

# 15 MOS Model 11, level 1102

# 15.1 Introduction

## General Remarks

MOS Model 11 (MM11, level 1102) is a new compact MOSFET model, intended for digital, analogue and RF circuit simulation in modern and future CMOS technologies [1] - [3]. MM11 is the successor of MOS Model 9, it was especially developed to give not only an accurate description of currents and charges and their first-order derivatives (i.e. transconductance, conductance, capacitances), but also of the higher-order derivatives, resulting in an accurate description of electrical distortion behaviour [3]. The latter is especially important for analog and RF circuit design. The model furthermore gives an accurate description of the noise behaviour of MOSFETs.

MOS Model 11 gives a complete description of all transistor-action related quantities: nodal currents, nodal charges and noise-power spectral densities. The equations describing these quantities are based on surface-potential formulations, resulting in equations valid over all operation regions (i.e. accumulation, depletion and inversion). Additionally, in order for the model to be valid for modern and future MOS devices, several important physical effects have been included in the model: mobility reduction, bias-dependent series-resistance, velocity saturation, drain-induced barrier lowering, static feedback, channel length modulation, self-heating, weak-avalanche (or impact ionization), gate current due to tunnelling, poly-depletion, quantum-mechanical effects on charges and bias-dependent overlap capacitances.

MOS Model 11 only provides a model for the intrinsic transistor and the gate/source- and gate/drain overlap regions. Junction charges, junction leakage currents and interconnect capacitances are not included. They are covered by separate models, which are not part of this documentation.

MOS Model 11, Level 1102, is an updated version of Level 1101 [2]. It uses slightly different equations than Level 1101.

The surface potential generally is implicitly related to the terminal voltages and has to be calculated iteratively. Since the iterative procedure was assumed to be time consuming, the surface potential has been approximated by an explicit expression [4] in previous levels of MM11[1]-[3]. In the Level 1102, the surface potential is calculated iteratively using a second-order Newton-Raphson procedure, resulting in a much more accurate description of surface potential which is obtained within 3 iterations. Owing to the increased accuracy, some of the basic equations used in Level 1101 can be simplified, and as a result Level 1102 is computationally as fast as Level 1101. In addition, a more physical and simpler velocity saturation expression is used, and as a consequence the saturation voltage expression has changed slightly as well. This all results in a more accurate description of transconductance in saturation.

The temperature scaling and geometrical scaling of parameters in MM11, Level 1102 is the same as in Level 1101. This implies that Level 1102 includes two types of geometrical scaling rules: physical rules and binning rules. It should be noted that using the source code of the Modelkit on the Philips' website (which can be found at [http://www.semiconductors.philips.com/Philips\\_Models](http://www.semiconductors.philips.com/Philips_Models)).

1. the physical geometry scaling rules can be selected by using Level 11020, while
2. the binning geometry scaling rules can be selected by using Level 11021.

## Structural Elements of MOS Model 11

The structure of MOS Model 11 is the same as the structure of MOS Model 9[5]. The model is separable into a number of relatively independent parts, namely:

- **Model embedding**

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

- **Preprocessing**

The complete set of all the parameters, as they occur in the equations for the various electrical quantities, is denoted as the set of actual parameters, usually called the "miniset". In MM11, Level 1102, the temperature scaling parameters are included in the "miniset". Each of these actual parameters can be determined by purely electrical measurements. Since most of these parameters scale with geometry the process as a whole is characterized by an enlarged set of parameters, which is denoted as the set of scaling parameters, usually called the "maxiset". This set of parameters contains most of the actual parameters for an infinitely long and broad device and a large set of sensitivity coefficients. From this, the actual parameters for an arbitrary transistor are obtained by applying a set of transformation rules. The transformation rules describe the dependencies of the actual parameters on the length, width, and temperature. This procedure is called preprocessing, as it is normally done only once, prior to the actual electrical simulation.

In MM11, Level 1102, parameter binning has been facilitated by adding a second, separate set of geometry scaling rules. Consequently, besides the *physical* geometrical scaling rules

there is also a set of *binning* geometrical scaling rules. The physical geometry scaling rules of Level 1102 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 this 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 Level 1102 are not straightforwardly applicable to binning strategies, since they may result in discontinuities in parameter values at the bin boundaries. Consequently, special geometrical binning scaling relations have been developed, which guarantee continuity in the model parameters at the bin boundaries.

- **Clipping**

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

- **Current equations**

These are all expressions needed to obtain the DC nodal currents as a function of the bias conditions. They are segmentable in equations for the channel current, the gate tunnelling current and the avalanche current.

- **Charge equations**

These are all the equations that are used to calculate both the intrinsic and extrinsic charge quantities, which are assigned to the nodes.

- **Noise equations**

The total noise output of a transistor consists of a thermal- and a flicker noise part. which create fluctuations in the channel current. Owing to the capacitive coupling between gate and channel region, current fluctuations in the gate current are induced as well, which is referred to as induced gate noise.

## 15.2 Physics

### 15.2.1 Comments and Physical Background

In this section some physical background on the current, charge and noise description of MOS Model 11, Level 1102 will be given. For the full details of the physical background of the drain-source channel current equations the reader is referred to [3], [4], [6]-[9]. The gate current, charge and noise equations have been newly developed and their physical background will be discussed in a future report. All equations referred to are to be found in section 15.2.3.

#### Comments on Current Equations

Conventional MOS models such as MOS Model 9 and BSIM4 are threshold-voltage-based models, which make use of approximate expressions of the drain-source channel current  $I_{DS}$  in the weak-inversion region (i.e. subthreshold) and in the strong-inversion region (i.e. well above threshold). These approximate equations are tied together using a mathematical smoothing function, resulting in neither a physical nor an accurate description of  $I_{DS}$  in the moderate inversion region (i.e. around threshold). With the constant downscaling of supply voltage the moderate inversion region becomes more and more important, and an accurate description of this region is thus essential.

A more accurate type of model is the surface-potential-based model, where the channel current  $I_{DS}$  is split up in a drift ( $I_{drift}$ ) and a diffusion ( $I_{diff}$ ) component, which are a function of the gate bias  $V_{GB}$  and the surface potential at the source ( $\psi_{s_0}$ ) and the drain ( $\psi_{s_L}$ ) side. In this way  $I_{DS}$  can be accurately described using one equation for all operating regions (i.e. weak, moderate and strong-inversion). MOS Model 1102 is a surface-potential-based model.

