factor

$$D_{nsub} = \mathbf{DNSUB} \cdot \text{MAXA}(0, V_{GS} + V_{SB} - \mathbf{VNSUB}, \mathbf{NSLP}) \quad (4.109)$$

$$G = \mathbf{G}_0 \cdot \sqrt{1 + D_{nsub}} \quad (4.110)$$

4.2.4 Interface States Including Bias Dependences

$$x_{g,ct} = V_{GB}^* / \phi_T \quad (4.111)$$

$$x_{s0,ct} = \frac{1}{2} \cdot \left(G^2 + 2 \cdot x_{g,ct} - G \cdot \sqrt{\text{MAXA}((G^2 + 4 \cdot x_{g,ct}), 0, 5)} \right) \quad (4.112)$$

$$x_{b,ct} = \frac{\phi_B + V_{sbx}}{\phi_T} \quad (4.113)$$

$$x_{s,ct} = \text{MINA}(x_{s0,ct}, (x_{b,ct} + 2), 5) \quad (4.114)$$

$$C_{T,eff} = \mathbf{C}_T \cdot \exp\left(\mathbf{CTG} \cdot \left(x_{s,ct} - (1 + \mathbf{CTB}) \cdot \left(x_{b,ct} - \frac{\phi_B}{2 \cdot \phi_T}\right)\right)\right) \quad (4.115)$$

$$\phi_T^* = \phi_T \cdot n_{SCE} \cdot (1 + C_{T,eff}) \quad (4.116)$$

$$x_g = V_{GB}^* / \phi_T^* \quad (4.117)$$

4.2.5 Surface Potential at Source Side and Related Variables

$$\xi = 1 + G / \sqrt{2} \quad (4.118)$$

$$x_{ns} = \frac{\phi_B + V_{SB}^*}{\phi_T^*} \quad (4.119)$$

$$\Delta_{ns} = \exp(-x_{ns}) \quad (4.120)$$

$$x_{mrg} = 10^{-5} \cdot \xi \quad (4.121)$$

$$\text{if } x_g < -x_{\text{mrg}} \left\{ \begin{array}{l}
y_g = -x_g \\
z = 1.25 \cdot y_g / \xi \\
\eta = \left[z + 10 - \sqrt{(z - 6)^2 + 64} \right] / 2 \\
a = (y_g - \eta)^2 + G^2 \cdot (\eta + 1) \\
c = 2 \cdot (y_g - \eta) - G^2 \\
\tau = -\eta + \ln(a/G^2) \\
y_0 = \sigma_1(a, c, \tau, \eta) \\
\Delta_0 = \exp(y_0) \\
p = 2 \cdot (y_g - y_0) + G^2 \cdot [\Delta_0 - 1 + \Delta_{\text{ns}} \cdot (1 - \chi'(y_0) - 1/\Delta_0)] \\
q = (y_g - y_0)^2 + G^2 \cdot [y_0 - \Delta_0 + 1 + \Delta_{\text{ns}} \cdot (1 + \chi(y_0) - 1/\Delta_0 - 2 \cdot y_0)] \\
x_s = -y_0 - \frac{2 \cdot q}{p + \sqrt{p^2 - 2 \cdot q \cdot \{2 - G^2 \cdot [\Delta_0 + \Delta_{\text{ns}} \cdot (1/\Delta_0 - \chi''(y_0))]\}}}
\end{array} \right. \quad (4.122)$$

$$\text{if } |x_g| \leq x_{\text{mrg}} \left\{ x_s = \frac{x_g}{\xi} \cdot \left[1 + G \cdot x_g \cdot \frac{1 - \Delta_{\text{ns}}}{\xi^2 \cdot 6 \cdot \sqrt{2}} \right] \right. \quad (4.123)$$

$$\text{if } x_g > x_{\text{mrg}} \left\{ \begin{array}{l}
\hat{x}_{g1} = \mathbf{x}_1 + G \cdot \sqrt{\exp(-\mathbf{x}_1) + \mathbf{x}_1 - 1} \\
\bar{x} = \frac{x_g}{\xi} \cdot \left[1 + x_g \cdot (\xi \cdot \mathbf{x}_1 - \hat{x}_{g1}) / \hat{x}_{g1}^2 \right] \\
x_0 = x_g + G^2/2 - G \cdot \sqrt{x_g + G^2/4 - 1 + \exp(-\bar{x})} \\
b_x = x_{\text{ns}} + 3 \\
\eta = \text{MINA}(x_0, b_x, 5) - (b_x - \sqrt{b_x^2 + 5}) / 2 \\
a = (x_g - \eta)^2 - G^2 \cdot [\exp(-\eta) + \eta - 1 - \Delta_{\text{ns}} \cdot (\eta + 1 + \chi(\eta))] \\
b = 1 - G^2/2 \cdot [\exp(-\eta) - \Delta_{\text{ns}} \cdot \chi''(\eta)] \\
c = 2 \cdot (x_g - \eta) + G^2 \cdot [1 - \exp(-\eta) - \Delta_{\text{ns}} \cdot (1 + \chi'(\eta))] \\
\tau = x_{\text{ns}} - \eta + \ln(a/G^2) \\
y_0 = \sigma_2(a, b, c, \tau, \eta) \\
\Delta_0 = \exp(y_0) \\
p = 2 \cdot (x_g - y_0) + G^2 \cdot [1 - 1/\Delta_0 + \Delta_{\text{ns}} \cdot (\Delta_0 - 1 - \chi'(y_0))] \\
q = (x_g - y_0)^2 - G^2 \cdot [y_0 + 1/\Delta_0 - 1 + \Delta_{\text{ns}} \cdot (\Delta_0 - y_0 - 1 - \chi(y_0))] \\
x_s = y_0 + \frac{2 \cdot q}{p + \sqrt{p^2 - 2 \cdot q \cdot \{1/\Delta_0 + \Delta_{\text{ns}} \cdot (\Delta_0 - \chi''(y_0))\}}}
\end{array} \right. \quad (4.124)$$

Eqs. (4.125)-(4.127) are only calculated for $x_g > 0$.

$$E_s = \exp(-x_s) \quad (4.125)$$

$$D_s = [1/E_s - x_s - 1 - \chi(x_s)] \cdot \Delta_{ns} \quad (4.126)$$

$$P_s = x_s - 1 + E_s \quad (4.127)$$

$$x_{gs} = \begin{cases} x_g - x_s & \text{for } x_g \leq 0 \\ G \cdot \sqrt{D_s + P_s} & \text{for } x_g > 0 \end{cases} \quad (4.128)$$

$$\psi_{ss} = \phi_T^* \cdot x_s \quad (4.129)$$

4.2.6 Drain Saturation Voltage

Eqs. (4.130)-(4.150) are only calculated for $x_g > 0$.

$$q_{is} = \frac{G^2 \cdot \phi_T^* \cdot D_s}{x_{gs} + G \cdot \sqrt{P_s}} \quad (4.130)$$

$$\alpha_s = 1 + \frac{G \cdot (1 - E_s)}{2 \cdot \sqrt{P_s}} \quad (4.131)$$

$$q_{bs} = \phi_T^* \cdot G \cdot \sqrt{P_s} \quad (4.132)$$

$$\rho_b = \begin{cases} 1 + \mathbf{RSB} \cdot V_{sbx} & \text{for } \mathbf{RSB} \geq 0 \\ \frac{1}{1 - \mathbf{RSB} \cdot V_{sbx}} & \text{for } \mathbf{RSB} < 0 \end{cases} \quad (4.133)$$

$$\rho_{g,s} = \begin{cases} \frac{1}{1 + \mathbf{RSG} \cdot q_{is}} & \text{for } \mathbf{RSG} \geq 0 \\ 1 - \mathbf{RSG} \cdot q_{is} & \text{for } \mathbf{RSG} < 0 \end{cases} \quad (4.134)$$

$$\rho_s = \theta_R \cdot \rho_b \cdot \rho_{g,s} \cdot q_{is} \quad (4.135)$$

$$\mu_x = \frac{1 + \mathbf{X}_{cor} \cdot V_{sbx}}{1 + 0.2 \cdot \mathbf{X}_{cor} \cdot V_{sbx}} \quad (4.136)$$

$$E_{eff,s} = \mathbf{E}_{eff0} \cdot (q_{bs} + \eta_\mu \cdot q_{is}) \quad (4.137)$$

$$G_{mob,s} = \frac{1 + (\mu_E \cdot E_{eff,s})^{\theta_\mu} + C_S \cdot \left(\frac{q_{bs}}{q_{is} + q_{bs}} \right)^{\theta_{cs}}}{\mu_x} + \rho_s \quad (4.138)$$

$$\xi_{tb} = \begin{cases} 1 + \mathbf{THESATB} \cdot V_{sbx} & \text{for } \mathbf{THESATB} \geq 0 \\ \frac{1}{1 - \mathbf{THESATB} \cdot V_{sbx}} & \text{for } \mathbf{THESATB} < 0 \end{cases} \quad (4.139)$$

$$w_{sat,s} = \frac{100 \cdot q_{is} \cdot \xi_{tb}}{100 + q_{is} \cdot \xi_{tb}} \quad (4.140)$$

$$\theta_{\text{sat},s}^* = \begin{cases} \frac{\theta_{\text{sat}}}{G_{\text{mob},s}} \cdot (1 + \text{THESATG} \cdot w_{\text{sat},s}) & \text{for } \text{THESATG} \geq 0 \\ \frac{\theta_{\text{sat}}}{G_{\text{mob},s}} \cdot \frac{1}{1 - \text{THESATG} \cdot w_{\text{sat},s}} & \text{for } \text{THESATG} < 0 \end{cases} \quad (4.141)$$

$$\phi_{\infty} = q_{\text{is}}/\alpha_s + \phi_{\text{T}}^* \quad (4.142)$$

$$y_{\text{sat}} = \begin{cases} \theta_{\text{sat},s}^* \cdot \phi_{\infty}/\sqrt{2} & \text{for NMOS} \\ \frac{\theta_{\text{sat},s}^* \cdot \phi_{\infty}/\sqrt{2}}{\sqrt{1 + \theta_{\text{sat},s}^* \cdot \phi_{\infty}/\sqrt{2}}} & \text{for PMOS} \end{cases} \quad (4.143)$$

$$z_a = \frac{2}{1 + \sqrt{1 + 4 \cdot y_{\text{sat}}}} \quad (4.144)$$

$$\phi_0 = \phi_{\infty} \cdot z_a \cdot \left[1 + 0.86 \cdot z_a \cdot y_{\text{sat}} \cdot \frac{1 - z_a^2 \cdot y_{\text{sat}}}{1 + 4 \cdot z_a^3 \cdot y_{\text{sat}}^2} \right] \quad (4.145)$$

$$a_{\text{sat}} = x_{\text{gs}} + G^2/2 \quad (4.146)$$

$$\phi_2 = \frac{\phi_{\text{T}}^* \cdot 0.98 \cdot G^2 \cdot D_s}{a_{\text{sat}} + \sqrt{a_{\text{sat}}^2 - 0.98 \cdot G^2 \cdot D_s}} \quad (4.147)$$

$$\phi_{\text{sat}} = \frac{2 \cdot \phi_0 \cdot \phi_2}{\phi_0 + \phi_2 + \sqrt{(\phi_0 + \phi_2)^2 - 3.96 \cdot \phi_0 \cdot \phi_2}} \quad (4.148)$$

$$V_{\text{dsat}} = \phi_{\text{sat}} - \phi_{\text{T}}^* \cdot \ln \left[1 + \frac{\phi_{\text{sat}} \cdot (\phi_{\text{sat}} - 2 \cdot a_{\text{sat}} \cdot \phi_{\text{T}}^*)}{G^2 \cdot D_s \cdot \phi_{\text{T}}^{*2}} \right] \quad (4.149)$$

$$V_{\text{dse}} = \frac{V_{\text{DS}}}{\left[1 + (V_{\text{DS}}/V_{\text{dsat}})^{\text{AX}} \right]^{1/\text{AX}}} \quad (4.150)$$

4.2.7 Surface Potential at Drain Side and Related Variables

Eqs. (4.151)-(4.160) are only calculated for $x_g > 0$.

$$x_{\text{nd}} = \frac{\phi_{\text{B}} + V_{\text{SB}}^* + V_{\text{dse}}}{\phi_{\text{T}}^*} \quad (4.151)$$

$$k_{\text{ds}} = \exp(-V_{\text{dse}}/\phi_{\text{T}}^*) \quad (4.152)$$

$$\Delta_{\text{nd}} = \Delta_{\text{ns}} \cdot k_{\text{ds}} \quad (4.153)$$

$$\text{if } x_g \leq x_{\text{mrg}} \left\{ x_{\text{d}} = \frac{x_g}{\xi} \cdot \left[1 + G \cdot x_g \cdot \frac{1 - \Delta_{\text{nd}}}{\xi^2 \cdot 6 \cdot \sqrt{2}} \right] \right. \quad (4.154)$$

$$\text{if } x_g > x_{\text{mrg}} \left\{ \begin{array}{l}
 b_x = x_{\text{nd}} + 3.0 \\
 \eta = \text{MINA}(x_0, b_x, 5) - (b_x - \sqrt{b_x^2 + 5}) / 2 \\
 a = (x_g - \eta)^2 - G^2 \cdot [\exp(-\eta) + \eta - 1 - \Delta_{\text{nd}} \cdot (\eta + 1 + \chi(\eta))] \\
 b = 1 - G^2 / 2 \cdot [\exp(-\eta) - \Delta_{\text{nd}} \cdot \chi''(\eta)] \\
 c = 2 \cdot (x_g - \eta) + G^2 \cdot [1 - \exp(-\eta) - \Delta_{\text{nd}} \cdot (1 + \chi'(\eta))] \\
 \tau = x_{\text{nd}} - \eta + \ln(a / G^2) \\
 y_0 = \sigma_2(a, b, c, \tau, \eta) \\
 \Delta_0 = \exp(y_0) \\
 p = 2 \cdot (x_g - y_0) + G^2 \cdot [1 - 1 / \Delta_0 + \Delta_{\text{nd}} \cdot (\Delta_0 - 1 - \chi'(y_0))] \\
 q = (x_g - y_0)^2 - G^2 \cdot [y_0 + 1 / \Delta_0 - 1 + \Delta_{\text{nd}} \cdot (\Delta_0 - y_0 - 1 - \chi(y_0))] \\
 x_d = y_0 + \frac{2 \cdot q}{p + \sqrt{p^2 - 2 \cdot q \cdot \{2 - G^2 \cdot [1 / \Delta_0 + \Delta_{\text{nd}} \cdot (\Delta_0 - \chi''(y_0))]\}}}
 \end{array} \right. \quad (4.155)$$

$$x_{\text{ds}} = x_d - x_s \quad (4.156)$$

$$\text{if } x_{\text{ds}} < 10^{-10} \left\{ \begin{array}{l}
 p = 2 \cdot x_{\text{gs}} + G^2 \cdot [1 - E_s + \Delta_{\text{nd}} \cdot (1 / E_s - 1 - \chi'(x_s))] \\
 q = G^2 \cdot (1 - k_{\text{ds}}) \cdot D_s \\
 \xi = 1 - G^2 / 2 \cdot [E_s + \Delta_{\text{nd}} (1 / E_s - \chi''(x_s))] \\
 x_{\text{ds}} = \frac{2 \cdot q}{p + \sqrt{p^2 - 4 \cdot \xi \cdot q}} \\
 x_d = x_s + x_{\text{ds}}
 \end{array} \right. \quad (4.157)$$

$$E_d = \exp(-x_d) \quad (4.158)$$

$$D_d = (1 / E_d - x_d - 1 - \chi(x_d)) \cdot \Delta_{\text{nd}} \quad (4.159)$$

$$\Delta\psi = \phi_{\text{T}}^* \cdot x_{\text{ds}} \quad (4.160)$$

$$\psi_{\text{sd}} = \phi_{\text{T}}^* \cdot x_d \quad (4.161)$$

4.2.8 Mid-Point Surface Potential and Related Variables

$$\text{if } x_g > 0 \left\{ \begin{array}{l}
 x_m = (x_s + x_d) / 2 \\
 E_m = \sqrt{E_s \cdot E_d} \\
 \bar{D} = (D_s + D_d) / 2 \\
 D_m = \bar{D} + x_{\text{ds}}^2 / 8 \cdot (E_m - 2 / G^2) \\
 P_m = x_m - 1 + E_m \\
 x_{\text{gm}} = G \cdot \sqrt{D_m + P_m}
 \end{array} \right. \quad (4.162)$$

$$\text{if } x_g \leq 0 \begin{cases} x_m = x_s \\ x_{gm} = x_g - x_s \end{cases} \quad (4.163)$$