#### Surface Potential

The surface potential  $\psi_s$  is defined as the electrostatic potential at the gate oxide/ substrate interface with respect to the neutral bulk (due to the band bending, see Figure 1a). For an n-MOS transistor with uniform doping concentration it can be calculated from the following implicit relation:

$$\left(\frac{V_{GB} - V_{FB} - \Psi_p - \Psi_s}{k_0}\right)^2 = \Psi_s + \phi_T \cdot \left[\exp\left(-\frac{\Psi_s}{\phi_T}\right) - 1\right] \\ + \phi_T \cdot \exp\left(-\frac{\phi_B + V}{m_{\phi_T}}\right) \cdot \left[\exp\left(\frac{\Psi_s}{m_{\phi_T}}\right) - \frac{\Psi_s}{m_{\phi_T}} - 1\right]$$

where  $V$  is the quasi-Fermi potential, which ranges from  $V_{SB}$  at the source side to  $V_{DB}$  at the drain side. The parameter  $m_0$  has been added to model the non-ideal subthreshold behaviour of short-channel transistors<sup>1</sup>, and  $\Psi_p$  is the potential drop in the polysilicon gate material due to the poly-depletion effect. The latter is given by<sup>2</sup>:

$$\Psi_p = \begin{cases} 0 & \text{for: } V_{GB} \leq V_{FB} \\ \left(\sqrt{V_{GB} - V_{FB} - \Psi_s + \frac{k_p^2}{4} - \frac{k_p}{2}}\right)^2 & \text{for: } V_{GB} > V_{FB} \end{cases}$$

In Figure 1b the surface potential is shown as a function of gate bias for a typical n-type MOS device. The surface potential  $\Psi_s$  is implicitly related to the gate bias  $V_{GB}$  and the quasi-Fermi potential  $V$ , and cannot be calculated analytically. It can only be calculated using an iterative solution, which in general is computation-time consuming. As a consequence, an explicit approximation of the surface potential was used in previous levels of MM11. In order to increase the accuracy of the calculated  $\Psi_s$ , however, in MM11, Level 1102, the surface potential is calculated using a second-order Newton-Raphson iterative procedure. In this way,  $\Psi_s$  is calculated with an accuracy of about  $2.5 \cdot 10^{-12}$  and this accuracy is reached within 3 iterations. Owing to the increased accuracy some of the basic equations used in Level 1101 can be simplified, and as a result Level 1102 is computationally as fast as Level 1101. A more complete overview of the iterative calculation of  $\Psi_s$  can be found in Section 15.5 on the implemented model equations.

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1. Parameter  $m_0 = 0$  for the ideal long-channel case.

2. For  $V_{GB} < V_{FB}$  an accumulation layer is formed in both the substrate silicon and the gate polysilicon, in this case  $\Psi_p$  is slightly negative and weakly dependent on  $V_{GB}$ . This effect has been neglected.

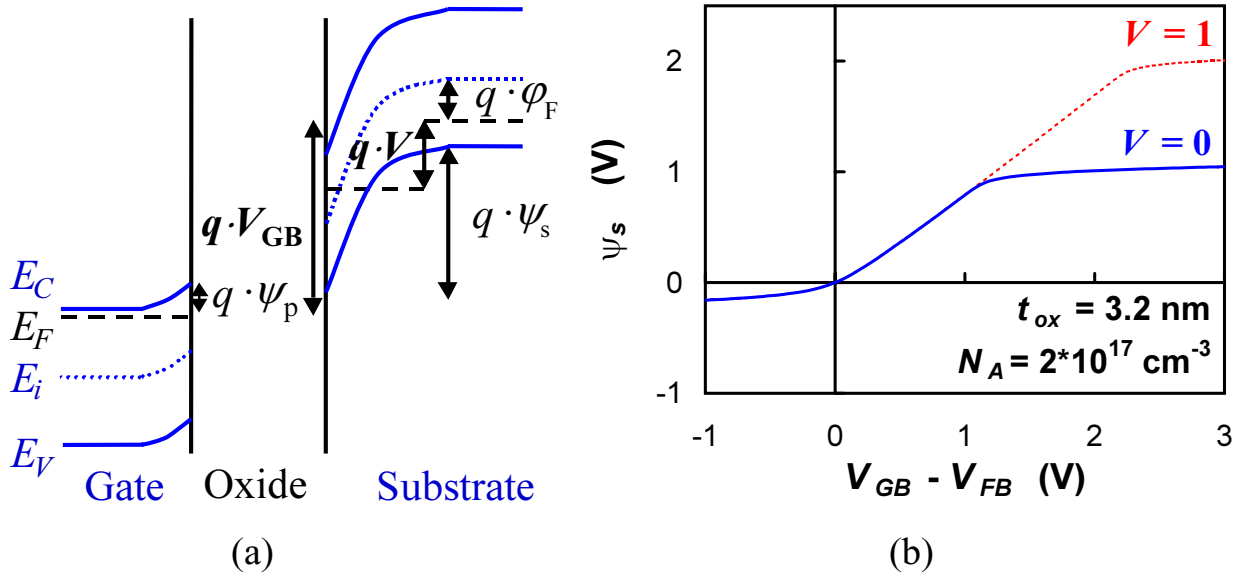


Figure 1: Left figure (a): The energy band diagram of an n-type MOS transistor in inversion ( $V_{GB} > V_{FB}$ ), where  $\psi_s$  is the surface potential,  $\psi_p$  is the potential drop in the gate due to the poly-depletion effect,  $V$  is the quasi-Fermi potential and  $\phi_F$  is the intrinsic Fermi-potential ( $\phi_B = 2 \cdot \phi_F$ ). Right figure (b): The surface potential as a function of gate bias for different values of quasi-Fermi potential  $V$  ( $m_0 = 0$ ).

A surface-potential-based model automatically incorporates the pinch-off condition at the drain side, and as a result it gives a description of both the linear (or ohmic) region and the saturation region for the ideal long-channel case. In this case the saturation voltage  $V_{DSAT}$  (i.e. the drain-source voltage above which saturation occurs) corresponds to Eq. (15.28). For short-channel devices, however, no real pinch-off occurs and the saturation voltage is affected by velocity saturation and series-resistance. In this case the saturation voltage  $V_{DSAT}$  is calculated using eqs. (15.28)-(15.33). The transition from linear to saturation region is no longer automatically described by the surface-potential-based model. This has been solved in the same way as in [11] by introducing an effective drain-source bias  $V_{DS_x}$  which changes smoothly from  $V_{DS}$  in the linear region to  $V_{DSAT}$  in the saturation region, see Eq. (15.34).

A surface-potential-based model makes no use of threshold voltage  $V_T$ . Circuit designers, however, are used to think in terms of threshold voltage, and as a consequence it would be useful to have a description of  $V_T$  in the framework of a surface-potential-model. It has been found that an accurate expression of threshold voltage is simply given by:

$$V_T = V_{FB} + \left(1 + \frac{k_0^2}{k_p^2}\right) \cdot (V_{SB} + \phi_B + 2 \cdot \phi_T) - V_{SB} + k_0 \cdot \sqrt{V_{SB} + \phi_B + 2 \cdot \phi_T}$$

The threshold voltage and other important parameters for circuit design are part of the operating point output as given in Section 15.7.1.