4.2.9 Polysilicon Depletion

Eqs. (4.164)-(4.178) are only calculated for $k_p > 0$ and $x_g > 0$ (otherwise $\eta_p = 1$):

$$x_m^{(0)} = x_m, \quad x_{ds}^{(0)} = x_{ds}, \quad D_m^{(0)} = D_m, \quad E_m^{(0)} = E_m, \quad (4.164)$$

$$d_0 = 1 - E_m^{(0)} + 2 \cdot x_{gm}/G^2 \quad (4.165)$$

$$\eta_p = 1/\sqrt{1 + k_p \cdot x_{gm}} \quad (4.166)$$

$$x_{pm} = k_p \cdot \left[\frac{\eta_p \cdot x_{gm}}{1 + \eta_p} \right]^2 \cdot \frac{D_m^{(0)}}{D_m^{(0)} + P_m} \quad (4.167)$$

$$p = 2 \cdot (x_{gm} - x_{pm}) + G^2 \cdot (1 - E_m^{(0)} + D_m^{(0)}) \quad (4.168)$$

$$q = x_{pm} \cdot (x_{pm} - 2 \cdot x_{gm}) \quad (4.169)$$

$$\xi_p = 1 - G^2/2 \cdot (E_m^{(0)} + D_m^{(0)}) \quad (4.170)$$

$$u_p = \frac{p \cdot q}{p^2 - \xi_p \cdot q} \quad (4.171)$$

$$x_m = x_m^{(0)} + u_p \quad (4.172)$$

$$E_m = E_m^{(0)} \cdot \exp(-u_p) \quad (4.173)$$

$$D_m = D_m^{(0)} \cdot \exp(u_p) \quad (4.174)$$

$$P_m = x_m - 1 + E_m \quad (4.175)$$

$$x_{gm} = G \cdot \sqrt{D_m + P_m} \quad (4.176)$$

$$x_{ds} = x_{ds}^{(0)} \cdot \frac{\exp(u_p) \cdot [\bar{D} + d_0]}{1 - E_m + 2 \cdot x_{gm} \cdot \eta_p/G^2 + \exp(u_p) \cdot \bar{D}} \quad (4.177)$$

$$\Delta\psi = \phi_T^* \cdot x_{ds} \quad (4.178)$$

4.2.10 Potential Mid-Point Inversion Charge and Related Variables

Eqs. (4.179)-(4.187) are only calculated for $x_g > 0$.

$$q_{im} = \frac{G^2 \cdot \phi_T^* \cdot D_m}{x_{gm} + G \cdot \sqrt{P_m}} \quad (4.179)$$

$$\alpha_m = \eta_p + \frac{G \cdot (1 - E_m)}{2 \cdot \sqrt{P_m}} \quad (4.180)$$

$$q_{im}^* = q_{im} + \phi_T^* \cdot \alpha_m \quad (4.181)$$

$$q_{bm} = \phi_T^* \cdot G \cdot \sqrt{P_m} \quad (4.182)$$

Series resistance:

$$\rho_g = \begin{cases} \frac{1}{1 + \mathbf{RSG} \cdot q_{im}} & \text{for } \mathbf{RSG} \geq 0 \\ 1 - \mathbf{RSG} \cdot q_{im} & \text{for } \mathbf{RSG} < 0 \end{cases} \quad (4.183)$$

$$\rho_s = \theta_R \cdot \rho_b \cdot \rho_g \cdot q_{im} \quad (4.184)$$

Mobility reduction:

$$E_{eff} = \mathbf{E_{eff0}} \cdot (q_{bm} + \eta_\mu \cdot q_{im}) \quad (4.185)$$

$$q_{eff1} = q_{bm} + \eta_{\mu,ac} \cdot q_{im} \quad (4.186)$$

$$G_{mob} = \frac{1 + (\mu_E \cdot E_{eff})^{\theta_\mu} + C_S \cdot \left(\frac{q_{bm}}{q_{im} + q_{bm}}\right)^{\theta_\mu} + \rho}{\mu_x} \quad (4.187)$$

4.2.11 Drain-Source Channel Current

Eqs. (4.188)-(4.199) are only calculated for $x_g > 0$:

Channel length modulation:

$$R_1 = q_{im}/q_{im}^* \quad (4.188)$$

$$R_2 = \phi_T^* \cdot \alpha_m / q_{im}^* \quad (4.189)$$

$$T_1 = \ln \left(\frac{1 + \frac{V_{DS} - \Delta\psi}{\mathbf{VP}}}{1 + \frac{V_{dse} - \Delta\psi}{\mathbf{VP}}} \right) \quad (4.190)$$

$$T_2 = \ln \left(1 + \frac{V_{dsx}}{\mathbf{VP}} \right) \quad (4.191)$$

$$\Delta L/L = \mathbf{ALP} \cdot T_1 \quad (4.192)$$

$$G_{\Delta L} = \frac{1}{1 + \Delta L/L + (\Delta L/L)^2} \quad (4.193)$$

$$\Delta L_1/L = \left[\mathbf{ALP} + \frac{\mathbf{ALP1}}{q_{im}^*} \cdot R_1 \right] \cdot T_1 + \mathbf{ALP2} \cdot q_{bm} \cdot R_2^2 \cdot T_2 \quad (4.194)$$

$$F_{\Delta L} = [1 + \Delta L_1/L + (\Delta L_1/L)^2] \cdot G_{\Delta L} \quad (4.195)$$

Velocity saturation:

$$w_{sat} = \frac{100 \cdot q_{im} \cdot \xi_{tb}}{100 + q_{im} \cdot \xi_{tb}} \quad (4.196)$$

$$\theta_{\text{sat}}^* = \begin{cases} \frac{\theta_{\text{sat}}}{G_{\text{mob},s} \cdot G_{\Delta L}} \cdot (1 + \mathbf{THESATG} \cdot w_{\text{sat}}) & \text{for } \mathbf{THESATG} \geq 0 \\ \frac{\theta_{\text{sat}}}{G_{\text{mob},s} \cdot G_{\Delta L}} \cdot \frac{1}{1 - \mathbf{THESATG} \cdot w_{\text{sat}}} & \text{for } \mathbf{THESATG} < 0 \end{cases} \quad (4.197)$$

$$z_{\text{sat}} = \begin{cases} (\theta_{\text{sat}}^* \cdot \Delta\psi)^2 & \text{for NMOS} \\ \frac{(\theta_{\text{sat}}^* \cdot \Delta\psi)^2}{1 + \theta_{\text{sat}}^* \cdot \Delta\psi} & \text{for PMOS} \end{cases} \quad (4.198)$$

$$G_{\text{vsat}} = \frac{G_{\text{mob}} \cdot G_{\Delta L}}{2} \cdot (1 + \sqrt{1 + 2 \cdot z_{\text{sat}}}) \quad (4.199)$$

Auxiliary Variables for Calculation of Intrinsic Charges and Gate Current. Eqs. (4.200)–(4.202) are only calculated for $x_g > 0$.

$$V_{\text{oxm}} = \phi_{\text{T}}^* \cdot x_{\text{gm}} \quad (4.200)$$

$$\alpha_{\text{m}}' = \alpha_{\text{m}} \cdot \left[1 + \frac{z_{\text{sat}}}{2} \cdot \left(\frac{G_{\text{mob}} \cdot G_{\Delta L}}{G_{\text{vsat}}} \right)^2 \right] \quad (4.201)$$

$$H = \frac{G_{\text{mob}} \cdot G_{\Delta L}}{G_{\text{vsat}}} \cdot \frac{q_{\text{im}}^*}{\alpha_{\text{m}}'} \quad (4.202)$$

In the remainder of this document, some variables (e.g., x_g) are labeled 'dc' or 'ac' (e.g., $x_{g,\text{dc}}$ or $x_{g,\text{ac}}$). Variables labeled 'dc' result from the *first* evaluation of Eqs. (4.103)–(4.202). For variables labeled 'ac', there are two possibilities. If **SWNUD** = 1 or **SWDELVTAC** = 1, their values result from the *second* evaluation of Eqs. (4.103)–(4.202). In any other case, their value is equal to their 'dc'-counterpart.

This applies to the following variables: x_g , $q_{\text{eff}1}$, V_{oxm} , q_{im} , q_{im}^* , α_{m} , $\Delta\psi$, $G_{\Delta L}$, $F_{\Delta L}$, H , η_p , G_{vsat} , V_{dse} , G_{mob} , x_m , G , x_{gm} , θ_{sat}^* .

Drain-Source channel current:

$$I_{\text{DS}} = \begin{cases} 0 & \text{for } x_{g,\text{dc}} \leq 0 \\ \beta \cdot F_{\Delta L,\text{dc}} \cdot \frac{q_{\text{im},\text{dc}}^*}{G_{\text{vsat},\text{dc}}} \cdot \Delta\psi_{\text{dc}} & \text{for } x_{g,\text{dc}} > 0 \end{cases} \quad (4.203)$$

4.2.12 Surface Potential in Gate Overlap Regions

$$x_{\text{sov}}(x_g) = \begin{cases} x'_g = (x_g + \sqrt{x_g^2 + \varepsilon_{\text{ov}}^2}) / 2 \\ x_{\text{sov}} = -x'_g - G_{\text{ov}}^2 / 2 + G_{\text{ov}} \cdot \sqrt{x'_g + G_{\text{ov}}^2 / 4 + a_{\text{ov}} + \delta_{\text{ov}}} \end{cases} \quad (4.204)$$

$$x_{\text{dov}}(x_g) = \begin{cases} x'_g = (x_g + \sqrt{x_g^2 + \varepsilon_{\text{dov}}^2}) / 2 \\ x_{\text{dov}} = -x'_g - G_{\text{dov}}^2 / 2 + G_{\text{dov}} \cdot \sqrt{x'_g + G_{\text{dov}}^2 / 4 + a_{\text{dov}} + \delta_{\text{dov}}} \end{cases} \quad (4.205)$$

$$\psi_{\text{sov}} = -\phi_{\text{T}_A} \cdot x_{\text{sov}} \left(-\frac{V_{\text{GS}}}{\phi_{\text{T}_A}} \right) \quad (4.206)$$

$$\psi_{\text{dov}} = -\phi_{\text{TA}} \cdot x_{\text{dov}} \left(-\frac{V_{\text{GS}} - V_{\text{DS}}}{\phi_{\text{TA}}} \right) \quad (4.207)$$

$$V_{\text{ov}0} = V_{\text{GS}} - \psi_{\text{sov}} \quad (4.208)$$

$$V_{\text{ovL}} = V_{\text{GS}} - V_{\text{DS}} - \psi_{\text{dov}} \quad (4.209)$$

4.2.13 Gate Current

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

Source/Drain gate overlap current:

$$I_{\text{GSov}}(V_{\text{GX}}, \psi_{\text{ov}}, V_{\text{ov}}) = \left\{ \begin{array}{l} V_{\text{ov}}^* = \sqrt{V_{\text{ov}}^2 + 10^{-6}} \\ z_{\text{g}} = \begin{cases} \text{MINA} \left(\frac{V_{\text{ov}}^*}{\text{CHIB}}, \text{GCQ}, 10^{-6} \right) & \text{for } \text{GC3} < 0 \\ \frac{V_{\text{ov}}^*}{\text{CHIB}} & \text{for } \text{GC3} \geq 0 \end{cases} \\ F_{\text{S1}} = \frac{3.0 \cdot \phi_{\text{TA}} + \psi_{\text{ov}}}{\phi_{\text{TA}}} \\ F_{\text{S2}} = -3.0 - \text{GCO} \\ F_{\text{S3}} = 30 \cdot V_{\text{GX}} \\ F_{\text{Sov}} = \text{MXE}(F_{\text{S2}}, \text{MNE}(F_{\text{S1}}, F_{\text{S3}}, 0.9), 0.3) \\ I_{\text{Gov}} = \text{IGOV} \cdot F_{\text{Sov}} \cdot \\ \exp \left(\text{BoV} \cdot \left[-\frac{3}{2} + z_{\text{g}} \cdot (\text{GC2} + \text{GC3} \cdot z_{\text{g}}) \right] \right) \end{array} \right. \quad (4.210)$$

$$I_{\text{GDov}}(V_{\text{GX}}, \psi_{\text{ov}}, V_{\text{ov}}) = \left\{ \begin{array}{l} V_{\text{ov}}^* = \sqrt{V_{\text{ov}}^2 + 10^{-6}} \\ z_{\text{g}} = \begin{cases} \text{MINA} \left(\frac{V_{\text{ov}}^*}{\text{CHIB}}, \text{GCQ}, 10^{-6} \right) & \text{for } \text{GC3} < 0 \\ \frac{V_{\text{ov}}^*}{\text{CHIB}} & \text{for } \text{GC3} \geq 0 \end{cases} \\ F_{\text{S1}} = \frac{3.0 \cdot \phi_{\text{TA}} + \psi_{\text{ov}}}{\phi_{\text{TA}}} \\ F_{\text{S2}} = -3.0 - \text{GCO} \\ F_{\text{S3}} = 30 \cdot V_{\text{GX}} \\ F_{\text{Sov}} = \text{MXE}(F_{\text{S2}}, \text{MNE}(F_{\text{S1}}, F_{\text{S3}}, 0.9), 0.3) \\ I_{\text{Gov}} = \text{IGOVD} \cdot F_{\text{Sov}} \cdot \\ \exp \left(\text{BoVd} \cdot \left[-\frac{3}{2} + z_{\text{g}} \cdot (\text{GC2} + \text{GC3} \cdot z_{\text{g}}) \right] \right) \end{array} \right. \quad (4.211)$$

$$I_{\text{GSov}} = I_{\text{GSov}}(V_{\text{GS}}, \psi_{\text{sov}}, V_{\text{ov}0}) \quad (4.212)$$

$$I_{GDov} = I_{GDov}(V_{GS} - V_{DS}, \psi_{dov}, V_{ovL}) \quad (4.213)$$

Gate-channel current:

$$V_m = V_{SB,dc}^* + \phi_T^* \cdot \left[\frac{x_{ds,dc}}{2} - \ln \left(\frac{1 + \exp(x_{ds,dc} - V_{dse,dc}/\phi_T^*)}{2} \right) \right] \quad (4.214)$$

$$D_{ch} = \mathbf{GCO} \cdot \phi_T^* \quad (4.215)$$

$$\psi_t = \text{MINA}(0, V_{oxm,dc} + D_{ch}, 0.01) \quad (4.216)$$

$$V_{oxm}^* = \sqrt{V_{oxm,dc}^2 + 10^{-6}} \quad (4.217)$$

$$z_g = \begin{cases} \text{MINA} \left(\frac{V_{oxm}^*}{\mathbf{CHIB}}, \mathbf{GCQ}, 10^{-6} \right) & \text{for } \mathbf{GC3} < 0 \\ \frac{V_{oxm}^*}{\mathbf{CHIB}} & \text{for } \mathbf{GC3} \geq 0 \end{cases} \quad (4.218)$$

$$\Delta_{Si} = \exp \left(x_{m,dc} - \frac{\alpha_b + V_m - \psi_t}{\phi_T^*} \right) \quad (4.219)$$

$$F_S = \ln \left[\frac{1 + \Delta_{Si}}{1 + \Delta_{Si} \cdot \exp \left(-\frac{V_{GS} + V_{SB,dc}^* - V_m}{\phi_T^*} \right)} \right] \quad (4.220)$$

$$I_{GCO} = \mathbf{GINV} \cdot F_S \cdot \exp(\mathbf{B} \cdot [-3/2 + z_g \cdot (\mathbf{GC2} + \mathbf{GC3} \cdot z_g)]) \quad (4.221)$$

$$\text{if } x_{g,dc} > 0 \left\{ \begin{array}{l} u_0 = \mathbf{CHIB} / [\mathbf{B} \cdot (\mathbf{GC2} + 2 \cdot \mathbf{GC3} \cdot z_g)] \\ x = \Delta\psi_{dc} / (2 \cdot u_0) \\ b = u_0 / H_{dc} \\ B_g = b \cdot (1 - b) / 2 \\ A_g = 1/2 - 3 \cdot B_g \\ p_{gc} = (1 - b) \cdot \frac{\sinh(x)}{x} + b \cdot \cosh(x) \\ p_{gd} = \frac{p_{gc}}{2} - B_g \cdot \sinh(x) - A_g \cdot \frac{\sinh(x)}{x} \cdot \left[\coth(x) - \frac{1}{x} \right] \end{array} \right. \quad (4.222)$$

$$\text{if } x_{g,dc} \leq 0 \left\{ \begin{array}{l} p_{gc} = 1 \\ p_{gd} = 1/2 \end{array} \right. \quad (4.223)$$

$$S_g = \frac{1}{2} \cdot \left(1 + \frac{x_{g,dc}}{\sqrt{x_{g,dc}^2 + 10^{-6}}} \right) \quad (4.224)$$

$$I_{GC} = I_{GCO} \cdot p_{gc} \cdot S_g \quad (4.225)$$

$$I_{GCD} = I_{GCO} \cdot p_{gd} \cdot S_g \quad (4.226)$$

$$I_{GCS} = I_{GC} - I_{GCD} \quad (4.227)$$

$$I_{GB} = I_{GCO} \cdot p_{gc} \cdot (1 - S_g) \quad (4.228)$$

4.2.14 Gate-Induced Drain/Source Leakage Current

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

$$I_{gisl}(V_{ov}, V) = \begin{cases} V_{tov} = \sqrt{V_{ov}^2 + \mathbf{CGIDL}^2 \cdot V^2 + 10^{-6}} \\ t = V \cdot V_{tov} \cdot V_{ov} \\ I_{gisl} = \begin{cases} -\mathbf{A}_{GIDL} \cdot t \cdot \exp\left(-\frac{\mathbf{B}_{GIDL}}{V_{tov}}\right) & \text{for } V_{ov} < 0 \\ 0 & \text{for } V_{ov} \geq 0 \end{cases} \end{cases} \quad (4.229)$$

$$I_{gidl}(V_{ov}, V) = \begin{cases} V_{tov} = \sqrt{V_{ov}^2 + \mathbf{CGIDL}^2 \cdot V^2 + 10^{-6}} \\ t = V \cdot V_{tov} \cdot V_{ov} \\ I_{gidl} = \begin{cases} -\mathbf{A}_{GIDL} \cdot t \cdot \exp\left(-\frac{\mathbf{B}_{GIDL}}{V_{tov}}\right) & \text{for } V_{ov} < 0 \\ 0 & \text{for } V_{ov} \geq 0 \end{cases} \end{cases} \quad (4.230)$$

$$I_{gisl} = I_{gisl}(V_{ov0}, V_{SB}) \quad (4.231)$$

$$I_{gidl} = I_{gidl}(V_{ovL}, V_{DS} + V_{SB}) \quad (4.232)$$

4.2.15 Edge Transistor Current

The equations in this Section are only calculated when **SWEDGE** = 1 and **BETNEDGE** > 0.