## Channel Current

Neglecting the influence of gate and bulk current, the channel current can be written as:  $I_{DS} = I_{drift} + I_{diff}$  where ideally the drift component  $I_{drift}$  can be approximated by (for  $V_{GB} > V_{FB}$ ):

$$I_{drift} = -\beta \cdot \frac{Q_{inv_0} + Q_{inv_L}}{2 \cdot C_{ox}} \cdot (\psi_{s_L} - \psi_{s_0})$$

and the diffusion component  $I_{diff}$  can be approximated by (for  $V_{GB} > V_{FB}$ ):

$$I_{diff} = \beta \cdot \phi_T \cdot \frac{(Q_{inv_L} - Q_{inv_0})}{C_{ox}}$$

Here,  $C_{ox}$  is given by  $\epsilon_{ox}/t_{ox}$ , and  $Q_{inv_0}$  and  $Q_{inv_L}$  denote the inversion-layer charge density at the source and drain side, respectively, which are given by eqs. (15.42)-(15.44) (where  $Q_{inv} = -\epsilon_{ox}/t_{ox} \cdot V_{inv}$ ).

In the non-ideal case the channel current is affected by several physical effects, such as drain-induced barrier lowering, static feedback, mobility reduction, series-resistance, velocity saturation, channel length modulation and self-heating, which have to be taken into account in the channel current expression:

- In threshold-voltage-based models drain-induced barrier lowering and static feedback are traditionally implemented as a decrease in threshold voltage with drain bias. Here these effects have been implemented as an increase in effective gate bias  $\Delta V_G$  given by eqs. (15.20)-(15.25). An effective drain-source voltage  $V_{DS_{eff}}$  has been used to preserve non-singular behaviour in the higher-order derivatives of  $I_{DS}$  at  $V_{DS} = 0$  V.
- The effects of mobility reduction and series-resistance on channel current have been described in [7], and have consequently been implemented using eqs. (15.53) and (15.57), respectively. For MOS Model 11, level 1102.3 and higher, the effect of the of Coulomb scat-

tering has been included in the mobility of the model. The equations for this have been adopted from the PSP model [8]

- The effect of velocity saturation has been modelled using the following electron velocity saturation expression [9]:

$$v = \frac{\mu \cdot E_{\parallel}}{\sqrt{1 + (\mu/v_{sat} \cdot E_{\parallel})^2}}$$

where  $E_{\parallel}$  is the lateral electric field  $E_{\parallel}$ . Using the expression above in the calculation of channel current  $I_{DS}$  results in the velocity saturation expression (15.56), where  $\theta_{sat}$  is theoretically equal to  $\mu_0/(v_{sat} \cdot L)$ . For holes, the expression is slightly different.

- The effect of channel length modulation and self-heating on channel current have been described in [9], and have consequently been implemented using eqs. (15.54) and (15.58), respectively.

All the above effects can be incorporated into the channel current expression using Eq. (15.59) and Eq. (15.62).

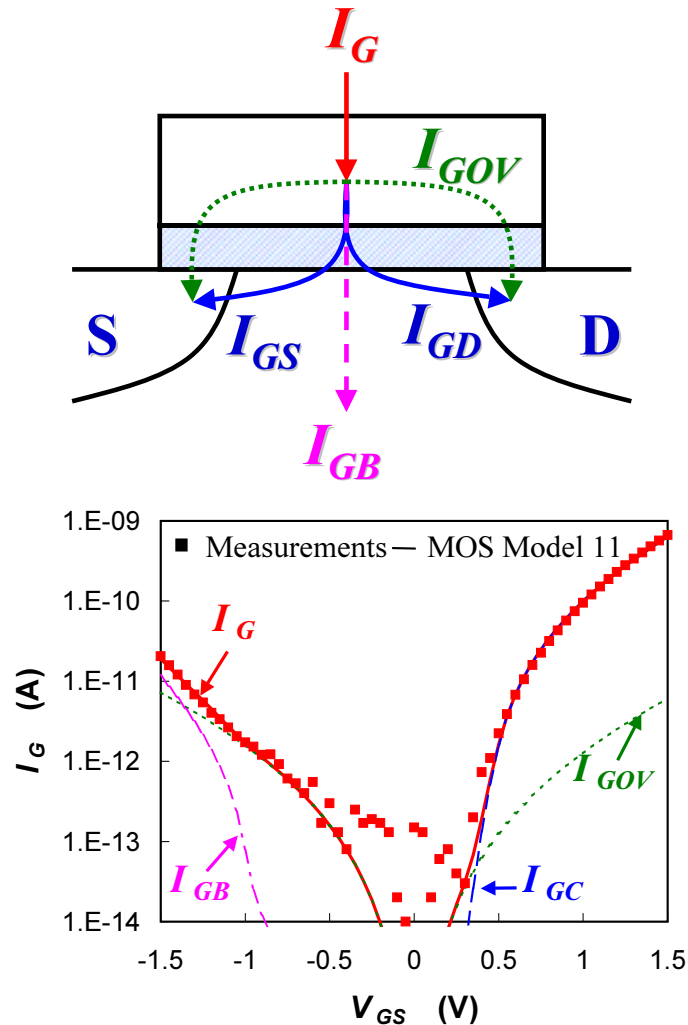


Figure 2: Upper figure (a): The different gate current components in a MOS transistor. One can distinguish the intrinsic components, i.e. the gate-to-channel current  $I_{GC}(= I_{GS}+I_{GD})$  and the gate-to-bulk current  $I_{GB}$ , and the extrinsic, i.e. the gate/source and gate/drain overlap components  $I_{GOV}$ .

Lower figure (b): Measured and modelled gate current as a function of gate bias  $V_{GS}$  at  $V_{DS} = V_{SB} = 0$  V, the different gate current components are also shown. NMOS-transistor,  $W/L = 10/0.6\mu m$  and  $t_{ox} = 2$  nm.

## Weak-Avalanche Current

At high drain bias, owing to the weak-avalanche effect (or impact ionization), a current  $I_{avl}$  will flow between drain and bulk<sup>1</sup>. The description of the weak-avalanche current has been

1. In reality, part of the generated avalanche current will also flow from drain to source [3], this has been neglected.

taken from MOS Model 9 [5], and is given by Eq. (15.63). With the down-scaling of supply voltage for modern CMOS technologies, weak-avalanche becomes less and less important.

### Gate Tunnelling Current

With CMOS technology scaling the gate oxide thickness is reduced and, due to the direct-tunnelling of carriers through the oxide, the gate current is no longer negligible, and has to be taken into account. Several gate current components can be distinguished, three components ( $I_{GS}$ ,  $I_{GD}$  and  $I_{GB}$ ) due to the intrinsic MOS channel, and two components ( $I_{Gov_0}$  and  $I_{Gov_L}$ ) due to gate/source and gate/drain overlap region, see Figure 2(a).

For an n-type MOS transistor operating in inversion, the intrinsic gate current density  $J_G$  consists of electrons tunnelling from the inversion layer to the gate, the so-called conductance band tunnelling, which in general can be written as [12] (for  $V_{GB} > V_{FB}$ ):

$$J_G \propto -V_{ox} \cdot Q_{inv} \cdot P_{tun}\{V_{ox}, \chi_B, B\}$$

where  $V_{ox}$  is the oxide voltage given by  $V_{ox} = V_{GB} - V_{FB} - \psi_p - \psi_s$ . The carrier tunnelling probability  $P_{tun}$  is a function of the oxide voltage  $V_{ox}$ , the oxide energy barrier  $\chi_B$  as observed by the inversion-layer carriers, and a parameter  $B$ . This probability is given by Eq. (15.71), where both direct-tunnelling for  $V_{ox} < \chi_B$  and Fowler-Nordheim tunnelling for  $V_{ox} > \chi_B$  have been taken into account.