$$\phi_{V,edge} = \text{MINA}(V_{SB}, V_{SB} + V_{DS}, \mathbf{b}_{\phi,edge}) + \phi_{X,edge} \quad (4.233)$$

$$V_{SB,edge}^* = V_{SB} - \text{MINA}(\phi_{V,edge}, 0, \mathbf{a}_{\phi,edge}) + \phi_{X,edge}^* \quad (4.234)$$

$$V_{sbx,edge} = V_{SB,edge}^* + 0.5 \cdot (V_{DS} - V_{dsx}) \quad (4.235)$$

$$n_{SCE,edge} = 1 + \mathbf{PSCEEDGE} \cdot (1 + \mathbf{PSCEEDGE} \cdot V_{dsx}) \cdot (1 + \mathbf{PSCEBEDGE} \cdot V_{sbx,edge}) \quad (4.236)$$

$$\phi_{T,edge}^* = \phi_{T0,edge}^* \cdot n_{SCE,edge} \quad (4.237)$$

$$V_{ds,edge}^* = \begin{cases} V_{dsx} & \text{for } \mathbf{CFDEEDGE} < 10^{-10} \\ 2 \cdot (\sqrt{1.0 + \mathbf{CFDEEDGE} \cdot V_{dsx}} - 1) / \mathbf{CFDEEDGE} & \text{for } \mathbf{CFDEEDGE} \geq 10^{-10} \end{cases} \quad (4.238)$$

$$\Delta V_{G,edge} = \mathbf{CFEDGE} \cdot V_{ds,edge}^* \cdot (1 + \mathbf{CFBEDGE} \cdot V_{sbx,edge}) \quad (4.239)$$

$$V_{\text{GB,edge}}^* = V_{\text{GS}} + V_{\text{SB,edge}}^* + \Delta V_{\text{G,edge}} - V_{\text{FB,edge}} \quad (4.240)$$

$$x_{\text{g,edge}} = V_{\text{GB,edge}}^* / \phi_{\text{T,edge}}^* \quad (4.241)$$

$$x_{\text{b,edge}} = \phi_{\text{B,edge}} / \phi_{\text{T,edge}}^* \quad (4.242)$$

$$\Delta x_{\text{th,edge}} = 2 \cdot \ln \left(\frac{x_{\text{b,edge}}}{G_{\text{edge}}} + \sqrt{x_{\text{b,edge}}} \right) \quad (4.243)$$

Inversion charge at the source side:

$$x_{\text{n,edge,s}} = V_{\text{SB,edge}}^* / \phi_{\text{T,edge}}^* \quad (4.244)$$

$$\left\{ \begin{array}{l} x_{\text{sth,edge,s}} = x_{\text{b,edge}} + x_{\text{n,edge,s}} \\ x_{\text{th0,edge,s}} = x_{\text{sth,edge,s}} + G_{\text{edge}} \cdot \sqrt{x_{\text{sth,edge,s}}} \\ x_{\text{th,edge,s}} = x_{\text{th0,edge,s}} + \Delta x_{\text{th,edge}} \\ n_{\text{edge,s}} = 1 + \frac{G_{\text{edge}}}{2 \cdot \sqrt{x_{\text{sth,edge,s}}}} \\ x_{\text{gt,edge,s}} = x_{\text{g,edge}} - x_{\text{th,edge,s}} \\ x_{\text{gt0,edge,s}} = x_{\text{gt,edge,s}} + \ln(G_{\text{edge}}^2) - 1 \\ x_{\text{gt0,edge,s}}^* = \frac{1}{2} \cdot \left(x_{\text{gt0,edge,s}} + \sqrt{x_{\text{gt0,edge,s}}^2 + 10} \right) \\ q_{\text{i0si,edge,s}} = x_{\text{gt,edge,s}} - n_{\text{edge,s}} \cdot \ln(x_{\text{gt0,edge,s}}^*) + \ln(G_{\text{edge}}^2) \\ q_{\text{i0,edge,s}} = \frac{1}{2} \cdot \left(q_{\text{i0si,edge,s}} + \sqrt{q_{\text{i0si,edge,s}}^2 + 2} \right) \\ \Delta_{\text{0,edge,s}} = (G_{\text{edge}}^2 \cdot \exp(x_{\text{gt,edge,s}} - q_{\text{i0,edge,s}}))^{1/n_{\text{edge,s}}} \\ q_{\text{ieff,edge,s}} = q_{\text{i0,edge,s}} - n_{\text{edge,s}} \cdot \left(\frac{\sqrt{n_{\text{edge,s}}^2 + (2 \cdot (q_{\text{i0,edge,s}} + n_{\text{edge,s}}) - \Delta_{\text{0,edge,s}}) \cdot \Delta_{\text{0,edge,s}} - n_{\text{edge,s}}} - 1}{\Delta_{\text{0,edge,s}}} \right) \end{array} \right. \quad (4.245)$$

Inversion charge at the drain side:

$$x_{\text{n,edge,d}} = (V_{\text{dse}} + V_{\text{SB,edge}}^*) / \phi_{\text{T,edge}}^* \quad (4.246)$$

if $q_{\text{ieff,edge,s}} < 10^{-3}$ and $V_{\text{dse}} < 10^{-6}$

$$\left\{ \begin{array}{l} q_{\text{ieff,edge,ds}} = q_{\text{ieff,edge,s}} \cdot (\exp(x_{\text{n,edge,s}} - x_{\text{n,edge,d}}) - 1) \\ q_{\text{ieff,edge,d}} = q_{\text{ieff,edge,ds}} + q_{\text{ieff,edge,s}} \end{array} \right. \quad (4.247)$$

else

$$\left\{ \begin{array}{l}
 x_{\text{sth,edge,d}} = x_{\text{b,edge}} + x_{\text{n,edge,d}} \\
 x_{\text{th0,edge,d}} = x_{\text{sth,edge,d}} + G_{\text{edge}} \cdot \sqrt{x_{\text{sth,edge,d}}} \\
 x_{\text{th,edge,d}} = x_{\text{th0,edge,d}} + \Delta x_{\text{th,edge}} \\
 n_{\text{edge,d}} = 1 + \frac{G_{\text{edge}}}{2 \cdot \sqrt{x_{\text{sth,edge,d}}}} \\
 x_{\text{gt,edge,d}} = x_{\text{g,edge}} - x_{\text{th,edge,d}} \\
 x_{\text{gt0,edge,d}} = x_{\text{gt,edge,d}} + \ln(G_{\text{edge}}^2) - 1 \\
 x_{\text{gt0,edge,d}}^* = \frac{1}{2} \cdot \left(x_{\text{gt0,edge,d}} + \sqrt{x_{\text{gt0,edge,d}}^2 + 10} \right) \\
 q_{\text{i0si,edge,d}} = x_{\text{gt,edge,d}} - n_{\text{edge,d}} \cdot \ln(x_{\text{gt0,edge,d}}^*) + \ln(G_{\text{edge}}^2) \\
 q_{\text{i0,edge,d}} = \frac{1}{2} \cdot \left(q_{\text{i0si,edge,d}} + \sqrt{q_{\text{i0si,edge,d}}^2 + 2} \right) \\
 \Delta_{0,\text{edge,d}} = (G_{\text{edge}}^2 \cdot \exp(x_{\text{gt,edge,d}} - q_{\text{i0,edge,d}}))^{1/n_{\text{edge,d}}} \\
 q_{\text{ieff,edge,d}} = q_{\text{i0,edge,d}} - \frac{n_{\text{edge,d}} \cdot \left(\sqrt{\frac{n_{\text{edge,d}}^2 + (2 \cdot (q_{\text{i0,edge,d}} + n_{\text{edge,d}}) - \Delta_{0,\text{edge,d}}) \cdot \Delta_{0,\text{edge,d}}}{\Delta_{0,\text{edge,d}}}} - 1 \right)}{2}
 \end{array} \right. \quad (4.248)$$

Drain to source current:

$$q_{\text{ieff,edge,ds}} = q_{\text{ieff,edge,d}} - q_{\text{ieff,edge,s}} \quad (4.249)$$

$$q_{\text{ieff,edge,m}} = \frac{q_{\text{ieff,edge,d}} + q_{\text{ieff,edge,s}}}{2} \quad (4.250)$$

$$\alpha_{\text{mb,edge}} = 1 - \frac{1}{2} \cdot \frac{G_{\text{edge}}}{\sqrt{x_{\text{g,edge}} - q_{\text{ieff,edge,m}} + \frac{1}{4} \cdot G_{\text{edge}}^2}} \quad (4.251)$$

$$I_{\text{DS,edge}} = -\frac{\beta_{\text{edge}} \cdot \phi_{\text{T,edge}}^{*2}}{G_{\text{mob}}} \cdot (\alpha_{\text{mb,edge}} \cdot q_{\text{ieff,edge,m}} + 1) \cdot q_{\text{ieff,edge,ds}} \quad (4.252)$$

4.2.16 Impact Ionization or Weak-Avalanche

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

$$a_2^* = a_2 \cdot \left[1 + \mathbf{A4} \cdot \left(\sqrt{V_{\text{SB,dc}}^* + \phi_{\text{B}}} - \sqrt{\phi_{\text{B}}} \right) \right] \quad (4.253)$$

$$\Delta V_{\text{sat}} = V_{\text{DS}} - \mathbf{A3} \cdot \Delta \psi_{\text{dc}} \quad (4.254)$$

$$M_{\text{avl}} = \begin{cases} 0 & \text{for } \Delta V_{\text{sat}} \leq 0 \\ \mathbf{A1} \cdot \Delta V_{\text{sat}} \cdot \exp\left(-\frac{a_2^*}{\Delta V_{\text{sat}}}\right) & \text{for } \Delta V_{\text{sat}} > 0 \end{cases} \quad (4.255)$$

$$I_{\text{avl}} = M_{\text{avl}} \cdot (I_{\text{DS}} + I_{\text{DS,edge}}) \quad (4.256)$$

4.2.17 Total Terminal Currents

$$I_D = I_{DS} + I_{DS,edge} + I_{avl} - I_{GDov} - I_{GCD} + I_{gidl} \quad (4.257)$$

$$I_S = -I_{DS} - I_{DS,edge} - I_{GSov} - I_{GCS} + I_{gisl} \quad (4.258)$$

$$I_G = I_{GC} + I_{GB} + I_{GDov} + I_{GSov} \quad (4.259)$$

$$I_B = -I_{avl} - I_{GB} - I_{gidl} - I_{gisl} \quad (4.260)$$

4.3 Charge Model

In this section, the charge model equations of the PSP-model are given. Use is made of the applied terminal bias values V_{GS} , V_{DS} and V_{SB} , the local parameters listed in Section 2.5.2 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 $\text{MINA}(\cdot)$, $\text{MAXA}(\cdot)$, $\chi(\cdot)$ and $\sigma_{1,2}(\cdot)$ can be found in Appendix A.

4.3.1 Quantum-Mechanical Corrections

$$q_{\text{eff},ac} = \begin{cases} V_{\text{oxm},ac} & \text{for } x_{g,ac} \leq 0 \\ q_{\text{eff1},ac} & \text{for } x_{g,ac} > 0 \end{cases} \quad (4.261)$$

$$C_{\text{OX}}^{\text{qm}} = \begin{cases} \text{COX} & \text{for } q_{\mathbf{q}} = 0 \\ \frac{\text{COX}}{1 + q_{\mathbf{q}}/(q_{\text{eff},ac}^2 + q_{\text{lim}}^2)^{1/6}} & \text{for } q_{\mathbf{q}} > 0 \end{cases} \quad (4.262)$$

4.3.2 Intrinsic Charge Model

$$\text{if } x_g > 0 \left\{ \begin{array}{l} F_j = \Delta\psi_{ac}/(2 \cdot H_{ac}) \\ q_{\Delta L} = (1 - G_{\Delta L,ac}) \cdot (q_{\text{im},ac} - \alpha_{m,ac} \cdot \Delta\psi_{ac}/2) \\ q_{\Delta L}^* = q_{\Delta L,ac} \cdot (1 + G_{\Delta L,ac}) \\ Q_G^{(i)} = C_{\text{OX}}^{\text{qm}} \cdot \left[V_{\text{oxm},ac} + \frac{\eta_{p,ac} \cdot \Delta\psi_{ac}}{2} \cdot \left(\frac{G_{\Delta L,ac}}{3} \cdot F_j + G_{\Delta L,ac} - 1 \right) \right] \\ Q_I^{(i)} = -C_{\text{OX}}^{\text{qm}} \cdot \left[G_{\Delta L,ac} \cdot \left(q_{\text{im},ac} + \frac{\alpha_{m,ac} \cdot \Delta\psi_{ac}}{6} \cdot F_j \right) + q_{\Delta L,ac} \right] \\ Q_D^{(i)} = -\frac{C_{\text{OX}}^{\text{qm}}}{2} \cdot \left[G_{\Delta L,ac}^2 \cdot \left(q_{\text{im},ac} + \frac{\alpha_{m,ac} \cdot \Delta\psi_{ac}}{6} \cdot \left[\frac{F_j^2}{5} + F_j - 1 \right] \right) + q_{\Delta L}^* \right] \end{array} \right. \quad (4.263)$$

$$\text{if } x_g \leq 0 \left\{ \begin{array}{l} Q_G^{(i)} = C_{\text{OX}}^{\text{qm}} \cdot V_{\text{oxm},ac} \\ Q_I^{(i)} = 0 \\ Q_D^{(i)} = 0 \end{array} \right. \quad (4.264)$$

$$Q_S^{(i)} = Q_I^{(i)} - Q_D^{(i)} \quad (4.265)$$

$$Q_B^{(i)} = -Q_I^{(i)} - Q_G^{(i)} \quad (4.266)$$

4.3.3 Extrinsic Charge Model

The charges of the source and drain overlap regions:

$$Q_{\text{sov}} = \text{CGOV} \cdot (V_{GS} - \psi_{\text{sov}}) \quad (4.267)$$

$$Q_{\text{dov}} = \mathbf{CGOVD} \cdot (V_{\text{GS}} - V_{\text{DS}} - \psi_{\text{dov}}) \quad (4.268)$$

The charge of the bulk overlap region

$$Q_{\text{bov}} = \mathbf{CGBOV} \cdot (V_{\text{GS}} + V_{\text{SB}}) \quad (4.269)$$

Outer fringe charge:

$$Q_{\text{ofs}} = \mathbf{CFR} \cdot V_{\text{GS}} \quad (4.270)$$

$$Q_{\text{ofd}} = \mathbf{CFRD} \cdot (V_{\text{GS}} - V_{\text{DS}}) \quad (4.271)$$

4.3.4 Total Terminal Charges

$$Q_{\text{G}} = Q_{\text{G}}^{(i)} + Q_{\text{sov}} + Q_{\text{dov}} + Q_{\text{ofs}} + Q_{\text{ofd}} + Q_{\text{bov}} \quad (4.272)$$

$$Q_{\text{S}} = Q_{\text{S}}^{(i)} - Q_{\text{sov}} - Q_{\text{ofs}} \quad (4.273)$$

$$Q_{\text{D}} = Q_{\text{D}}^{(i)} - Q_{\text{dov}} - Q_{\text{ofd}} \quad (4.274)$$

$$Q_{\text{B}} = Q_{\text{B}}^{(i)} - Q_{\text{bov}} \quad (4.275)$$

4.4 Noise Model

Eqs. (4.312)-(4.302) are only calculated for $x_g > 0$. In these equations f_{op} represents the operation frequency of the transistor and $j = \sqrt{-1}$.