Owing to quantum-mechanical energy quantization in the potential well at the SiO<sub>2</sub>-surface, the electrons in the inversion layer are not situated at the bottom of the conduction band, but in the lowest energy subband which lies  $\Delta\chi_B$  above the conduction band. Assuming that only the lowest energy subband is occupied by electrons, the value of  $\Delta\chi_B$  can be given by Eq. (15.78) [13]. As a result the oxide barrier  $\chi_{B,eff}$  has to be lowered by an amount of  $\Delta\chi_B$ , see Eq. (15.79).

In inversion the total intrinsic gate current consists of electrons tunnelling from inversion layer to gate, the so-called gate-to-channel current  $I_{GC}$ . These electrons are supplied by both source ( $I_{GS}$ ) and drain ( $I_{GD}$ ). The gate-to-channel current  $I_{GC}$  can be calculated from:

$$I_{GC} = W \cdot \int_0^L J_G \cdot dx$$

where  $x$  is the coordinate along the channel. Using a first-order perturbation approximation, i.e. assuming the gate current is small enough so that it does not change the distribution of surface potential along the channel,  $I_{GC}$  can be calculated by eqs. (15.78)-(15.87). In the same way the partitioning of  $I_{GC}$  into  $I_{GS}$  and  $I_{GD}$  can be calculated using:

$$I_{GS} = W \cdot \int_0^L \left(1 - \frac{x}{L}\right) \cdot J_G \cdot dx$$

$$I_{GD} = W \cdot \int_0^L \frac{x}{L} \cdot J_G \cdot dx$$

which results in expressions for  $I_{GS}$  and  $I_{GD}$  as given by eqs. (15.88)-(15.90). The gate-to-channel current  $I_{GC}$  can be seen in Figure 2(b) as a function of gate bias for a typical n-MOS transistor at  $V_{DS} = 0$  (i.e.  $I_{GS} = I_{GD} = 1/2 \cdot I_{GC}$ ).

For an n-type MOS transistor operating in accumulation, an accumulation layer of holes is formed in the p-type substrate and an accumulation layer of electrons is formed in the n<sup>+</sup>-type polysilicon gate. Since the oxide energy barrier for electrons  $\chi_{B_N}$  is considerably lower than that for holes  $\chi_{B_p}$ , the gate current will mainly consist of electrons tunnelling from the gate to the bulk silicon, where they are swept to the bulk terminal. In this case the (intrinsic) gate current density  $J_G$  can be written as [12] (for  $V_{GB} < V_{FB}$ ):

$$J_G \propto -V_{ox} \cdot Q_{acc} \cdot P_{tun}\{-V_{ox}, \chi_B, B\}$$

where  $Q_{acc}$  is the accumulation charge density in the gate given by  $\epsilon_{ox}/t_{ox} \cdot V_{ox}$ . In order to limit calculation time the quantum-mechanical oxide barrier lowering in this case is neglected, and the resulting expression for  $I_{GB}$  is given by eqs. (15.76)-(15.77). The gate-to-bulk current  $I_{GB}$  can be seen in Figure 2(b) as a function of gate bias for a typical n-MOS transistor at  $V_{DS} = 0$ .

Apart from the intrinsic components  $I_{GC}$  and  $I_{GB}$ , considerable gate current can be generated in the gate/source- and gate/drain-overlap regions. Concentrating on the gate/source<sup>1</sup>-overlap region, in order to calculate the overlap gate current, the overlap region is treated as an n<sup>+</sup>-gate/oxide/n<sup>+</sup>-bulk MOS capacitance where the source acts as bulk. Although the impurity doping concentration in the n<sup>+</sup>-source extension region is non-uniform in both lat-

1. In the following derivation, the same can be done for the gate/drain-overlap region by replacing the source by the drain.

eral and transversal direction, it is assumed that an effective flat-band voltage  $V_{FBov}$  and body-factor  $k_{ov}$  can be defined for this structure. Furthermore, assuming that only accumulation and depletion occur in the  $n^+$ -source region<sup>1</sup>, a surface potential  $\psi_{s_{ov}}$  can be calculated using:

$$\left( \frac{V_{GS} - V_{FBov} - \psi_{p_{ov}} - \psi_{ov}}{k_{ov}} \right)^2 = -\psi_{ov} + \phi_T \cdot \left[ \exp\left( \frac{\psi_{s_{ov}}}{\phi_T} \right) - 1 \right]$$

where the potential drop in the polysilicon gate material due to the poly-depletion effect  $\psi_{p_{ov}}$  is given by:

$$\psi_{p_{ov}} = \begin{cases} 0 & \text{for: } V_{GS} \leq V_{GBov} \\ \left( \sqrt{V_{GS} - V_{FBov} - \psi_{ov} + \frac{k_p^2}{4} - \frac{k_p}{2}} \right)^2 & \text{for: } V_{GS} > V_{FBov} \end{cases}$$

Again, the surface potential  $\psi_{p_{ov}}$  is calculated a second-order Newton-Raphson iterative procedure, see eqs. (15.64)-(15.70). A more complete overview of the iterative calculation of  $\psi_{p_{ov}}$  can be found in Section 15.5 on the implemented model equations.

For  $V_{GS} > V_{FBov}$  a negatively charged accumulation layer is formed in the overlapped  $n^+$ -source extension and a positively charged depletion layer is formed in the overlapping gate. In this case the overlap gate current will mostly consist of electrons tunnelling from the source accumulation layer to the gate, it is given by:

$$I_{G_{ov}} \propto -V_{ov} \cdot Q_{ov} \cdot P_{tun}\{V_{ov}, \chi_B, B\}$$

where  $V_{ov}$  is the oxide voltage for the gate/source-overlap ( $= V_{GS} - V_{FBov} - \psi_{p_{ov}} - \psi_{s_{ov}}$ ), given by eqs. (15.65)-(15.70), and  $Q_{ov}$  is the total charge density in the  $n^+$ -source region ( $= \epsilon_{ox}/t_{ox} \cdot V_{ov}$ ). For  $V_{GS} < V_{FBov}$  the situation is reversed, a positively charged depletion layer is formed in the overlapped  $n^+$ -source extension and a negatively charged accumulation layer is formed in the overlapping gate. In this case the overlap gate current will mostly consist of electrons tunnelling from the gate accumulation layer to the source, it is given by:

$$I_{G_{ov}} \propto \alpha \cdot V_{ov} \cdot Q_{ov} \cdot P_{tun}\{-V_{ov}, \chi_B, B\}$$

1. Since the source extension has a very high doping concentration, an inversion layer in the gate/source overlap will only be formed at very negative gate-source bias values. This effect has been neglected.

The overlap gate current components can now be given by eqs. (15.72)-(15.75). In Figure 2(b) the gate overlap current  $I_{G_{ov}}$  is shown as a function of gate bias for a typical n-MOS transistor at  $V_{DS} = 0$  (i.e.  $I_{G_{ovL}} = I_{G_{ov0}}$ ). For n-type and p-type MOS transistors the gate current behaviour is different due to the type of carriers that constitute the different gate current components<sup>1</sup>. The difference is summarized in Table 17.

*Table 17:* The type of carriers that contribute to the gate tunnelling current in the various operation regions for the intrinsic MOSFET, the gate/drain- and gate/source-overlap regions. The type of carriers determine the value of oxide energy barrier  $\chi_B$  that has to be used ( $\chi_{B_N}$  for electrons,  $\chi_{B_P}$  for holes). In the last row the direction of gate current is indicated.

| Type | Intrinsic MOSFET |                 | Overlap Regions |
|------|------------------|-----------------|-----------------|
|      | Accumulation     | Inversion       |                 |
| NMOS | electrons        | electrons       | electrons       |
| PMOS | electrons        | holes           | holes           |
|      | $I_{GB}$         | $I_{GS}/I_{GD}$ | $I_{GS}/I_{GD}$ |

### Comments on Charge Equations

In a typical MOS structure we can distinguish intrinsic and extrinsic charges. The latter are due to the gate/source and gate/drain overlap regions. The drain/source junctions also contribute to the capacitance behaviour of a MOSFET, but this is not taken into account in MOS Model 11; it is described by a separate junction diode model.

### Intrinsic Charges

In the intrinsic MOS transistor charges can be attributed to the four terminals. The gate charge  $Q_G$  can be simply calculated from:

1. It is assumed here that the gate current is only determined by conductance band tunnelling. For high values of gate bias (i.e.  $q \cdot V_{ox} > E_g$ ) electrons in the bulk valence band may also tunnel through the oxide to the gate conduction band. This mechanism is referred to as valence band tunnelling, and it has not been taken into account in MOS Model 1101.

$$Q_G = -W \cdot \int_0^L Q_{tot} \cdot dx$$

where  $Q_{tot}$  is the total charge density in the silicon bulk ( $Q_{tot} = -\epsilon_{ox}/t_{ox} \cdot V_{ox}$ ). The total inversion-layer charge  $Q_{inv}$  is split up in a source  $Q_S$  and a drain  $Q_D$  charge, they can be calculated using the Ward-Dutton charge partitioning scheme [14]:

$$Q_S = W \cdot \int_0^L \left(1 - \frac{x}{L}\right) \cdot Q_{inv} \cdot dx$$

$$Q_D = W \cdot \int_0^L \frac{x}{L} \cdot Q_{inv} \cdot dx$$

Since charge neutrality holds for the complete transistor, the gate charge is simply given by:

$$Q_B = -Q_S - Q_D - Q_G$$

These equations have been solved, and the charges are given by eqs. (15.97)-(15.102). In these equations  $C_{ox_{eff}}$  is the effective oxide capacitance, which is smaller than the ideal oxide capacitance  $C_{ox}$  due to quantum-mechanical effects: Quantum-mechanically, the inversion/accumulation charge concentration is not maximum at the Si-SiO<sub>2</sub>-interface (as it would be in the classical case), but reaches a maximum at a distance  $\Delta z$  from the interface [13]. This quantum-mechanical effect can be taken into account by an effective oxide thickness  $t_{ox} + \epsilon_{ox}/\epsilon_{si} \cdot \Delta z$ , where  $\Delta z$  is dependent on the effective electric field  $E_{eff}$  [13], [15] ( $E_{eff} = -\epsilon_{ox}/\epsilon_{si} \cdot V_{eff}/t_{ox}$ ). The effective oxide thickness results in an effective oxide capacitance  $C_{ox_{eff}}$ , see Eq. (15.97).

It should be noted that the above charge model is quasi-static. A phase-shift between drain channel current and gate voltage is not taken into account. This implies that for a few applications at high frequencies approaching the cut-off frequency, errors have to be expected due to non-quasi-static effects. Nevertheless non-quasi-effects can be taken into account using a segmentation model as described in [16].

### Extrinsic Charges

The gate/source- and gate/drain-overlap regions act as bias-dependent capacitances. In order to take this bias-dependence into account the overlap regions are treated as an n<sup>+</sup>-gate/oxide/n<sup>+</sup>-bulk MOS capacitance along the same lines as was done for the overlap gate

current, see the section titled *Comments on Current Equations*. The charge in the overlap regions can simply be given by eqs. (15.95)-(15.96). The quantum-mechanical effect on oxide thickness has been neglected here in order to reduce calculation time.

## Comments on Noise Equations

In a MOS transistor generally three different types of noise can be observed:  $1/f$ -noise, thermal noise and induced gate noise. The gate tunnel current and the bulk avalanche current will also exhibit noisy behaviour (due to shot noise), however this has been neglected in MOS Model 11.

### $1/f$ -Noise

At low frequencies flicker (or  $1/f$ ) noise becomes dominant in MOSFETs. In the past this type of noise has been interpreted either in terms of trapping and detrapping of charge carriers in the gate oxide or in terms of mobility fluctuations. Over the past years, a general model for  $1/f$ -noise which combines both of the above physical origins [20], [21], has found wide acceptance in the field of MOS modelling. The model assumes that the carrier number in the channel fluctuates due to trapping/detrapping in the gate oxide, and that these number fluctuations also affect the carrier mobility resulting in (correlated) mobility fluctuations.

The same model is part of MOS Model 9 [22], and has been used to calculate the  $1/f$ -noise for MOS Model 11. The calculations have been performed in such a way that the resulting expression for spectral density is valid for all operation regions (i.e. both in subthreshold and above threshold), it is given by eqs. (15.118)-(15.122).

### Thermal Noise

Since the MOSFET channel can be considered as a non linear resistor, the channel current is subject to thermal noise. For an ideal MOSFET, where the mobility is position independent, the thermal noise is given by the so-called Klaassen-Prins equation [10]. Let thermal noise current sources be parallel connected to each infinitesimal short element of the channel, it can be shown that the noise spectral density, which is defined by [10]:

$$\langle \Delta i_{th}^2 \rangle = \int_0^\infty s_{th}(f) df$$

is given by a generalized Nyquist relation:

$$S_{th} = \frac{N_T}{L^2} \cdot \int_0^L g(x) dx$$

where  $N_T$  is equal to  $4 \cdot k_B \cdot T$  and  $g(x)$  is the local specific channel conductance:

$$g(x) = -\mu(x) \cdot W \cdot Q_{inv}(x)$$

In reality, however, the mobility  $\mu(x)$  is position dependent mainly due to the effect of velocity saturation. In this case, the conventional Klaassen-Prins approach does not hold, and an improved Klaassen-Prins approach has been derived [10]. This improved approach results in the spectral density given by eqs. (15.104)-(15.112). Again continuity of the noise model is assured along all modes of operation. The above thermal noise model has been found to accurately describe experimental results for various CMOS technologies without having to invoke carrier heating effects [10].