4.4.1 Flicker noise

$$N^* = \frac{C_{ox}}{q} \cdot \alpha_{m,dc} \cdot \phi_T \quad (4.276)$$

$$N_m^* = \frac{C_{ox}}{q} \cdot q_{im,dc}^* \quad (4.277)$$

$$\Delta N = \frac{C_{ox}}{q} \cdot \alpha_{m,dc} \cdot \Delta\psi_{dc} \quad (4.278)$$

$$S_{fl} = \frac{q \cdot \phi_T^2 \cdot \beta \cdot I_{DS}}{(f_{op})^{EF} \cdot C_{ox} \cdot G_{vsat,dc} \cdot N^*} \cdot \left[(\mathbf{NFA} - \mathbf{NFB} \cdot N^* + \mathbf{NFC} \cdot N^{*2}) \cdot \ln \left(\frac{N_m^* + \Delta N/2}{N_m^* - \Delta N/2} \right) + (\mathbf{NFB} + \mathbf{NFC} \cdot [N_m^* - 2 \cdot N^*]) \cdot \Delta N \right] \quad (4.279)$$

4.4.2 Thermal noise

Intrinsic thermal noise

$$H_0 = \frac{q_{im,dc}^*}{\alpha_{m,dc}} \quad (4.280)$$

$$t_1 = \frac{q_{im,dc}}{q_{im,dc}^*} \quad (4.281)$$

$$t_2 = \left(\frac{\Delta\psi_{dc}}{12 \cdot H_0} \right)^2 \quad (4.282)$$

$$R = \frac{H_0}{H} - 1 \quad (4.283)$$

$$l_c = 1 - 12 \cdot t_2 \cdot R \quad (4.284)$$

$$g_{ideal} = \frac{\beta \cdot q_{im,dc}^*}{G_{vsat,dc}} \cdot F_{\Delta L,dc} \quad (4.285)$$

$$C_{Geff} = \left(\frac{G_{vsat,ac}}{G_{mob,ac} \cdot G_{\Delta L,ac}} \right)^2 \cdot C_{OX}^{qm} \cdot \eta_{p,ac} \quad (4.286)$$

$$m_{id,int} = \frac{g_{ideal}}{l_c^2} \cdot [t_1 + 12 \cdot t_2 - 24 \cdot (1 + t_1) \cdot t_2 \cdot R] \quad (4.287)$$

$$m_{ig,int} = \frac{1}{l_c^2 \cdot g_{ideal}} \cdot \left[\frac{t_1}{12} - t_2 \cdot \left(t_1 + \frac{1}{5} - 12 \cdot t_2 \right) - \frac{8}{5} \cdot t_2 \cdot (t_1 + 1 - 12 \cdot t_2) \cdot R \right] \quad (4.288)$$

$$m_{igid,int} = \frac{\sqrt{t_2}}{l_c^2} \cdot \left[1 - 12 \cdot t_2 - \left(t_1 + \frac{96}{5} \cdot t_2 - 12 \cdot t_1 \cdot t_2 \right) \cdot R \right] \quad (4.289)$$

Excess thermal noise

For short (sub-100-nm) devices, it has been shown that the conventional local source for thermal noise gets a field dependent extra term [7, 8] and changes from

$$\langle i_n^2 \rangle = 4 \cdot k \cdot T \cdot g$$

to

$$\langle i_n^2 \rangle = 4 \cdot k \cdot T \cdot g \cdot \left[1 + 3 \cdot \frac{(q \cdot E \cdot \tau)^2}{m^* \cdot k \cdot T} \right] = 4 \cdot k \cdot T \cdot g + 12 \cdot g \cdot m^* \cdot \mu^2 \cdot E^2.$$

Here, g denotes the local channel conductance. Integration along the channel (following the improved Klaassen-Prins method) leads to expressions for the drain-current noise, induced gate noise, and correlation.

Excess thermal noise equations:

$$\theta_{\text{sat,exc}}^* = \begin{cases} \frac{\theta_{\text{sat}}}{G_{\text{mob,dc}}} \cdot (1 + \text{THESATG} \cdot w_{\text{sat}}) & \text{for } \text{THESATG} \geq 0 \\ \frac{\theta_{\text{sat}}}{G_{\text{mob,dc}}} \cdot \frac{1}{1 - \text{THESATG} \cdot w_{\text{sat}}} & \text{for } \text{THESATG} < 0 \end{cases} \quad (4.290)$$

$$z_{\text{sat,exc}} = \begin{cases} (\theta_{\text{sat,exc}}^* \cdot \Delta\psi_{\text{dc}})^2 & \text{for NMOS} \\ \frac{(\theta_{\text{sat,exc}}^* \cdot \Delta\psi_{\text{dc}})^2}{1 + \theta_{\text{sat,exc}}^* \cdot \Delta\psi_{\text{dc}}} & \text{for PMOS} \end{cases} \quad (4.291)$$

$$G_{\text{vsat,exc}} = \frac{G_{\text{mob,dc}}}{2} \cdot (1 + \sqrt{1 + 2 \cdot z_{\text{sat,exc}}}) \quad (4.292)$$

$$g_{\text{fac}} = \frac{G_{\text{mob,dc}}}{G_{\text{vsat,exc}} \cdot l_c} \quad (4.293)$$

$$m_{\text{id,exc}} = \frac{\text{FNTEXC} \cdot m_0}{4 \cdot k_B \cdot T_{\text{KD}}} \cdot g_{\text{fac}}^2 \cdot I_{\text{DS}} \cdot V_{\text{dse,dc}} \quad (4.294)$$

$$m_{\text{ig,exc}} = m_{\text{id,exc}} \cdot \frac{1 + 12 \cdot t_2}{12 \cdot g_{\text{ideal}}^2} \quad (4.295)$$

$$m_{\text{igid,exc}} = -m_{\text{id,exc}} \cdot \frac{\sqrt{t_2} \cdot (1 + R)}{g_{\text{ideal}}} \quad (4.296)$$

Total thermal noise

$$m_{\text{id}} = m_{\text{id,int}} + m_{\text{id,exc}} \quad (4.297)$$

$$m_{\text{ig}} = m_{\text{ig,int}} + m_{\text{ig,exc}} \quad (4.298)$$

$$m_{\text{igid}} = m_{\text{igid,int}} + m_{\text{igid,exc}} \quad (4.299)$$

$$S_{\text{id}} = N_{\text{T}} \cdot m_{\text{id}} \quad (4.300)$$

$$S_{\text{ig}} = N_{\text{T}} \cdot \frac{(2 \cdot \pi \cdot f_{\text{op}} \cdot C_{\text{Geff}})^2 \cdot m_{\text{ig}}}{1 + (2 \cdot \pi \cdot f_{\text{op}} \cdot C_{\text{Geff}} \cdot m_{\text{ig}})^2} \quad (4.301)$$

$$S_{\text{igid}} = N_{\text{T}} \cdot \frac{2 \cdot \pi \cdot j \cdot f_{\text{op}} \cdot C_{\text{Geff}} \cdot m_{\text{igid}}}{1 + 2 \cdot \pi \cdot j \cdot f_{\text{op}} \cdot C_{\text{Geff}} \cdot m_{\text{ig}}} \quad (4.302)$$

Thermal noise for parasitic resistances (see Fig. 3.2)

$$S_{R_G} = 4 \cdot k_B \cdot T_{KD} / R_{gate} \quad (4.303)$$

$$S_{R_{BULK}} = 4 \cdot k_B \cdot T_{KD} / R_{bulk} \quad (4.304)$$

$$S_{R_{WELL}} = 4 \cdot k_B \cdot T_{KD} / R_{well} \quad (4.305)$$

$$S_{R_{JUNS}} = 4 \cdot k_B \cdot T_{KD} / R_{juns} \quad (4.306)$$

$$S_{R_{JUND}} = 4 \cdot k_B \cdot T_{KD} / R_{jund} \quad (4.307)$$

4.4.3 Shot noise

Gate current shot noise:

$$S_{igs} = 2 \cdot q \cdot (I_{GCS} + I_{GSov}) \quad (4.308)$$

$$S_{igd} = 2 \cdot q \cdot (I_{GCD} + I_{GDov}) \quad (4.309)$$

Avalanche current shot noise:

$$S_{avl} = 2 \cdot q \cdot (1 + M_{avl}) \cdot I_{avl} \quad (4.310)$$

4.4.4 Edge transistor noiseThe equations in this Section are only calculated when **SWEDGE** = 1 and **BETNEDGE** > 0 and $x_{g,edge} > 0$.

Flicker noise:

$$\alpha_{noise,edge} = \frac{\sqrt{\frac{4}{G_{edge}^2} \cdot (x_{g,edge} - q_{ieff,edge,m}) + 1}}{\sqrt{\frac{4}{G_{edge}^2} \cdot (x_{g,edge} - q_{ieff,edge,m}) + 1.1 - 1}} \quad (4.311)$$

$$N_{edge}^* = \frac{C_{ox}}{q} \cdot \phi_T \cdot \alpha_{noise,edge} \quad (4.312)$$

$$N_{m,edge}^* = \frac{C_{ox}}{q} \cdot \phi_T \cdot (q_{ieff,edge,m} + \alpha_{noise,edge}) \quad (4.313)$$

$$\Delta N_{edge} = -\frac{C_{ox}}{q} \cdot \phi_T \cdot \alpha_{noise,edge} \cdot \alpha_{mb,edge} \cdot q_{ieff,edge,ds} \quad (4.314)$$

$$S_{fl,edge} = \frac{q \cdot \phi_T^2 \cdot \beta_{edge} \cdot I_{DS,edge}}{(f_{op})^{EFEDGE} \cdot C_{ox} \cdot G_{vsat,dc} \cdot N_{edge}^*} \cdot \left[(\mathbf{NFAEDGE} - \mathbf{NFBEDGE} \cdot N_{edge}^* \right. \\ \left. + \mathbf{NFCEDGE} \cdot N_{edge}^{*2}) \cdot \ln \left(\frac{N_{m,edge}^* + \Delta N_{edge}/2}{N_{m,edge}^* - \Delta N_{edge}/2} \right) \right. \\ \left. + (\mathbf{NFBEDGE} + \mathbf{NFCEDGE} \cdot [N_{m,edge}^* - 2 \cdot N_{edge}^*]) \cdot \Delta N_{edge} \right] \quad (4.315)$$

Thermal noise:

$$H_{0,edge} = \phi_{\mathbf{T}} \cdot \left(\frac{q_{ieff,edge,m}}{\alpha_{noise,edge}} + 1 \right) \quad (4.316)$$

$$t_{1,edge} = \frac{\phi_{\mathbf{T}}^*}{\phi_{\mathbf{T}}} \cdot \frac{q_{ieff,edge,m}}{q_{ieff,edge,m} + \alpha_{noise,edge}} \quad (4.317)$$

$$t_{2,edge} = \left(\frac{\phi_{\mathbf{T}} \cdot \alpha_{mb,edge} \cdot q_{ieff,edge,ds}}{12 \cdot H_{0,edge}} \right)^2 \quad (4.318)$$

$$R_{edge} = \frac{\alpha_{noise,edge} \cdot H_{0,edge}}{\alpha_m \cdot H} - 1 \quad (4.319)$$

$$l_{c,edge} = 1 - 12 \cdot t_{2,edge} \cdot R_{edge} \quad (4.320)$$

$$g_{ideal,edge} = \frac{\beta_{edge} \cdot \phi_{\mathbf{T}} \cdot (q_{ieff,edge,m} + \alpha_{noise,edge})}{G_{vsat,dc}} \cdot F_{\Delta L,dc} \quad (4.321)$$

$$m_{id,edge} = \frac{g_{ideal,edge}}{l_{c,edge}^2} \cdot [t_{1,edge} + 12 \cdot t_{2,edge} - 24 \cdot (1 + t_{1,edge}) \cdot t_{2,edge} \cdot R_{edge}] \quad (4.322)$$

$$S_{id,dge} = N_{\mathbf{T},edge} \cdot m_{id,edge} \quad (4.323)$$

4.5 Self heating

Fig. 4.1 shows the simple thermal network that is implemented in PSP. The current that reflects the power dissipation is given by

$$P_{\text{diss}} = I_{\text{DS}} \cdot V_{\text{DS}} + I_{\text{impact}} \cdot (V_{\text{DS}} + V_{\text{SB}}) + \frac{V_{\text{SIS}}^2}{R_{\text{source}}} + \frac{V_{\text{DID}}^2}{R_{\text{drain}}}. \quad (4.324)$$

If $\mathbf{RTH} < 10^{-3}$, $P_{\text{diss}} = 0$. This can be used to switch off self heating.

The built-in thermal network of PSP can be bypassed (e.g., to replace it with an externally connected thermal network) by setting $\mathbf{CTH} = 0$ and assigning a very large value to \mathbf{RTH} .

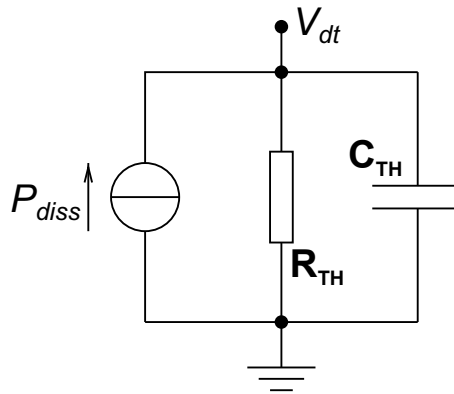


Figure 4.1: Internal thermal network of PSP

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:

$$\begin{cases} \frac{dQ_1}{dt} = f_1(Q_1, \dots, Q_N) \\ \vdots \\ \frac{dQ_N}{dt} = f_N(Q_1, \dots, Q_N) \end{cases} \quad (5.1)$$

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 5.3. More background information can be found in literature [9, 10].

5.3 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 ϕ_T^*) at a certain position.

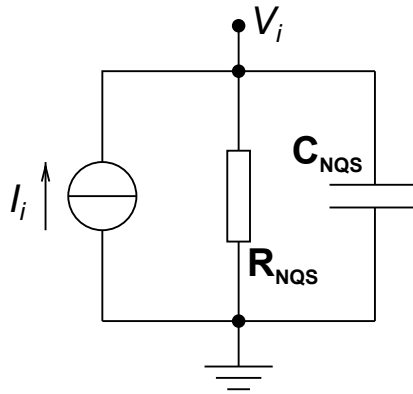


Figure 5.1: The subcircuit used to solve one of the differential equations of Eq. (5.1). The current is set to $I_i = C_{NQS} \cdot f(V_1, \dots, V_N)$, where the voltage V_i represents the charge density Q_i at the i -th collocation point and is solved by the circuit simulator. N of these circuits are 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.

5.3.1 Internal constants

Eqs. (5.2)–(5.7) are independent of bias conditions and time. Consequently, they have to be computed only once.

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

$$n = SWNQS + 1 \tag{5.2}$$

$$h = 1/n \tag{5.3}$$

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. 5.25. They are computed using the following algorithm (adapted from [11]):

1. Initial values:

$$A_{i,j} = 0 \quad \text{for } 0 \leq i, j \leq n \tag{5.4}$$

$$v_i = 0 \quad \text{for } 0 \leq i \leq n \tag{5.5}$$

2. First loop:

$$\left. \begin{aligned} p &= 2 + v_{i-1}/2 \\ v_i &= -1/(2 \cdot p) \\ A_{i,i-1} &= 1/h \\ A_{i,i} &= -2/h \\ A_{i,i+1} &= 1/h \\ A_{i,j} &= \frac{1}{p} \cdot (3 \cdot A_{i,j}/h - A_{i-1,j}/2) \end{aligned} \right\} \begin{array}{l} \text{for } i = 1 \dots (n - 1) \\ \text{for } j = 0 \dots n \end{array} \tag{5.6}$$

3. Second loop (back substitution):

$$A_{i,j} = v_i \cdot A_{i+1,j} + A_{i,j} \quad \text{for } j = 0 \dots n \quad \left. \vphantom{A_{i,j}} \right\} \text{for } i = (n-1) \dots 0 \quad (5.7)$$

5.3.2 Position independent quantities

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

$$\text{if } x_{g,ac} > 0 \quad \left\{ \begin{array}{l} y_m = \frac{1}{2} \cdot \left(1 + \frac{\Delta\psi_{ac}}{4 \cdot H_{ac}} \right) \\ p_d = \frac{x_{gm,ac}}{x_{g,ac} - x_{m,ac}} \\ G_p = G_{ac}/p_d \end{array} \right. \quad (5.8)$$

$$\text{if } x_{g,ac} \leq 0 \quad \left\{ \begin{array}{l} y_m = 1/2 \\ p_d = 1 \\ G_p = G_{ac} \end{array} \right. \quad (5.9)$$

$$a_p = 1 + G_p/\sqrt{2} \quad (5.10)$$

$$p_{mrg} = 10^{-5} \cdot a_p \quad (5.11)$$

5.3.3 Position dependent surface potential and charge

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

$$\Psi(y) = x_{m,ac} + \frac{H_{ac}}{\phi_T^*} \cdot \left(1 - \sqrt{1 - \frac{2 \cdot \Delta\psi_{ac}}{H_{ac}} \cdot (y - y_m)} \right) \quad (5.12)$$

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

$$q_b(x) = -\text{sgn}(x) \cdot G_p \cdot \sqrt{\exp(-x) + x - 1} \quad (5.13)$$

$$q'_b(x) = \frac{G_p^2 \cdot [1 - \exp(-x)]}{2 \cdot q_b(x)} \quad (5.14)$$

$$q''_b(x) = -q'_b(x) - \frac{q'_b(x)^2 - G_p^2/2}{q_b(x)} \quad (5.15)$$

Surface potential as a function of normalized inversion charge (note that these equations are identical to Eq. (4.204), despite the different notation and physical background):

$$\Pi(x_g) = \begin{cases} \left. \begin{array}{l} \text{if } x_g < -p_{\text{mrg}} \\ \text{if } |x_g| \leq p_{\text{mrg}} \\ \text{if } x_g > p_{\text{mrg}} \end{array} \right\} \left\{ \begin{array}{l} y_g = -x_g \\ z = 1.25 \cdot y_g / a_p \\ \eta = \left[z + 10 - \sqrt{(z - 6)^2 + 64} \right] / 2 \\ a = (y_g - \eta)^2 + G_p^2 \cdot (\eta + 1) \\ c = 2 \cdot (y_g - \eta) - G_p^2 \\ \tau = -\eta + \ln(a / G_p^2) \\ y_0 = \sigma_1(a, c, \tau, \eta) \\ \Delta_0 = \exp(y_0) \\ \xi = 1 - G_p^2 \cdot \Delta_0 / 2 \\ p = 2 \cdot (y_g - y_0) + G_p^2 \cdot (\Delta_0 - 1) \\ q = (y_g - y_0)^2 + G_p^2 \cdot (y_0 - \Delta_0 + 1) \\ \Pi = -y_0 - \frac{2 \cdot q}{p + \sqrt{p^2 - 4 \cdot q \cdot \xi}} \\ \Pi = \frac{x_g}{a_p} \\ \hat{x}_{g1} = x_1 + G_p \cdot \sqrt{\exp(-x_1) + x_1 - 1} \\ \bar{x} = \frac{x_g}{a_p} \cdot [1 + x_g \cdot (x_1 \cdot a_p / \hat{x}_{g1} - 1) / \hat{x}_{g1}] \\ x_0 = x_g + G_p^2 / 2 - G_p \cdot \sqrt{x_g + G_p^2 / 4 - 1 + \exp(-\bar{x})} \\ \Delta_0 = \exp(-x_0) \\ \xi = 1 - G_p^2 \cdot \Delta_0 / 2 \\ p = 2 \cdot (x_g - x_0) + G_p^2 \cdot (1 - \Delta_0) \\ q = (x_g - x_0)^2 - G_p^2 \cdot (x_0 + \Delta_0 - 1) \\ \Pi = x_0 + \frac{2 \cdot q}{p + \sqrt{p^2 - 4 \cdot q \cdot \xi}} \end{array} \right. \end{cases} \quad (5.16)$$

$$X(x_g, q_{\text{inv}}) = \Pi(x_g + q_{\text{inv}} / p_d) \quad (5.17)$$

Auxiliary functions:

$$q(x) = -p_d \cdot (x_g - x) - q_b(x) \quad (5.18)$$

$$\psi(q, q_{x1}) = \frac{q}{q_{x1}} - 1 \quad (5.19)$$

$$\phi(q, q_{x1}, q_{x2}) = \left(1 - \frac{q \cdot q_{x2}}{q_{x1}^2} \right) / q_{x1} \quad (5.20)$$

Normalized right-hand-side of continuity equation:

$$f(x_g, q, q', q'') = \begin{cases} x_z = X(x_g, q) \\ q_{x1} = \frac{\partial q}{\partial x}(x_z) = p_d - q'_b(x_z) \\ q_{x2} = \frac{\partial^2 q}{\partial x^2}(x_z) = q''_b(x_z) \\ f_0 = \psi(q, q_{x1}) \cdot q'' + \phi(q, q_{x1}, q_{x2}) \cdot q'^2 \\ x_{y1} = \frac{\partial x_z}{\partial y} = q'/q_{x1} \\ z_{\text{sat}} = \begin{cases} (\theta_{\text{sat,ac}}^* \cdot \phi_T^* \cdot x_{y1})^2 & \text{for NMOS} \\ \frac{(\theta_{\text{sat,ac}}^* \cdot \phi_T^* \cdot x_{y1})^2}{1 + \theta_{\text{sat,ac}}^* \cdot \Delta\psi_{\text{ac}}} & \text{for PMOS} \end{cases} \\ \zeta = \sqrt{1 + 2 \cdot z_{\text{sat}}} \\ F_{\text{vsat}} = 2/(1 + \zeta) \\ f = F_{\text{vsat}} \cdot \left[f_0 - F_{\text{vsat}} \cdot \frac{z_{\text{sat}}}{\zeta} \cdot \psi(q, q_{x1}) \cdot (q'' + x_{y1}^2 \cdot q''_b(x_z)) \right] \end{cases} \quad (5.21)$$

Normalization constant:

$$T_{\text{norm}} = \frac{\text{MUNQS} \cdot \phi_T^* \cdot \beta}{C_{\text{OX}}^{\text{qm}}} \cdot G_{\text{mob,ac}} \cdot G_{\Delta L, \text{ac}} \quad (5.22)$$

5.3.4 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 $q_i(t)$.

$$q''_0 = 0 \quad (5.23)$$

$$q''_n = 0 \quad (5.24)$$

$$q''_i = \sum_{j=0}^n A_{i,j} \cdot q_i \quad \text{for } 1 \leq i \leq n-1 \quad (5.25)$$

$$q'_i = \frac{q_{i+1} - q_i}{h} - \frac{h}{6} \cdot (2 \cdot q''_i + q''_{i+1}) \quad \text{for } 1 \leq i \leq n-1 \quad (5.26)$$

5.3.5 Continuity equation

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

$$x_{i,0} = \Psi(i \cdot h) \quad (5.27)$$

$$q_{i,0} = q(x_{i,0}) \quad (5.28)$$

Note: $x_{0,0} = x_s$ and $x_{n,0} = x_d$. 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.

$$\boxed{\begin{cases} \frac{\partial q_i}{\partial t}(t) + T_{\text{norm}} \cdot f\left(x_{g,\text{ac}}, q_i(t), \frac{\partial q_i}{\partial y}(t), \frac{\partial^2 q_i}{\partial y^2}(t)\right) = 0 & \text{for } 1 \leq i \leq n-1 \\ q_i(0) = q_{i,0} \end{cases}} \quad (5.29)$$

Note that the boundary points $q_0(t) = q(x_s) = q_{is}$ and $q_n(t) = q(x_d) = q_{id}$ 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.

5.3.6 Non-quasi-static terminal charges

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

$$S_0 = \sum_{i=1}^{n-1} q_i \quad (5.30)$$

$$S_2 = \sum_{i=1}^{n-1} q_i'' \quad (5.31)$$

$$q_I^{\text{NQS}} = \int_0^1 q(y) dy = h \cdot S_0 + \frac{h}{2} \cdot (u_0 + u_n) - \frac{h^3}{12} \cdot S_2 \quad (5.32)$$

$$U_0 = \sum_{i=1}^{n-1} i \cdot q_i \quad (5.33)$$

$$U_2 = \sum_{i=1}^{n-1} i \cdot q_i'' \quad (5.34)$$

$$q_D^{\text{NQS}} = \int_0^1 y \cdot q(y) dy = h^2 \cdot U_0 + \frac{h^2}{6} \cdot [q_0 + (3n-1)u_n] - \frac{h^4}{12} \cdot U_2 \quad (5.35)$$

$$q_S^{\text{NQS}} = q_I^{\text{NQS}} - q_D^{\text{NQS}} \quad (5.36)$$

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):

$$q_G^{\text{NQS}} = p_d \cdot \left[x_{g,\text{ac}} - \frac{h}{3} \cdot \left(X(x_{g,\text{ac}}, q_0) + 4 \cdot \sum_{i=1}^{n/2} X(x_{g,\text{ac}}, q_{2i-1}) + 2 \cdot \sum_{i=1}^{n/2-1} X(x_{g,\text{ac}}, q_{2i}) + X(x_{g,\text{ac}}, q_n) \right) \right] \quad (5.37)$$

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

$$q_G^{\text{NQS}} = p_d \cdot \left[x_{g,\text{ac}} - \frac{3 \cdot h}{8} \cdot (X(x_{g,\text{ac}}, q_0) + 3 \cdot X(x_{g,\text{ac}}, q_1) + 3 \cdot X(x_{g,\text{ac}}, q_2) + X(x_{g,\text{ac}}, q_3)) \right] \quad (5.38)$$

Convert back to conventional units:

$$Q_S^{\text{NQS}} = C_{\text{OX}}^{\text{qm}} \cdot \phi_T^* \cdot q_S^{\text{NQS}} \quad (5.39)$$

$$Q_D^{\text{NQS}} = C_{\text{OX}}^{\text{qm}} \cdot \phi_T^* \cdot q_D^{\text{NQS}} \quad (5.40)$$

$$Q_G^{\text{NQS}} = C_{\text{OX}}^{\text{qm}} \cdot \phi_T^* \cdot q_G^{\text{NQS}} \quad (5.41)$$

$$Q_B^{\text{NQS}} = -(Q_S^{\text{NQS}} + Q_D^{\text{NQS}} + Q_G^{\text{NQS}}) \quad (5.42)$$

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.

From PSP 103.0 onwards, the global, local and binning models are unified. All three models are called by the same *name* or **LEVEL**. Model flavor selection is done by setting parameter **SWGEO**.

Simulator	Model selection by	Global (geom.)	Global (binning)	Local
Spectre	psp103			
Pstar	LEVEL = 103	SWGEO = 1	SWGEO = 2	SWGEO = 0
ADS	psp103			
Verilog-A	PSP103VA			

6.2 Case of parameters

Throughout this document, all parameter names are printed in uppercase characters. Similarly, in the Verilog-A code provided by the PSP model developers, the parameters are in upper case characters. However, in other PSP implementations a different choice can be made. For example, the parameter names may be in lowercase characters (possibly first character capitalized) if this is conform the conventions of the circuit simulator.

6.3 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 $V_{DS} < 0$. 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 $V_{DS} = 0$. In other words, no singularities will occur in the higher-order derivatives at $V_{DS} = 0$.

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.

6.3.1 Selection of device type

In the SiMKit-based and built-in version of PSP in certain circuit simulators, the selection of device type (nmos or pmos) is done using a different parameter, or using different parameter values. The correct values for some circuit simulators are given in the table below.

Simulator	Parameter	Value NMOS	value PMOS
Spectre	type	n	p
Pstar	type	1	-1
ADS	gender	1	0
Verilog-A	TYPE	1	-1

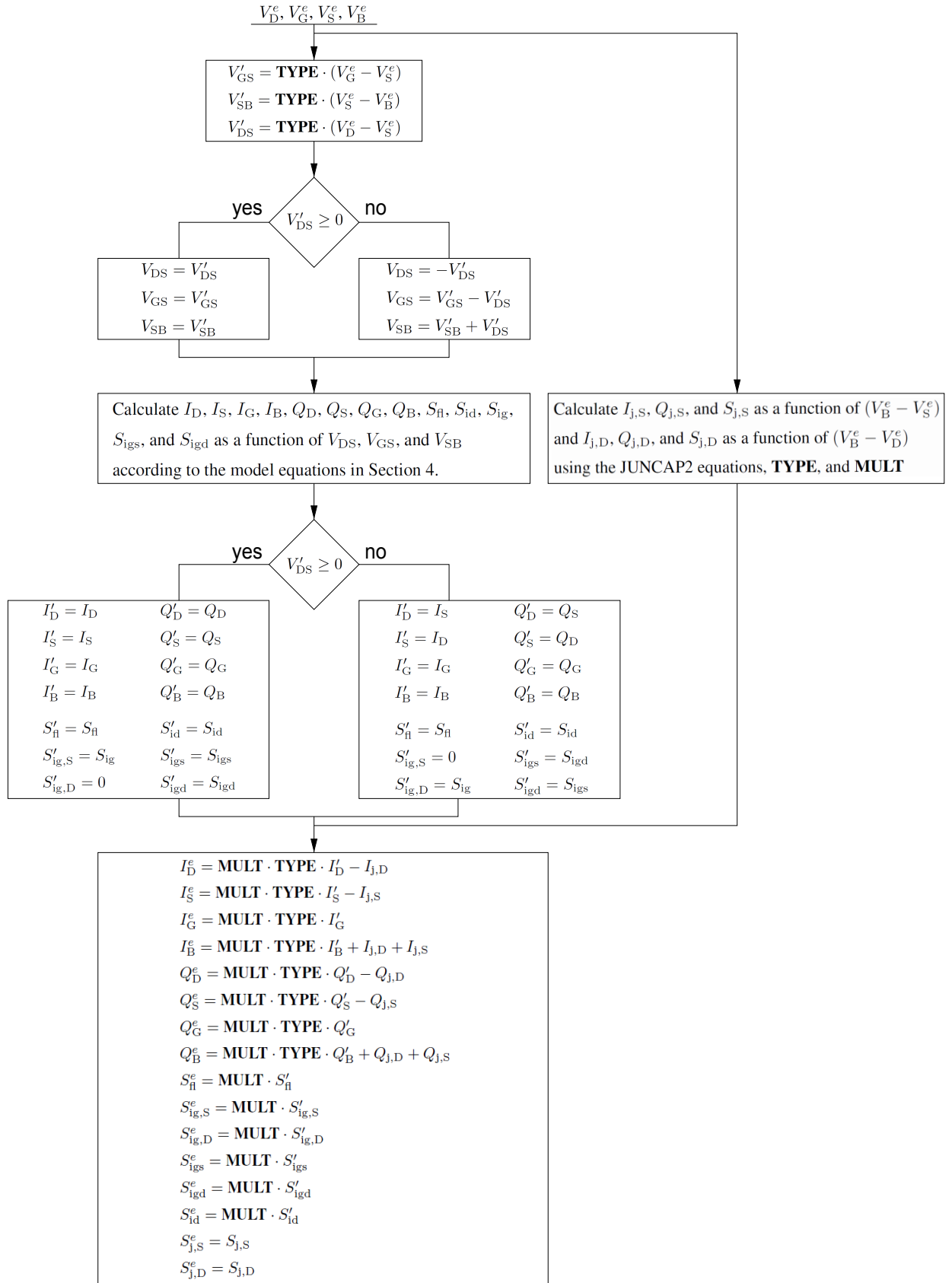


Figure 6.1: Schematic overview of source-drain interchange and handling of **TYPE** and **MULT**. Note that **TYPE** and **MULT** are included in the JUNCAP2 model equations.

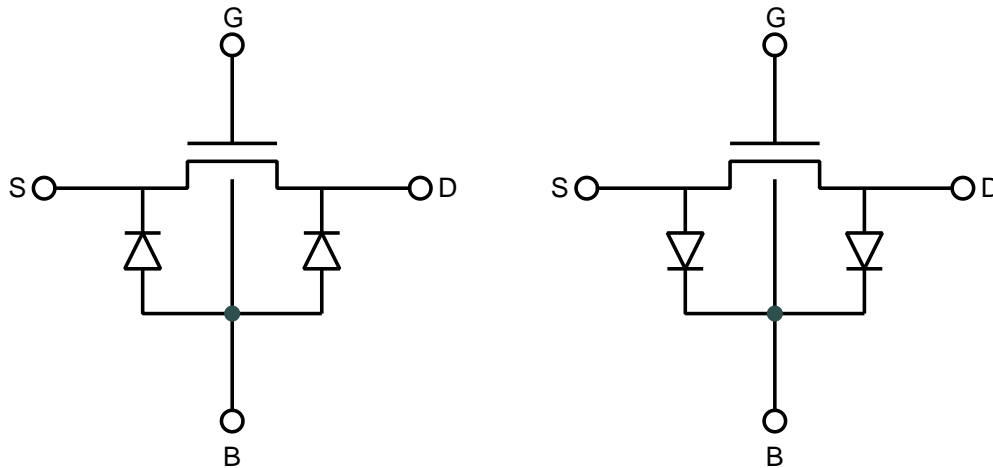


Figure 6.2: Topology of the PSP model. *Left*: n -channel MOSFET; *Right*: p -channel MOSFET. In PSP, the correct diode polarity is automatically chosen via the **TYPE**-parameter.

6.4 Integration of JUNCAP2 in PSP

Introduction

The JUNCAP2 model 200.3 is an integral part of PSP 102.2. 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 [12]. 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 $V_{DS} < 0$ (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 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 Section 2.5.1.

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 $I_{j,S}$, $Q_{j,S}$, $S_{j,S}$, $I_{j,D}$, $Q_{j,D}$, and $S_{j,D}$ in Fig. 6.1.

6.5 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.

6.5.1 Implementation of GMIN

In both implementations, there is an additional term in Eqs. (4.257) and (4.258), resulting in

$$I_D = I_{DS} + I_{DS,edge} + I_{avl} - I_{GDov} - I_{GCD} + I_{gidl} + G_{min} \cdot V_{DS} \quad (6.1)$$

and

$$I_S = -I_{DS} - I_{DS,edge} - I_{GSov} - I_{GCS} + I_{gisl} - G_{min} \cdot V_{DS}. \quad (6.2)$$

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

6.5.2 Implementation of parasitic resistances

From PSP 102.2 and PSP 103.0 onwards, a network of parasitic resistors has been inserted around the intrinsic MOSFET. If the user sets one or more of these resistance values to zero, the associated internal node(s) could be shorted to one of its neighbors, reducing the size of the matrix in the circuit simulator. This phenomenon is called ‘node collapse’ and is supported by most major circuit simulators.

¹If 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.

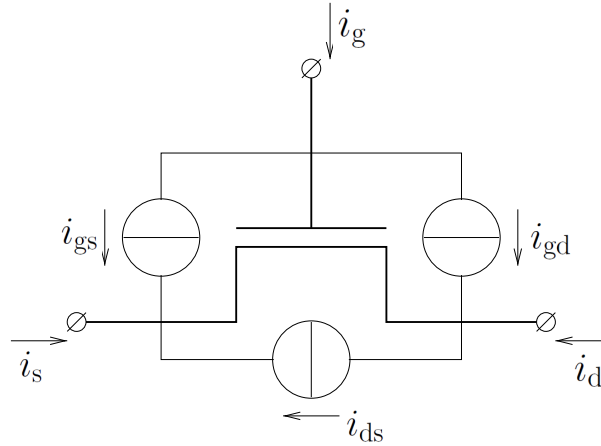


Figure 6.3: Definition of noise currents.

Flexible topology (and thus node collapse) is presently supported by most Verilog-A compilers. As a result, node collapse is functional in the official PSP Verilog-A in the majority of today's circuit simulators.

From SiMKit 3.0 onwards, the SiMKit architecture allows for flexible topologies and therefore supports node collapse in PSP. This functionality is therefore available in circuit simulations with that can work with SiMKit. Besides, many circuit simulators that have a native implementation of PSP support node collapse.