### Induced Gate Noise

Owing to capacitive coupling between gate and channel, the fluctuating channel current induces noise in the gate terminal at high frequencies. Using the previously mentioned improved Klaassen-Prins approach [10], we can derive eqn. (15.113) for the induced gate current noise. In addition, since  $S_{th}$  and  $S_{ig}$  have the same physical origin, both spectral densities are correlated. Using the approach described, this can be expressed by eqn. (15.114):

The induced gate noise  $S_{ig}$  is a so-called non-quasi static (NQS) effect. Since the use of the channel current noise description in an NQS segmentation model [16] would automatically result in a correct description of induced gate noise,  $S_{ig}$  can be made equal to zero by using parameter GATENOISE, see Eq. (15.113).

## 15.2.2 Calculation of Temperature-Dependent Parameters

In this section, the temperature scaling rules for the parameters of the electrical model will be given. In contrast to the geometry scaling rules, as treated in Section 15.4, the temperature scaling is the same for both level 11020 and 11021.

### 3 Note

Note the addition of the voltage  $V_{dT}$  of the thermal node in order to include self-heating, see Section 15.6.

### Calculation of Transistor Temperature

$$T_{KR} = T_0 + T_R \tag{15.1}$$

$$T_{amb} = T_0 + T_A + \Delta T_A \quad (15.2)$$

$$T_{KD} = T_0 + T_A + \Delta T_A + V_{dT} \quad (15.3)$$

### Calculation of Threshold-Voltage Parameters

$$\phi_T = \frac{k_B \cdot T_{KD}}{q} \quad (15.4)$$

$$V_{FB_T} = V_{FB} + (T_{KD} - T_{KR}) \cdot S_{T;V_{FB}} \quad (15.5)$$

$$\phi_{B_T} = \phi_B + (T_{KD} - T_{KR}) \cdot S_{T;\phi_B} \quad (15.6)$$

### Calculation of Mobility/Series-Resistance Parameters

$$\beta_T = \beta \cdot \left( \frac{T_{KR}}{T_{KD}} \right)^{\eta\beta} \quad (15.7)$$

$$\theta_{sr_T} = \theta_{sr} \cdot \left( \frac{T_{KR}}{T_{KD}} \right)^{\eta_{sr}} \quad (15.8)$$

$$\theta_{ph_T} = \theta_{ph} \cdot \left( \frac{T_{KD}}{T_{KR}} \right)^{\eta_{ph}} \quad (15.9)$$

$$\eta_{mob_T} = \eta_{mob} \cdot [1 + (T_{KD} - T_{KR}) \cdot S_{T;\eta_{mob}}] \quad (15.10)$$

$$v_T = 1 + (v - 1) \cdot (T_{KR}/T_{KD})^{v_{exp}} \quad (15.11)$$

$$C_{s_T} = C_s \cdot \left( \frac{T_{KR}}{T_{KD}} \right)^{\eta_{C_s}} \quad (15.12)$$

$$\theta_{R_T} = \theta_R \cdot \left( \frac{T_{KR}}{T_{KD}} \right)^{\eta_R} \quad (15.13)$$

$$\theta_{sat_T} = \theta_{sat} \cdot \left( \frac{T_{KR}}{T_{KD}} \right)^{\eta_{sat}} \quad (15.14)$$

### Calculation of Conductance Parameters

$$\theta_{Th_T} = \theta_{Th} \cdot \left( \frac{T_{KR}}{T_{KD}} \right)^{\eta_{\beta}} \quad (15.15)$$

### Calculation of Weak-Avalanche Parameters

$$a_{1_T} = a_1 \cdot [1 + (T_{KD} - T_{KR}) \cdot S_{T;a_1}] \quad (15.16)$$

### Calculation of Gate-Induced Drain Leakage Parameters

$$B_{GIDL_T} = B_{GIDL} \cdot [1 + (T_{KD} - T_{KR}) \cdot S_{T;B_{GIDL}}] \quad (15.17)$$

### Calculation of Noise Parameters

$$N_{T_T} = \frac{T_{KD}}{T_{KR}} \cdot N_T \quad (15.18)$$

**Calculation of Thermal Resistance**

$$R_{Th_T} = R_{Th} \cdot \left( \frac{T_{amb}}{T_{KR}} \right)^{A_{Th}} \quad (15.19)$$

### 15.2.3 Basic Equations

The equations listed in the following sections, are the basic equations of MOS model 11 without any adaptation necessary for numerical reasons. As such they form the base for parameter extraction. In the following, a function is denoted by  $F\{variable, \dots\}$ , where  $F$  denotes the function name and the function variables are enclosed by braces  $\{\}$ .

#### Internal Parameters

$$\varepsilon_1 = 1 \cdot 10^{-2}$$

$$\varepsilon_2 = 4 \cdot 10^{-2}$$

$$\varepsilon_3 = 1 \cdot 10^{-4}$$

$$\varepsilon_4 = 1 \cdot 10^{-14}$$

$$P_D = 1 + (k_0/k_p)^2$$

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

$$\theta_{R_{eff}} = \frac{1}{2} \cdot \theta_{R_T} \cdot \left( 1 + \frac{\theta_{R1}}{1/2 + \theta_{R2}} \right)$$

$$m_{\phi_T} = (1 + m_0) \cdot \phi_T$$

$$Acc = \left. \frac{\partial \psi_s}{\partial V_{GB}} \right|_{V_{GB} = V_{FB_T}} = \frac{1}{1 + k_0 / \sqrt{2} \cdot \phi_T}$$

$$Acc_{ov} = \left. \frac{\partial \psi_{sov}}{\partial V_{GB}} \right|_{V_{GB} = V_{FBov}} = \frac{1}{1 + k_{ov} / \sqrt{2} \cdot \phi_T}$$

$$QM_{\Psi} = \begin{cases} QM_N \cdot (\epsilon_{ox}/t_{ox})^{2/3} & \text{for NMOS} \\ QM_N \cdot (\epsilon_{ox}/t_{ox})^{2/3} & \text{for PMOS} \end{cases}$$

$$QM_{tox} = \frac{2}{5} \cdot QM_{\Psi}$$

$$\chi_{B_{inv}} = \begin{cases} \chi_{B_N} & \text{for NMOS} \\ \chi_{B_P} & \text{for PMOS} \end{cases}$$

$$\chi_{B_{acc}} = \chi_{B_N}$$

### Basic Current Equations

#### Drain induced barrier lowering and Static Feedback:

$$V_{GB_{eff}} = \begin{cases} 0 & \text{for: } V_{GS} + V_{SB} - V_{FB_T} \leq 0 \\ V_{GS} + V_{SB} - V_{FB} & \text{for: } V_{GS} + V_{SB} - V_{FB_T} > 0 \end{cases} \quad (15.20)$$