6.5.3 Implementation of the noise-equations

Definition of noise model

Eqs. (4.300), (4.301), and (4.302) describe the noise power spectral density of the thermal noise. In this section, the relationship between the quantities S_{id} , S_{ig} , and S_{igid} (as calculated in these equations) and noise sources in the model is defined.

Fig. 6.3 shows a schematic representation of a noiseless transistor (model) and three noise sources. The small-signal noise currents of these noise current sources are indicated by i_{ds} , i_{gs} , and i_{gd} . The two noise sources connected to G are fully correlated. Moreover, each of them is partly correlated with the noise source between S and D. More precisely, the noise powers and correlations associated with these sources are given by

$$\begin{aligned}
 \langle i_{ds} \cdot i_{ds}^* \rangle &= S_{id} \\
 \langle i_{gd} \cdot i_{ds}^* \rangle &= S_{igid}/2 \\
 \langle i_{gs} \cdot i_{ds}^* \rangle &= S_{igid}/2 \\
 \langle i_{gd} \cdot i_{gd}^* \rangle &= S_{ig}/4 \\
 \langle i_{gs} \cdot i_{gd}^* \rangle &= S_{ig}/4 \\
 \langle i_{gs} \cdot i_{gs}^* \rangle &= S_{ig}/4
 \end{aligned} \tag{6.3}$$

The non-listed elements follow from the fact that this is a complex correlation matrix and therefore self-adjoint. This defines the noise model of PSP.

For completeness, we will give the noise correlation matrix associated with the *terminal* currents i_d , i_g and i_s , because it is closer related to the numbers that are obtained in a circuit simulation. Because $i_d = i_{ds} - i_{gs}$,

$i_g = i_{gs} + i_{gd}$ and $i_s = i_{gs} - i_{ds}$, we find by straightforward substitution and some basic arithmetic

$$\begin{aligned}
 \langle i_d \cdot i_d^* \rangle &= S_{id} + S_{ig}/4 - \text{Re}(S_{igid}) \\
 \langle i_g \cdot i_d^* \rangle &= S_{igid} - S_{ig}/2 \\
 \langle i_s \cdot i_d^* \rangle &= -S_{id} + S_{ig}/4 - \text{Im}(S_{igid}) \\
 \langle i_g \cdot i_g^* \rangle &= S_{ig} \\
 \langle i_s \cdot i_g^* \rangle &= -S_{igid}^* - S_{ig}/2 \\
 \langle i_s \cdot i_s^* \rangle &= S_{id} + S_{ig}/4 + \text{Re}(S_{igid})
 \end{aligned} \tag{6.4}$$

Verilog-A

In Verilog-A it is not possible to define noise sources that are frequency dependent (except for $1/f$ -noise), nor is it possible to directly define correlations between noise sources. Instead, the desired model must be created by using controlled sources and the frequency transfer of passive elements.²

The goal is to create the three noise sources shown in Fig. 6.3 with the noise powers (including frequency dependence and correlation) as described by Eq. (6.3).

To simplify notation, we rewrite Eqs. (4.301) and (4.302) as

$$S_{ig} = \frac{N_T}{m_{ig}} \cdot |T|^2 \tag{6.5}$$

and

$$S_{igid} = \frac{N_T}{m_{ig}} \cdot m_{igid} \cdot T, \tag{6.6}$$

where

$$T = \frac{j \cdot \omega \cdot \tau}{1 + j \cdot \omega \cdot \tau}, \tag{6.7}$$

$\tau = m_{ig} \cdot C_{\text{Geff}}$ and ω is the operating frequency.

Correlation between noise sources in verilog-A can be created by making linear combinations of independent sources. Therefore, we start with two *independent* white noise sources with current noise spectral densities S_1 and S_2 and noise currents i_1 and i_2 . If we set

$$i_{gs} = i_{gd} = \frac{1}{2} \cdot \alpha_1 \cdot i_1 \tag{6.8}$$

$$i_{ds} = \beta_1 \cdot i_1 + \beta_2 \cdot i_2, \tag{6.9}$$

where α_1 , β_1 , and β_2 are certain (complex) coefficients, we get

$$\begin{aligned}
 S_{ig} &= 4 \cdot \langle i_{gd} \cdot i_{gd}^* \rangle = |\alpha_1|^2 \cdot \langle i_1 \cdot i_1^* \rangle \\
 &= |\alpha_1|^2 \cdot S_1
 \end{aligned} \tag{6.10}$$

$$\begin{aligned}
 S_{id} &= \langle i_{ds} \cdot i_{ds}^* \rangle = |\beta_1|^2 \cdot \langle i_1 \cdot i_1^* \rangle + \beta_1 \cdot \beta_2^* \cdot \langle i_1 \cdot i_2^* \rangle + |\beta_2|^2 \cdot \langle i_2 \cdot i_2^* \rangle \\
 &= |\beta_1|^2 \cdot S_1 + |\beta_2|^2 \cdot S_2
 \end{aligned} \tag{6.11}$$

$$\begin{aligned}
 S_{igid} &= 2 \cdot \langle i_{gd} \cdot i_{ds}^* \rangle = \alpha_1 \cdot \beta_1^* \cdot \langle i_1 \cdot i_1^* \rangle + \alpha_1 \cdot \beta_2^* \cdot \langle i_1 \cdot i_2^* \rangle \\
 &= \alpha_1 \cdot \beta_1^* \cdot S_1.
 \end{aligned} \tag{6.12}$$

Here we used that the noise currents i_1 and i_2 are independent, such that $\langle i_1 \cdot i_2^* \rangle = 0$. We need to choose proper values for the coefficients α_1 , β_1 and β_2 , as well as S_1 and S_2 , such that S_{ig} , S_{id} , and S_{igid} get the correct value.

²Although this appears to be a limitation, it is in fact very helpful to ensure that the resulting noise model is consistent with time-domain simulations.

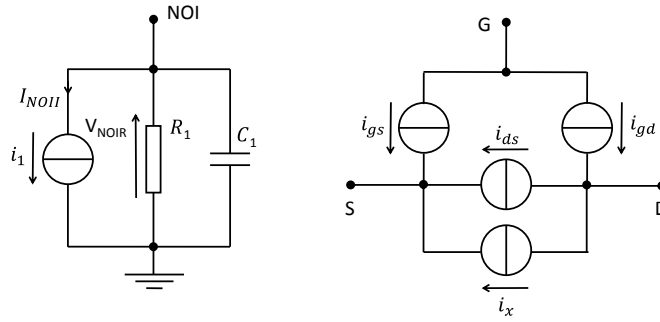


Figure 6.4: The subcircuit used in PSP's Verilog-A implementation to model the correct frequency dependence of induced gate noise and its correlation with the channel thermal noise.

There is some freedom in choosing the numbers; the values that are used in the verilog-A implementation of PSP are:

$$\alpha_1 = T \quad (6.13)$$

$$\beta_1 = m_{\text{igid}} \quad (6.14)$$

$$\beta_2 = 1 \quad (6.15)$$

$$S_1 = N_{\text{T}}/m_{\text{ig}} \quad (6.16)$$

$$S_2 = N_{\text{T}} \cdot (1 - C_{\text{igid}}^2) \cdot m_{\text{id}}, \quad (6.17)$$

where

$$C_{\text{igid}} = \frac{m_{\text{igid}}}{\sqrt{m_{\text{ig}} \cdot m_{\text{id}}}}, \quad (6.18)$$

and m_{id} , m_{ig} , and m_{igid} are given by Eqs. (4.297), (4.298), and (4.299), respectively.

Compared with previous version of PSP, the verilog-A code of PSP103.4 and later, a single equivalent circuit is used to implement frequency dependence. This subcircuit, shown in Fig. 6.4, contains a parallel connection of a white noise source with a resistor R_1 and a capacitance C_1 . The parameters of these components are given by:

$$S_1 = \langle i_1 \cdot i_1^* \rangle = N_{\text{T}} \quad (6.19)$$

$$R_1 = 1 \Omega \quad (6.20)$$

$$C_1 = m_{\text{ig}} \cdot C_{\text{Geff}} \quad (6.21)$$

where the values of C_{Geff} is given by Eqs. (4.286).

The two noise sources connected to the gate in Fig. 6.4 are as two voltage-controlled current sources with:

$$i_{\text{gd}} = i_{\text{gs}} = \frac{1}{2} \cdot T \cdot V_{\text{NOI}} \quad (6.22)$$

The third source in Fig. 6.3 (between source and drain) is realized by putting two elements in parallel, as illustrated in Fig. 6.4:

- A current-controlled current source i_x controlled by I_{NOI} ;
- A white noise source with current power spectral density $S_2 = N_{\text{T}} \cdot (1 - C_{\text{igid}}^2) \cdot m_{\text{id}}$.

Where the current i_x is given by:

$$i_x = C_{\text{igid}} \cdot \sqrt{m_{\text{id}}} \cdot I_{\text{NOII}} \quad (6.23)$$

To complete the model, we remark that from Fig. 6.3 it is clear that source-drain interchange only affects the sign of i_{ds} .

In summary, the relevant portion of the verilog-A implementation is given by (mult-scaling and labels are not included for clarity):

```

electrical NOI;

branch (NOI) NOII;
branch (NOI) NOIR;
branch (NOI) NOIC;

// subcircuit
I(NOII)    <+  white_noise((nt / mig));
I(NOIR)    <+  V(NOIR) / mig;
I(NOIC)    <+  ddt(CGeff * V(NOIC));

// noise sources ids, igs, and igd
I(GP,SI)   <+  -ddt(sqrt(MULT_i) * 0.5 * CGeff * V(NOIC));
I(GP,DI)   <+  -ddt(sqrt(MULT_i) * 0.5 * CGeff * V(NOIC));
I(DI,SI)   <+  sigVds * sqrt(MULT_i) * migid * I(NOII);
I(DI,SI)   <+  white_noise(MULT_i * sqid * sqid * (1.0 - c_igid * c_igid));

```

It is straightforward to verify that this implementation of PSP's noise model in Verilog-A naturally yields the desired correlations and frequency dependence. However, it requires two additional internal nodes.

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 SiMKit, the frequency dependence and correlation of the noise sources indicated in Fig. 6.3 are implemented directly according to Eq. (6.3). The result is therefore equivalent to the verilog-A implementation.

In summary, even though the SiMKit-implementation of the noise model in PSP is different from that in verilog-A (as it does not make use of additional internal nodes) the result of noise noise simulations will be identical.

6.5.4 Clip warnings

From SiMKit 3.7 onwards, it is possible to set the level of clip-warning information through the value of the parameter **PARAMCHK**. This functionality is available for most SiMKit models. It is *not* available in the verilog-A version of PSP.

If the value of **PARAMCHK** is

- < 0 All clip warnings are suppressed.
- ≥ 0 (default) Clip warnings for instance parameters.
- ≥ 1 Clip warnings for model parameters.
- ≥ 2 Clip warnings for internally computed local parameters during model initialization.
- ≥ 3 Clip warnings for internally computed local parameters during model evaluation.

This works in an accumulative manner: if a higher value of **PARAMCHK** is used, the warnings associated with lower levels are still included. Note that the highest level is of interest only for self heating models, where electrical parameters may change dependent on temperature. Also note that the default value (0) results in less clip warnings than in earlier versions of the model.

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}
 $V_{GS} = 0 \dots V_{sup}$ (with steps of maximum 50 mV).
 $V_{DS} = 25$ or 50 mV
 $V_{BS} = 0 \dots -V_{sup}$ (3 or more values)
- **Measurement II** (“idvgh”): I_D vs. V_{GS}
 $V_{GS} = 0 \dots V_{sup}$ (with steps of maximum 50 mV).
 $V_{DS} = V_{sup}$
 $V_{BS} = 0 \dots -V_{sup}$ (3 or more values)

¹The 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}
 $V_{GS} = 0 \dots V_{sup}$ (3 or more values)
 $V_{DS} = 0 \dots V_{sup}$ (with steps of maximum 50 mV).
 $V_{BS} = 0$ V

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

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

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

- **Measurement VII** (“cgvg”): C_{CG} vs. V_{GS}
 $V_{GS} = -V_{sup} \dots V_{sup}$ (with steps of maximum 50 mV).
 $V_{DS} = 0$ V
 $V_{BS} = 0$ V

- **Measurement VIII** (“ccvg”): C_{CG} vs. V_{GS}
 $V_{GS} = -V_{sup} \dots V_{sup}$ (with steps of maximum 50 mV).
 $V_{DS} = 0$ V
 $V_{BS} = 0$ 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 be measured by the system (noise limit) and I_T is defined as 10% of the largest measured value of $|I_D|$ 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., $L = L_{min}$) 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 °C and 125 °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. (3.74), using **AXO** ~ 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_{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_{GG}	Relative	–
2	CGOV , NOV	VIII: C_{CG}	Relative	$V_{GS} < 0$
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_{GG} in Measurement VII for a long, wide device.

Next, **NOV** and **CGOV** can be extracted from C_{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 $\mathbf{COX} = \epsilon_{ox} \cdot L \cdot W / \mathbf{TOX}$. 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

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

few short/wide devices of different lengths, one can extract **TOX** and ΔL from a series of extracted values of **COX** vs. L_{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. (3.13) / Eq. (3.34) 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.

In devices with strong lateral non-uniform doping, the threshold voltage in AC-measurements may deviate significantly from that in DC-measurements. If that is the case, values for **NEFF** and **DPHIB** obtained from DC-measurements may not be satisfactory to describe AC-measurements. Then, one has the option to set **SWDELVTAC** = 1, **DELVTAC** = $\text{DPHIB}_{\text{ac}} - \text{DPHIB}_{\text{dc}}$, and **FACNEFFAC** = $\text{NEFF}_{\text{ac}}/\text{NEFF}_{\text{dc}}$ to get a good description of both the DC and the AC 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 local parameters in Section 2.5.2 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.

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

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 2.5.2) can be used as initial value.

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

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 , GFACNUD	I: I_D	Relative	$I_{\min} < I_D < I_T$
3	MUE , THEMU ^a , CS , THECS , 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	$I_G > I_{\min}$
8	IGOV , (GCO ^a)	V: I_G	Relative	$V_{GS} < 0 \text{ V}$, $I_G < -I_{\min}$
9	A1 , A2 ^a , A3	V: I_B	Relative	$V_{GS} > 0 \text{ V}$, $I_B < -I_{\min}$
10	A4	VI: I_B	Relative	$V_{GS} > 0 \text{ V}$, $I_B < -I_{\min}$
11	AGIDL , BGIDL ^a	V: I_B	Relative	$V_{GS} < 0 \text{ V}$, $I_B < -I_{\min}$
12	CGIDL ^a	VI: I_B	Relative	$V_{GS} < 0 \text{ V}$, $I_B < -I_{\min}$
13	Repeat Steps 2 – 12			

^aOnly extracted for the *widest* long channel device and fixed for all other geometries.

case if $V_{\text{sup}} \gtrsim |\text{VFB}|$. 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.

After completion of the extraction for the long-channel device, it is recommended to first extract parameters for the shortest-channel device (of the same width). The mobility-reduction parameters (**MUE**, **THEMU**) and the gate tunneling probability factors (**GCO**, **GC2**, **GC3**) found from the corresponding long-channel device should be used. The extraction procedure as given in Table 7.5 should be used.

Once the value for **RS** has been found from the shortest device, it should be copied into the long-channel parameter set and steps 2–3 (Table 7.4) should be repeated, possibly leading to some readjustment of **MUE** and **THEMU**. If necessary, this procedure must be repeated. Similarly—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**.

If consistent parametersets have been found for the longest and shortest channel device, the extraction procedure

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 , GFACNUD , VSBNUD ^b , DVSBNUD ^b	I: I_D	Relative	$I_{\min} < I_D < I_T$
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	$ I_G > I_{\min}$
9	A1 , A3	V: I_B	Relative	$V_{GS} > 0 \text{ V}$, $I_B < -I_{\min}$
10	AGIDL	V: I_B	Relative	$V_{GS} < 0 \text{ V}$, $I_B < -I_{\min}$
11	Repeat Steps 2 – 10			

^aOnly extracted for the *shortest* channel of each width and fixed for all other geometries.

^bOnly extracted for the *shortest widest* device and fixed for all other geometries.

as given in Table 7.5 can be executed for all intermediate channel lengths. The extracted parameter values of the next-longer device can be used as initial values.

Finally, the parameters **GFACNUD**, **VSBNUD**, and **DVSBNUD** should only be used if the description of the body effect is not satisfactory otherwise. For this, the NUD-model must be invoked by setting **SWNUD** = 1.

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 by local parameters in Section 2.5.2 can be used. Again the parameter extraction scheme is 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**, **STTHECS** 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 7.6: 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	$I_D < I_T$
2	STBETN ^a , STMUE , STTHEMU , STCS , STTHECS , STXCOR	I: I_D	Absolute	–
3	STTHESAT ^a	II: I_D	Absolute	–
4	STIG	V: I_G	Relative	$ I_G > I_{\min}$
5	STA2	V: I_B	Relative	$V_{GS} > 0 \text{ V}, I_B < -I_{\min}$
6	STBGIDL	V: I_B	Relative	$V_{GS} < 0 \text{ V}, I_B < -I_{\min}$

^aAlso extracted for one or more long *narrow* devices.

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	$V_{GS} < V_T$
2	STBETN , STRS ^a	I: I_D	Absolute	$V_{GS} > V_T$
3	STTHESAT	II: I_D	Absolute	–

^aOnly 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 2.5.2) 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. (3.7) and (3.8).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 $1/\mathbf{BETN}$ 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 [13, 14]. Another, more accurate method is to measure the gate-to-bulk capacitance C_{GB} in accumulation for different

³Note 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.

channel lengths [14, 15]. 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 [16]. In this case gate current parameter **IGINV** plotted as a function of channel length L may be used to extract ΔL [16]. 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**, **STHEMUO**, **STCSO**, **STHECSO**, **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.