$$\Psi_{sat_0} = \left( \frac{\sqrt{P_D \cdot V_{GB_{eff}} + k_0^2/4} - k_0/2}{P_D} \right)^2 \quad (15.21)$$

$$D_{dibl} = \sigma_{dibl} \cdot \sqrt{V_{SB} + \phi_{B_T}} \quad (15.22)$$

$$D_{sf} = \begin{cases} 0 & \text{for: } \Psi_{sat_0} - V_{SB} - \phi_{B_T} \leq 0 \\ \sigma_{sf} \cdot \sqrt{\Psi_{sat_0} - V_{SB} - \phi_{B_T}} & \text{for: } \Psi_{sat_0} - V_{SB} - \phi_{B_T} > 0 \end{cases} \quad (15.23)$$

$$V_{DS_{eff}} = \frac{V_{DS}^4}{(V_{limit}^2 + V_{DS}^2)^{3/2}} \quad (15.24)$$

$$\Delta V_G = \sqrt{D_{dibl}^2 + D_{sf}^2} \cdot V_{DS_{eff}} \quad (15.25)$$

**Effective Gate-Bulk Voltage:**

$$V_{GB}^* = V_{GS} + V_{SB} + \Delta V_G - V_{FB_T} \quad (15.26)$$

**Drain Saturation Voltage:**

$$\Psi_{SAT_1} = \begin{cases} 0 & \text{for: } V_{GB}^* \leq 0 \\ ([\sqrt{P_D \cdot V_{GB}^* + k_0^2/4} - k_0/2]/P_D)^2 & \text{for: } V_{GB}^* > 0 \end{cases} \quad (15.27)$$

$$V_{DSAT_{long}} = \Psi_{sat_1} - V_{SB} - \phi_{B_T} \quad (15.28)$$

$$T_{sat} = \begin{cases} \theta_{sat_T} & \text{for NMOS} \\ \frac{\theta_{sat_T}}{(1 + \theta_{sat_T}^2 \cdot V_{DSAT_{longX}}^2)^{1/4}} & \text{for PMOS} \end{cases} \quad (15.29)$$

$$V_{DSAT_{longX}} = \sqrt{(V_{DSAT_{long}}^2 + \epsilon_1)}, \text{ where } \epsilon_1 = 0.01 \quad (15.30)$$

$$\Delta_{SAT} = \frac{(T_{sat} - \theta_{R_{eff}}) \cdot V_{DSAT_{long}}}{\frac{1}{2} \cdot \left( \sqrt{2} + \sqrt{2 + 2 \cdot T_{sat}^2 \cdot V_{DSAT_{long}}^2} \right) + \theta_{R_{eff}} \cdot V_{DSAT_{long}}} \quad (15.31)$$

$$V_{DSAT_{short}} = V_{DSAT_{long}} \cdot \left[ 1 - \frac{44/45 \cdot \Delta_{SAT}}{1 + \sqrt{1 - \frac{(\sqrt{2} - 1) \cdot T_{sat} - \theta_{R_{eff}} \cdot \Delta_{SAT}}{T_{sat} - \theta_{R_{eff}}} \cdot \Delta_{SAT}^2}} \right] \quad (15.32)$$

$$V_{DSAT} = \begin{cases} V_{limit} & \text{for: } V_{DSAT_{short}} \leq V_{limit} \\ V_{DSAT_{short}} & \text{for: } V_{DSAT_{short}} > V_{limit} \end{cases} \quad (15.33)$$

$$V_{DS_x} = \frac{V_{DS}}{[1 + (V_{DS}/V_{DSAT})^{2 \cdot m}]^{\frac{1}{2 \cdot m}}} \quad (15.34)$$

### Surface Potential:

The surface potential  $\psi_s$  is given by the following implicit relation:

$$F\{\psi_s, \theta\} = -V_{OX}\{\psi_s\}^2 + k_0^2 \cdot d\{\psi_s, \phi\} = 0 \quad (15.35)$$

where  $\phi$  can be either  $V_{SB} + \phi_{B_T}$  or  $V_{DS_x} + V_{SB} + \phi_{B_T}$ , and:

$$V_{OX}\{\Psi_S\} = \begin{cases} V_{GB}^* - \Psi_S & \text{for: } V_{GB}^* - \Psi_S \leq 0 \\ \frac{2 \cdot (V_{GB}^* - \Psi_S)}{1 + \sqrt{1 + 4/k_p^2 \cdot (V_{GB}^* - \Psi_S)}} & \text{for: } V_{GB}^* - \Psi_S > 0 \end{cases} \quad (15.36)$$

$$d\{\Psi_S, \phi\} = \Psi_S + \phi_T \cdot \left[ \exp\left(-\frac{\Psi_S}{\phi_T}\right) - 1 \right] + \phi_T \cdot \exp\left(-\frac{\phi}{m_{\phi T}}\right) \cdot \left[ \exp\left(\frac{\Psi_S}{m_{\phi T}}\right) - \frac{\Psi_S}{m_{\phi T}} - 1 \right] \quad (15.37)$$

The surface potential is iteratively calculated using a second-order Newton Raphson procedure. The surface potential at the source  $\Psi_{S_0}$  and at the drain  $\Psi_{S_L}$  are calculated iteratively using a second-order Newton Raphson procedure from the following implicit relations:

$$F\{\Psi_{S_0}, V_{SB} + \phi_{B_T}\} = 0 \quad (15.38)$$

$$F\{\Psi_{S_L}, V_{DS_X} + V_{SB} + \phi_{B_T}\} = 0 \quad (15.39)$$

#### Auxiliary Variables:

$$\Delta\Psi = \Psi_{S_L} - \Psi_{S_0} \quad (15.40)$$

$$\bar{\Psi} = \frac{\Psi_{S_L} + \Psi_{S_0}}{2} \quad (15.41)$$

Inversion-Layer Charge ( $Q_{inv} = -\epsilon_{ox}/t_{ox} \cdot V_{inv}$ ):

$$V_{inv}\{\psi, \phi\} = \begin{cases} 0 & \text{for: } V_{GB}^* - \psi_s \leq 0 \\ \frac{k_0 \cdot \phi_T \cdot \exp(-\phi/m_{\phi_T}) \cdot [\exp(\psi_s/m_{\phi_T}) - \psi_s/m_{\phi_T} - 1]}{\sqrt{d\{\phi, \psi_s\}} + \sqrt{\psi_s + \phi_T \cdot [\exp(-\psi_s/\phi_T) - 1]}} & \text{for: } V_{GB}^* - \psi_s > 0 \end{cases} \quad (15.42)$$

$$V_{inv_0} = V_{inv}\{\psi_{s_0}, V_{SB} + \phi_{B_T}\} \quad (15.43)$$

$$V_{inv_L} = V_{inv}\{\psi_{s_L}, V_{DS_x} + V_{SB} + \phi_{B_T}\} \quad (15.44)$$

$$\bar{V}_{inv} = \frac{V_{inv_0} + V_{inv_L}}{2} \quad (15.45)$$

$$\bar{V}_{ox} = \frac{V_{ox}\{\psi_{s_0}\} + V_{ox}\{\psi_{s_L}\}}{2} \quad (15.46)$$