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 3.2 is Eq. (3.39), 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. (3.39) 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 2.5.2 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 $\text{BETN}_{\text{sq}} \stackrel{\text{def}}{=} \text{BETN} \cdot L_E/W_E$ 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 (reverse short channel effect), while **FOL1** and **FOL2** are used to describe the decrease of **NEFF** for very short channels (short channel effect).
- Then **NSUBW** and **WSEG** can be determined from 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 3.3. 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*.

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

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

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

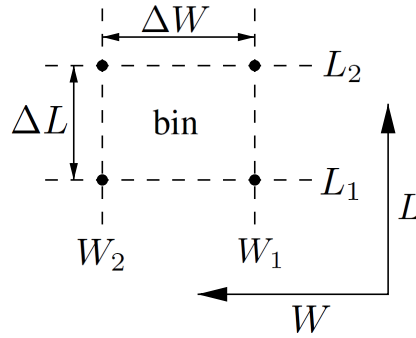


Figure 7.1: Schematic view of a bin, showing the coordinates of the four corners. Note that L_1 , L_2 , W_1 , and W_2 denote the *effective* length and width (L_E and W_E) at the bin corners.

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

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

2. Coefficients for type II scaling

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

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

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

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

3. Coefficients for type III scaling

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

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

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

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

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.

7.6.1 Binning of BETN

From PSP 103.0 onwards, the binning rule of **BETN** is changed to better match its typical scaling behavior.

- Extract the parameters **POBETN**, **PLBETN**, **PWBETN**, and **PLWBETN** for type I binning by applying Eq. (7.1)-(7.4) to $(L_E/W_E) \cdot \mathbf{BETN}$ (i.e., not to **BETN** itself).

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: $P_D = 1 + k_p \cdot G/4$, where k_p is defined in Eq. (4.24).

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 $V'_{DS} \geq 0$, –1 otherwise	Flag for source-drain interchange
Current components				
2	ise	A	$I_S - I_{JS}$	Total source current
3	ige	A	I_G	Total gate current
4	ide	A	$I_D - I_{JD}$	Total drain current
5	ibe	A	$I_B + I_{JS} + I_{JD}$	Total bulk current
6	ids	A	I_{DS}	Drain current, excl. avalanche and tunnel currents
7	idb	A	$I_{avl} + I_{gidl} - I_{JD}$	Drain-to-bulk current
8	isb	A	$I_{gisl} - I_{JS}$	Source-to-bulk current
9	igs	A	$I_{GCS} + I_{GSov}$	Gate-source tunneling current
10	igd	A	$I_{GCD} + I_{GDov}$	Gate-drain tunneling current
11	igb	A	I_{GB}	Gate-bulk tunneling current
12	idedge	A	$I_{DS,edge}$	Drain current of edge transistor

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No.	Name	Unit	Value	Description
13	igcs	A	I_{GCS}	Gate-channel tunneling current (source component)
14	igcd	A	I_{GCD}	Gate-channel tunneling current (drain component)
15	iavl	A	I_{avl}	Substrate current due to weak-avalanche
16	igisl	A	I_{gisl}	Gate-induced source leakage current
17	igidl	A	I_{gidl}	Gate-induced drain leakage current
Junction currents				
18	ijs	A	I_{JS}	Total source junction current
19	ijsbot	A	$I_{JS,bot}$	Source junction current, bottom component
20	ijsgat	A	$I_{JS,gat}$	Source junction current, gate-edge component
21	ijssti	A	$I_{JS,sti}$	Source junction current, STI-edge component
22	ijd	A	I_{JD}	Total drain junction current
23	ijdbot	A	$I_{JD,bot}$	Drain junction current, bottom component
24	ijdgat	A	$I_{JD,gat}$	Drain junction current, gate-edge component
25	ijdsti	A	$I_{JD,sti}$	Drain junction current, STI-edge component
Voltages				
26	vds	V	V_{DS}	Drain-source voltage
27	vgs	V	V_{GS}	Gate-source voltage
28	vsb	V	V_{SB}	Source-bulk voltage
29	vto	V	$\mathbf{VFB} + P_D \cdot (\phi_B + 2 \cdot \phi_T^*) + G \cdot \sqrt{\phi_T^* \cdot (\phi_B + 2 \cdot \phi_T^*)}$	Zero-bias threshold voltage
30	vts	V	$\mathbf{VFB} + P_D \cdot (V_{SB}^{nud} + \phi_B + 2 \cdot \phi_T^*) - V_{SB}^{nud} + G \cdot \sqrt{\phi_T^* \cdot (V_{SB}^{nud} + \phi_B + 2 \cdot \phi_T^*)}$	Threshold voltage including back-bias effects
31	vth	V	$\mathbf{vts} - \Delta V_G$	Threshold voltage including back-bias and drain-bias effects
32	vgt	V	$\mathbf{vgs} - \mathbf{vth}$	Effective gate drive voltage including drain- and back-bias effects
33	vdss	V	V_{dsat}	Drain saturation voltage at actual bias
34	vsat	V	$V_{DS} - V_{dsat}$	Saturation limit
(Trans-)conductances				
35	gm	A/V	$\partial \mathbf{ide} / \partial V_{GS}$	Transconductance
36	gmb	A/V	$-\partial \mathbf{ide} / \partial V_{SB}$	Substrate-transconductance
37	gds	A/V	$\partial \mathbf{ide} / \partial V_{DS}$	Output conductance

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No.	Name	Unit	Value	Description
38	gjs	A/V	$-\partial i_{js}/\partial V_{SB}$	Source junction conductance
39	gjd	A/V	$-(\partial i_{jd}/\partial V_{DS} + \partial i_{jd}/\partial V_{SB})$	Drain junction conductance
Capacitances				
40	cdd	F	$\partial Q_D^{(i)}/\partial V_{DS}$	Drain capacitance
41	cdg	F	$-\partial Q_D^{(i)}/\partial V_{GS}$	Drain-gate capacitance
42	cds	F	cdd - cdg - cdb	Drain-source capacitance
43	cdb	F	$\partial Q_D^{(i)}/\partial V_{SB}$	Drain-bulk capacitance
44	cgd	F	$-\partial Q_G^{(i)}/\partial V_{DS}$	Gate-drain capacitance
45	egg	F	$\partial Q_G^{(i)}/\partial V_{GS}$	Gate capacitance
46	cgs	F	egg - cgd - cgb	Gate-source capacitance
47	cgb	F	$\partial Q_G^{(i)}/\partial V_{SB}$	Gate-bulk capacitance
48	csd	F	$-\partial Q_S^{(i)}/\partial V_{DS}$	Source-drain capacitance
49	csg	F	$-\partial Q_S^{(i)}/\partial V_{GS}$	Source-gate capacitance
50	css	F	csg + csd + csb	Source capacitance
51	csb	F	$\partial Q_S^{(i)}/\partial V_{SB}$	Source-bulk capacitance
52	cbd	F	$-\partial Q_B^{(i)}/\partial V_{DS}$	Bulk-drain capacitance
53	cbg	F	$-\partial Q_B^{(i)}/\partial V_{GS}$	Bulk-gate capacitance
54	cbs	F	cbb - cbd - cbg	Bulk-source capacitance
55	cbb	F	$-\partial Q_B^{(i)}/\partial V_{SB}$	Bulk capacitance
56	cgisol	F	$\partial(Q_{sov} + Q_{ofs})/\partial V_{GS}$	Total gate-source overlap capacitance
57	cgdol	F	$\partial(Q_{dov} + Q_{ofd})/\partial V_{DS}$	Total gate-drain overlap capacitance
Junction capacitances				
58	cjs	F	C_{JS}	Total source junction capacitance
59	cjsbot	F	$C_{JS,bot}$	Source junction capacitance, bottom component
60	cjsgat	F	$C_{JS,gat}$	Source junction capacitance, gate-edge component
61	cjssti	F	$C_{JS,sti}$	Source junction capacitance, STI-edge component
62	cjd	F	C_{JD}	Total drain junction capacitance
63	cjdbot	F	$C_{JD,bot}$	Drain junction capacitance, bottom component
64	cjdgat	F	$C_{JD,gat}$	Drain junction capacitance, gate-edge component
65	cjdsti	F	$C_{JD,sti}$	Drain junction capacitance, STI-edge component
Miscellaneous				
66	weff	m	W_E	Effective channel width for geometrical models
67	leff	m	L_E	Effective channel length for geometrical models

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No.	Name	Unit	Value	Description
68	u	-	gm/gds	Transistor gain
69	rout	Ω	1/gds	Small-signal output resistance
70	vearly	V	 ide /gds	Equivalent Early voltage
71	beff	A/V ²	2 · ide /vgt²	Gain factor
72	fug	Hz	gm/[2 · π · (cgg + cgsol + cgdol)]	Unity gain frequency at actual bias
73	rg	Ω	RG	Gate resistance
Noise				
74	sfl	A ² /Hz	$S_{fl}(1\text{ Hz})$	Flicker noise current spectral density at 1 Hz
75	sqrtsff	V/ $\sqrt{\text{Hz}}$	$\sqrt{S_{fl}(1\text{ kHz})}/\mathbf{gm}$	Input-referred RMS white noise voltage spectral density at 1 kHz
76	sqrtsfw	V/ $\sqrt{\text{Hz}}$	$\sqrt{S_{id}}/\mathbf{gm}$	Input-referred RMS white noise voltage spectral density
77	sid	A ² /Hz	S_{id}	Channel thermal noise current spectral density
78	sig	A ² /Hz	$S_{ig}(1\text{ kHz})$	Induced gate noise current spectral density at 1 kHz
79	cigid	-	$\frac{m_{igid}}{\sqrt{m_{ig} \cdot m_{id}}}$	Imaginary part of correlation coefficient between S_{ig} and S_{id}
80	fknee	Hz	$1\text{ Hz} \cdot S_{fl}(1\text{ Hz})/S_{id}$	Cross-over frequency above which white noise is dominant
81	sigs	A ² /Hz	S_{igs}	Gate-source current noise spectral density
82	sigd	A ² /Hz	S_{igd}	Gate-drain current noise spectral density
83	siavl	A ² /Hz	S_{avI}	Impact ionization current noise spectral density
84	ssi	A ² /Hz	$S_{S,I}$	Total source junction current noise spectral density
85	sdi	A ² /Hz	$S_{D,I}$	Total drain junction current noise spectral density
86	sfledge	A ² /Hz	$S_{fl,edge}(1\text{ Hz})$	Flicker noise current spectral density of edge transistor at 1 Hz
87	sidedge	A ² /Hz	$S_{id,edge}$	Channel thermal noise current spectral density of edge transistor
Self heating				
88	tk	K	T_{KD}	Device temperature
89	pdiss	W	P_{diss}	Power dissipation
90	dtsh	K	$T_{KD} - T_{KA}$	Temperature rise due to self heating

From PSP 103.0 onwards, the values of local parameters are provided in the operating point output. They are listed in the table below.

No.	Name	Unit	Description
Process Parameters			
0	lp_vfb	V	Local parameter VFB after T-scaling and clipping
1	lp_stvfb	V/K	Local parameter STVFB after clipping
2	lp_st2vfb	K ⁻¹	Local parameter ST2VFB after clipping
3	lp_tox	m	Local parameter TOX after clipping
4	lp_epsrox	–	Local parameter EPSROX after clipping
5	lp_neff	m ⁻³	Local parameter NEFF after clipping
6	lp_facneffac	–	Local parameter FACNEFFAC after clipping
7	lp_gfacnud	–	Local parameter GFACNUD after clipping
8	lp_vsbnud	V	Local parameter VSBNUD after clipping
9	lp_dvsbnud	V	Local parameter DVSBNUD after clipping
10	lp_vnsub	V	Local parameter VNSUB after clipping
11	lp_nslp	V	Local parameter NSLP after clipping
12	lp_dnsud	V ⁻¹	Local parameter DNSUB after clipping
13	lp_dphib	V	Local parameter DPHIB after clipping
14	lp_delvtac	V	Local parameter DELVTAC after clipping
15	lp_np	m ⁻³	Local parameter NP after clipping
16	lp_toxov	m	Local parameter TOXOV after clipping
17	lp_toxovd	m	Local parameter TOXOVD after clipping
18	lp_nov	m ⁻³	Local parameter NOV after clipping
19	lp_novd	m ⁻³	Local parameter NOVD after clipping
Interface States Parameters			
20	lp_ct	–	Local parameter CT after clipping
21	lp_ctg	V ⁻¹	Local parameter CTG after clipping
22	lp_ctb	V ⁻¹	Local parameter CTB after clipping
23	lp_stct	–	Local parameter STCT after clipping
DIBL Parameters			
24	lp_cf	–	Local parameter CF after clipping
25	lp_cfb	V ⁻¹	Local parameter CFB after clipping
26	lp_cfd	V ⁻¹	Local parameter CFD after clipping
Subthreshold Slope Parameters			
27	lp_psce	–	Local parameter PSCE after clipping
28	lp_psceb	V ⁻¹	Local parameter PSCEB after clipping
29	lp_psced	V ⁻¹	Local parameter PSCED after clipping
Mobility Parameters			
30	lp_betn	m ² /V/s	Local parameter BETN after T-scaling and clipping
31	lp_stbet	–	Local parameter STBET after clipping
32	lp_mue	m/V	Local parameter MUE after T-scaling and clipping

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No.	Name	Unit	Description
33	lp_stmue	–	Local parameter STMUE after clipping
34	lp_themu	–	Local parameter THEMU after T-scaling and clipping
35	lp_stthemu	–	Local parameter STTHEMU after clipping
36	lp_cs	–	Local parameter CS after T-scaling and clipping
37	lp_stcs	–	Local parameter STCS after clipping
38	lp_thecs	–	Local parameter THECS after clipping
39	lp_sttheecs	–	Local parameter STTHECS after clipping
40	lp_xcor	V ⁻¹	Local parameter XCOR after T-scaling and clipping
41	lp_stxcor	–	Local parameter STXCOR after clipping
42	lp_feta	–	Local parameter FETA after clipping
Series Resistance Parameters			
43	lp_rs	Ω	Local parameter RS after T-scaling and clipping
44	lp_strs	–	Local parameter STRS after clipping
45	lp_rsb	V ⁻¹	Local parameter RSB after clipping
46	lp_rsg	V ⁻¹	Local parameter RSG after clipping
Velocity Saturation Parameters			
47	lp_thesat	V ⁻¹	Local parameter THESAT after T-scaling and clipping
48	lp_stthesat	–	Local parameter STTHESAT after clipping
49	lp_thesatb	V ⁻¹	Local parameter THESATB after clipping
50	lp_thesatg	V ⁻¹	Local parameter THESATG after clipping
Saturation Voltage Parameters			
51	lp_ax	–	Local parameter AX after clipping
Channel Length Modulation (CLM) Parameters			
52	lp_alp	–	Local parameter ALP after clipping
53	lp_alp1	V	Local parameter ALP1 after clipping
54	lp_alp2	V ⁻¹	Local parameter ALP2 after clipping
55	lp_vp	V	Local parameter VP after clipping
Impact Ionization (II) Parameters			
56	lp_a1	–	Local parameter A1 after clipping
57	lp_a2	V	Local parameter A2 after T-scaling and clipping
58	lp_sta2	–	Local parameter STA2 after clipping
59	lp_a3	–	Local parameter A3 after clipping
60	lp_a4	1/√V	Local parameter A4 after clipping
Gate Current Parameters			
61	lp_gco	–	Local parameter GCO after clipping
62	lp_iginv	A	Local parameter IGINV after T-scaling and clipping
63	lp_igov	A	Local parameter IGOV after T-scaling and clipping
64	lp_igovd	A	Local parameter IGOVD after T-scaling and clipping
65	lp_stig	–	Local parameter STIG after clipping

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No.	Name	Unit	Description
66	lp_gc2	–	Local parameter GC2 after clipping
67	lp_gc3	–	Local parameter GC3 after clipping
68	lp_chib	V	Local parameter CHIB after clipping
Gate-Induced Drain Leakage Parameters			
69	lp_agidl	A/V^3	Local parameter AGIDL after clipping
70	lp_agidld	A/V^3	Local parameter AGIDLD after clipping
71	lp_bgidl	V	Local parameter BGIDL after T-scaling and clipping
72	lp_bgidld	V	Local parameter BGIDLD after T-scaling and clipping
73	lp_stbgidl	V/K	Local parameter STBGIDL after clipping
74	lp_stbgidld	V/K	Local parameter STBGIDLD after clipping
75	lp_cgidl	–	Local parameter CGIDL after clipping
76	lp_cgidld	–	Local parameter CGIDLD after clipping
Charge Model Parameters			
77	lp_cox	F	Local parameter COX after clipping
78	lp_cgov	F	Local parameter CGOV after clipping
79	lp_cgovd	F	Local parameter CGOVD after clipping
80	lp_cgbov	F	Local parameter CGBOV after clipping
81	lp_cfr	F	Local parameter CFR after clipping
82	lp_cfrd	F	Local parameter CFRD after clipping
Noise Model Parameters			
83	lp_fnt	–	Local parameter FNT after clipping
84	lp_fntexc	–	Local parameter FNTEXC after clipping
85	lp_nfa	$1/V/m^4$	Local parameter NFA after clipping
86	lp_nfb	$1/V/m^2$	Local parameter NFB after clipping
87	lp_nfc	V^{-1}	Local parameter NFC after clipping
88	lp_ef	–	Local parameter EF after clipping
Edge Transistor Parameters			
89	lp_vfbedge	V	Local parameter VFEDGE after T-scaling and clipping
90	lp_stvfbedge	V/K	Local parameter STVFEDGE after clipping
91	lp_dphibedge	V	Local parameter DPHIBEDGE after clipping
92	lp_neffedge	m^{-3}	Local parameter NEFFEDGE after clipping
93	lp_ctedge	–	Local parameter CTEDGE after clipping
94	lp_betnedge	$m^2/V/s$	Local parameter BETNEEDGE after T-scaling and clipping
95	lp_stbetedge	–	Local parameter STBETEDGE after clipping
96	lp_psceedge	–	Local parameter PSCEEDGE after clipping
97	lp_pscebedge	V^{-1}	Local parameter PSCEBEDGE after clipping
98	lp_pscededge	V^{-1}	Local parameter PSCEDEEDGE after clipping
99	lp_cfedge	–	Local parameter CFEDGE after clipping
100	lp_cfdedge	V^{-1}	Local parameter CFDEEDGE after clipping
101	lp_cfbedge	V^{-1}	Local parameter CFBEDGE after clipping

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No.	Name	Unit	Description
102	lp_fntedge	–	Local parameter FNTEDGE after clipping
103	lp_nfaedge	1/V/m ⁴	Local parameter NFAEDGE after clipping
104	lp_nfbedge	1/V/m ²	Local parameter NFBEDGE after clipping
105	lp_nfcedge	V ⁻¹	Local parameter NFCEDGE after clipping
106	lp_efedge	–	Local parameter EFEDGE after clipping
Parasitic Resistance Parameters			
107	lp_rg	Ω	Local parameter RG after clipping
108	lp_rse	Ω	Local parameter RSE after clipping
109	lp_rde	Ω	Local parameter RDE after clipping
110	lp_rbulk	Ω	Local parameter RBULK after clipping
111	lp_rwell	Ω	Local parameter RWELL after clipping
112	lp_rjuns	Ω	Local parameter RJUNS after clipping
113	lp_rjund	Ω	Local parameter RJUND after clipping
Self Heating Parameters			
114	lp_rth	K/W	Local parameter RTH after T-scaling and clipping
115	lp_cth	J/K	Local parameter CTH after clipping
116	lp_strth	–	Local parameter STRTH after clipping
Junction Parameters			
117	cjosbot	F	Bottom component of total zero-bias source junction capacitance at device temperature
118	cjossti	F	STI-edge component of total zero-bias source junction capacitance at device temperature
119	cjosgat	F	Gate-edge component of total zero-bias source junction capacitance at device temperature
120	vbisbot	V	Built-in voltage of source-side bottom junction at device temperature
121	vbissti	V	Built-in voltage of source-side STI-edge junction at device temperature
122	vbisgat	V	Built-in voltage of source-side gate-edge junction at device temperature
123	idsatsbot	A	Total source-side bottom junction saturation current
124	idsatssti	A	Total source-side STI-edge junction saturation current
125	idsatsgat	A	Total source-side gate-edge junction saturation current
126	cjosbotd	F	Bottom component of total zero-bias drain junction capacitance at device temperature
127	cjosstid	F	STI-edge component of total zero-bias drain junction capacitance at device temperature
128	cjosgatd	F	Gate-edge component of total zero-bias drain junction capacitance at device temperature
129	vbisbotd	V	Built-in voltage of drain-side bottom junction at device temperature
130	vbisstid	V	Built-in voltage of drain-side STI-edge junction at device temperature

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No.	Name	Unit	Description
131	vbigatd	V	Built-in voltage of drain-side gate-edge junction at device temperature
132	idsatsbotd	A	Total drain-side bottom junction saturation current
133	idsatsstid	A	Total drain-side STI-edge junction saturation current
134	idsatsgatd	A	Total drain-side gate-edge junction saturation current
NQS Parameters			
135	lp_munqs	–	Local parameter MUNQS after clipping

References

- [1] L. Lemaitre, C. C. McAndrew, and S. Hamm, “ADMS – Automatic Device Model Synthesize”, *Proc. IEEE CICC*, 2002. See also <http://sourceforge.net/projects/mot-adms>
- [2] G. Gildenblat *et al.*, “From BSIM3/4 to PSP: Translation of Flicker Noise and Junction Parameters”, available for download at <http://www.nxp.com/models/simkit/mos-models/model-bsp.html>
- [3] X. Xi *et al.*, *BSIM4.4.0 MOSFET Model, User’s Manual*, 2004, available for download at http://www-device.eecs.berkeley.edu/bsim/?page=BSIM4_Arc
- [4] T.B. Hook *et al.*, “Lateral Ion Implant Straggle and Mask Proximity Effect,” *IEEE Trans. on Electron Devices*, Vol. 50, No. 9, pp. 1946-1951, 2003.
- [5] X. Xi *et al.*, *BSIM4.5.0 MOSFET Model, User’s Manual*, 2005, available for download at http://www-device.eecs.berkeley.edu/bsim/?page=BSIM4_Arc
- [6] M. Basel, J. Watts *et al.*, *Guidelines for Extracting Well Proximity Instance Parameters*, December 2006, available for download at http://www.si2.org/cmc_index.php
- [7] R. Landauer, “Solid-state shot noise”, *Phys. Rev. B*, vol. 47, no. 24, pp. 16427–16432, 1993.
- [8] G.D.J. Smit *et al.*, “Experimental Demonstration and Modeling of Excess RF Noise in Sub-100-nm CMOS Technologies”, *Electron Dev. Lett.*, vol. 31, no. 8, pp. 884–886, 2010.
- [9] H. Wang, T.-L. Chen, and G. Gildenblat, “Quasi-static and Nonquasi-static Compact MOSFET Models Based on Symmetric Linearization of the Bulk and Inversion Charges,” *IEEE trans. Electron Dev.* **50**(11), pp. 2262-2272, 2003.
- [10] H. Wang *et al.*, “Unified Non-Quasi-Static MOSFET Model for Large-Signal and Small-Signal Simulations,” *CICC 2005*.
- [11] W. H. Press *et al.*, “Numerical recipes in C”, 2nd edition, Cambridge University Press (1993), available for download at <http://apps.nrbook.com/c/index.html>
- [12] A.J. Scholten *et al.*, “JUNCAP2, version 200.3”, available for download at <http://psp.ewi.tudelft.nl/>
- [13] M. Minondo, G. Gouget, and A. Juge, “New Length Scaling of Current Gain Factor and Characterization Method for Pocket Implanted MOSFET’s,” *Proc. ICMTS 2001*, pp. 263-267, 2001.
- [14] A.J. Scholten, R. Duffy, R. van Langevelde, and D.B.M. Klaassen, “Compact Modelling of Pocket-Implanted MOSFETs,” *Proc. ESSDERC 2001*, pp. 311-314, 2001.
- [15] T.S. Hsieh, Y.W. Chang, W.J. Tsai, and T.C. Lu, “A New Leff Extraction Approach for Devices with Pocket Implants,” *Proc. ICMTS 2001*, pp. 15-18, 2001.
- [16] R. van Langevelde *et al.*, “Gate Current: modelling, ΔL Extraction and Impact on RF Performance,” *IEDM 2001 Tech. Digest*, pp. 289-292, 2001.

Appendix A

Auxiliary Equations

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

The MINA-smoothing function:

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

The MAXA-smoothing function:

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

The MNE- and MXE-smoothing functions:

$$\text{MNE}(x, y, \varepsilon) = \frac{2}{A} \left[x + y - \sqrt{(x + y)^2 - A \cdot xy} \right] \quad (\text{A.3})$$

$$\text{MXE}(x, y, \varepsilon) = \frac{2}{A} \left[x + y + \sqrt{(x + y)^2 - A \cdot xy} \right] \quad (\text{A.4})$$

$$A = 4 - \varepsilon; \quad \varepsilon \in (0, 1) \quad (\text{A.5})$$

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

$$\chi(y) = \frac{y^2}{2 + y^2} \quad (\text{A.6})$$

$$\chi'(y) = \frac{4y}{(2 + y^2)^2} \quad (\text{A.7})$$

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

$$\nu = a + c \quad (\text{A.9})$$

$$\mu_1 = \frac{\nu^2}{\tau} + \frac{c^2}{2} - a \quad (\text{A.10})$$

$$\sigma_1(a, c, \tau, \eta) = \frac{a \cdot \nu}{\mu_1 + (c^2/3 - a) \cdot c \cdot \nu / \mu_1} + \eta \quad (\text{A.11})$$

$$\mu_2 = \frac{v^2}{\tau} + \frac{c^2}{2} - a \cdot b \quad (\text{A.12})$$

$$\sigma_2(a, b, c, \tau, \eta) = \frac{a \cdot \nu}{\mu_2 + (c^2/3 - a \cdot b) \cdot c \cdot \nu / \mu_2} + \eta \quad (\text{A.13})$$

Appendix B

Layout parameter calculation

In post-layout simulations, various PSP instance parameters should be supplied either manually or by a layout extraction tool. In this appendix, it is shown how these parameters should be calculated.

Note: These equations are *not* part of the PSP model.

B.1 Stress parameters

B.1.1 Layout effects for irregular shapes

For irregular shapes the following effective values for **SA** and **SB** are to be used (see Fig B.1).

$$\frac{1}{\mathbf{SA}_{\text{eff}} + 0.5 \cdot L} = \sum_{i=1}^n \frac{\mathbf{SW}_i}{W} \cdot \frac{1}{\mathbf{SA}_i + 0.5 \cdot L} \quad (\text{B.1})$$

$$\frac{1}{\mathbf{SB}_{\text{eff}} + 0.5 \cdot L} = \sum_{i=1}^n \frac{\mathbf{SW}_i}{W} \cdot \frac{1}{\mathbf{SB}_i + 0.5 \cdot L} \quad (\text{B.2})$$

B.2 Well proximity effect parameters

The values of the instance parameters **SCA**, **SCB** and **SCC** can be calculated from layout parameters using the equations below.

$$f_A(u) = \frac{\mathbf{SCREF}^2}{u^2} \quad (\text{B.3})$$

$$f_B(u) = \frac{u}{\mathbf{SCREF}} \cdot \exp\left(-10 \cdot \frac{u}{\mathbf{SCREF}}\right) \quad (\text{B.4})$$

$$f_C(u) = \frac{u}{\mathbf{SCREF}} \cdot \exp\left(-20 \cdot \frac{u}{\mathbf{SCREF}}\right) \quad (\text{B.5})$$

$$A_{\text{corner}} = \sum_{i=m+1}^{m+k} \left(\frac{L}{2} \cdot \int_{\mathbf{SCX}_i + \mathbf{SCY}_i}^{\mathbf{SCX}_i + \mathbf{SCY}_i + W} f_A(u) du \right) + \sum_{i=n+1}^{n+k} \left(\frac{W}{2} \cdot \int_{\mathbf{SCX}_i + \mathbf{SCY}_i}^{\mathbf{SCX}_i + \mathbf{SCY}_i + L} f_A(u) du \right) \quad (\text{B.6})$$

$$\begin{aligned}
B_{\text{corner}} = & \sum_{i=m+1}^{m+k} \left(\frac{L}{2} \cdot \int_{\text{SCX}_i+\text{SCY}_i}^{\text{SCX}_i+\text{SCY}_i+W} f_B(u) \, du \right) \\
& + \sum_{i=n+1}^{n+k} \left(\frac{W}{2} \cdot \int_{\text{SCX}_i+\text{SCY}_i}^{\text{SCX}_i+\text{SCY}_i+L} f_B(u) \, du \right) \quad (\text{B.7})
\end{aligned}$$

$$\begin{aligned}
C_{\text{corner}} = & \sum_{i=m+1}^{m+k} \left(\frac{L}{2} \cdot \int_{\text{SCX}_i+\text{SCY}_i}^{\text{SCX}_i+\text{SCY}_i+W} f_C(u) \, du \right) \\
& + \sum_{i=n+1}^{n+k} \left(\frac{W}{2} \cdot \int_{\text{SCX}_i+\text{SCY}_i}^{\text{SCX}_i+\text{SCY}_i+L} f_C(u) \, du \right) \quad (\text{B.8})
\end{aligned}$$

$$\begin{aligned}
\mathbf{SCA} = & \frac{1}{W \cdot L} \cdot \left[\sum_{i=1}^n \left(W_i \cdot \int_{\text{SC}_i}^{\text{SC}_i+L} f_A(u) \, du \right) \right. \\
& \left. + \sum_{i=n+1}^{n+m} \left(L_i \cdot \int_{\text{SC}_i}^{\text{SC}_i+W} f_A(u) \, du \right) + A_{\text{corner}} \right] \quad (\text{B.9})
\end{aligned}$$

$$\begin{aligned}
\mathbf{SCB} = & \frac{1}{W \cdot L} \cdot \left[\sum_{i=1}^n \left(W_i \cdot \int_{\text{SC}_i}^{\text{SC}_i+L} f_B(u) \, du \right) \right. \\
& \left. + \sum_{i=n+1}^{n+m} \left(L_i \cdot \int_{\text{SC}_i}^{\text{SC}_i+W} f_B(u) \, du \right) + B_{\text{corner}} \right] \quad (\text{B.10})
\end{aligned}$$

$$\begin{aligned}
\mathbf{SCC} = & \frac{1}{W \cdot L} \cdot \left[\sum_{i=1}^n \left(W_i \cdot \int_{\text{SC}_i}^{\text{SC}_i+L} f_C(u) \, du \right) \right. \\
& \left. + \sum_{i=n+1}^{n+m} \left(L_i \cdot \int_{\text{SC}_i}^{\text{SC}_i+W} f_C(u) \, du \right) + C_{\text{corner}} \right] \quad (\text{B.11})
\end{aligned}$$

Here, m and n are the number of projections of the well edge along the length and width of the devices, respectively. Moreover, k is the number of corners selected to account for the ‘corner’ effects.

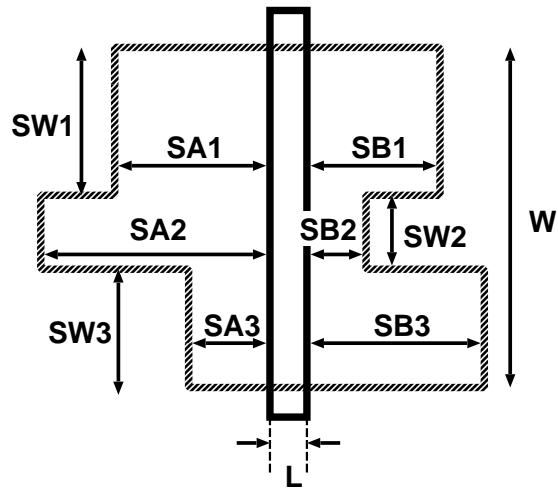


Figure B.1: A typical layout of MOS devices with more instance parameters (SW_i , SA_i and SB_i) in addition to the traditional L and W .

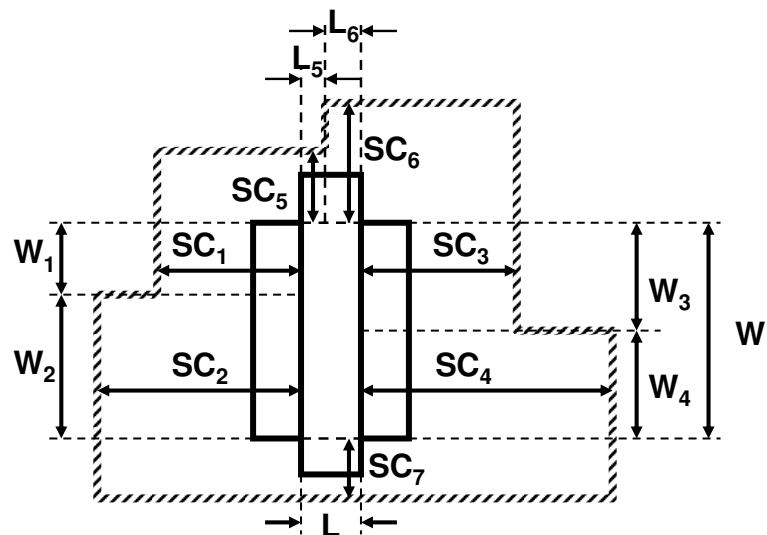


Figure B.2: A typical layout of MOS devices with **WPE** instance parameters

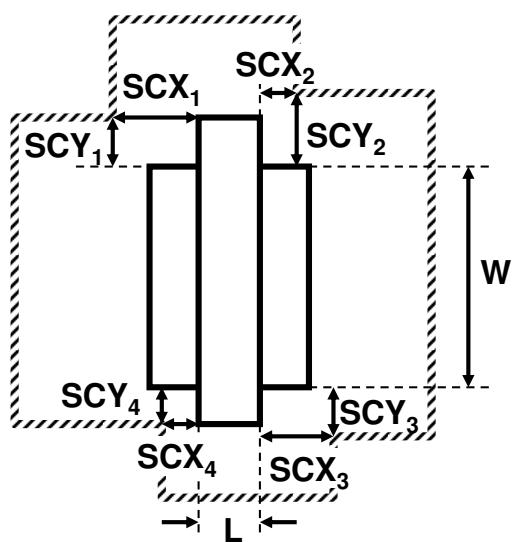


Figure B.3: A layout of MOS devices for corner terms calculation