$$V_{eff} = \bar{V}_{inv} + \eta_{mob_T} \cdot (\bar{V}_{ox} - \bar{V}_{inv}) \quad (15.47)$$

$$\xi_{ox}\{\psi_s\} = -\phi_T \frac{\dot{V}_{\partial V_{ox}}}{\partial \psi_s} = \begin{cases} \phi_T & \text{for: } V_{GB}^* - \psi_s \leq 0 \\ \frac{\phi_T}{\sqrt{1 + 4/k_p^2 \cdot (V_{GB}^* - \psi_s)}} & \text{for: } V_{GB}^* - \psi_s > 0 \end{cases} \quad (15.48)$$

$$\bar{\xi}_{ox} = \frac{\xi_{ox}\{\psi_{s_0}\} + \xi_{ox}\{\psi_{s_L}\}}{2} \quad (15.49)$$

$$\xi\{\psi_s\} = -\phi_T \frac{\partial V_{inv}}{\partial \psi_s} = \begin{cases} \xi_{ox}\{\psi_s\} + \phi_T \cdot \left[ \frac{1}{Acc} - 1 \right] & \text{for: } V_{GB}^* - \psi_s \leq 0 \\ \xi_{ox}\{\psi_s\} + \phi_T \cdot \frac{k_0 \cdot [1 - \exp(-\psi_s/\phi_T)]}{2 \cdot \sqrt{\psi_s + \phi_T} \cdot [\exp(-\psi_s/\phi_T) - 1]} & \text{for: } V_{GB}^* - \psi_s > 0 \end{cases} \quad (15.50)$$

$$\bar{\xi} = \frac{\xi\{\psi_{s0}\} + \xi\{\psi_{sL}\}}{2} \quad (15.51)$$

$$\bar{V}_{inv}^* = \bar{V}_{inv} + \{1 + m_0\} - \bar{\xi} \quad (15.52)$$

## Second-Order Effects

### Mobility Degradation:

$$G_{mob} = \frac{\mu_0}{\mu} = \begin{cases} 1 + \left[ (\theta_{ph_T} \cdot V_{eff})^{v_T/3} + (\theta_{sr_T} \cdot V_{eff})^{2 \cdot v_T} \right]^{1/v_T} + C_{sr_T} \cdot \left( \frac{\bar{V}_{dep}}{\bar{V}_{dep} + \bar{V}_{inv}} \right)^2 & \text{for NMOS} \\ \left[ 1 + (\theta_{ph_T} \cdot V_{eff})^{v_T/3} + (\theta_{sr_T} \cdot V_{eff})^{v_T} \right]^{1/v_T} + C_{sr_T} \cdot \left( \frac{\bar{V}_{dep}}{\bar{V}_{dep} + \bar{V}_{inv}} \right)^2 & \text{for PMOS} \end{cases} \quad (15.53)$$

### Channel Length Modulation:

$$G_{\Delta L} = 1 - \frac{\Delta L}{L} = 1 - \alpha \cdot \ln \left[ \frac{V_{DS} - V_{DS_x} + \sqrt{(V_{DS} - V_{DS_x})^2 + V_P^2}}{V_P} \right] \quad (15.54)$$

**Velocity Saturation:**

$$x_{sat} = \begin{cases} \frac{\theta_{sat_T} \cdot \Delta\psi}{G_{mob}} & \text{for NMOS} \\ \frac{\theta_{sat_T}}{G_{mob}} \cdot \frac{\Delta\psi}{[1 + (\theta_{sat_T} \cdot \Delta\psi / G_{mob})^2]^{1/4}} & \text{for PMOS} \end{cases} \quad (15.55)$$

$$G_{vsat} = \frac{G_{mob}}{2} \cdot [1 + \sqrt{1 + 2 \cdot x_{sat}^2}] \quad (15.56)$$

**Series Resistance and Self-Heating:**

$$G_R = \theta_{R_T} \cdot \left(1 + \frac{\theta_{R1}}{\theta_{R2} + \bar{V}_{inv}^*}\right) \cdot \bar{V}_{inv}^* \quad (15.57)$$

$$G_{Th} = \theta_{Th_T} \cdot V_{DS} \cdot \Delta\psi \cdot \bar{V}_{inv}^* \quad (15.58)$$

$$G_{tot} = G_{Th} + \frac{G_{vsat} \cdot G_{\Delta L} + G_R}{2} + \sqrt{\frac{(G_{vsat} \cdot G_{\Delta L} + G_R)^2}{4} - \frac{G_R}{G_{mob}} \cdot \frac{x_{sat}^2}{\sqrt{1 + 2 \cdot x_{sat}^2}}} \quad (15.59)$$

**Drain-Source Channel Current**

$$I_{drift} = \beta_T \cdot \bar{V}_{inv} \cdot \Delta\psi \quad (15.60)$$

$$I_{diff} = \beta_T \cdot m_{\phi_T} \cdot (V_{inv_0} - V_{inv_L}) \quad (15.61)$$

$$I_{DS} = \frac{I_{drift} + I_{diff}}{G_{tot}} \quad (15.62)$$

### Weak-Avalanche

$$I_{avl} = \begin{cases} 0 & \text{for: } V_{DS} \leq a_3 \cdot V_{DSAT} \\ a_{1T} \cdot I_{DS} \cdot \exp\left(-\frac{a_2}{V_{DS} - a_3 \cdot V_{DSAT}}\right) & \text{for: } V_{DS} > a_3 \cdot V_{DSAT} \end{cases} \quad (15.63)$$

### Surface Potential in Gate Overlap Regions

The surface potential in the overlap region  $\psi_{ov}$  is given by the following implicit relation:

$$F_{ov}\{V_{GX}, \psi_{ov}\} = -V_{ov}\{V_{GX}, \psi_{ov}\}^2 + k_{ov}^2 \cdot d_{ov}\{\psi_{ov}\} = 0 \quad (15.64)$$

where  $V_{GX}$  can be either  $V_{GS}$  or  $V_{GD}$ , and:

$$V_{ov}\{V_{GX}, \psi_{ov}\} = \begin{cases} V_{GX} - V_{FBov} - \psi_{ov} & \text{for: } V_{GX} - \psi_{ov} \leq V_{FBov} \\ \frac{V_{GX} - V_{FBov} - \psi_{ov}}{1 + \sqrt{1 + 4/k_p^2 \cdot (V_{GX} - V_{FBov} - \psi_{ov})}} & \text{for: } V_{GX} - \psi_{ov} > V_{FBov} \end{cases} \quad (15.65)$$

$$d_{ov}\{\psi_{ov}\} = -\psi_{ov} + \phi_T \cdot \left[ \exp\left(\frac{\psi_{ov}}{\phi_T}\right) - 1 \right] \quad (15.66)$$

The surface potentials in the gate/source overlap  $\psi_{ov_0}$  and in the gate/drain  $\psi_{ov_L}$  are calculated iteratively using a second-order Newton Raphson procedure from the following implicit relations:

$$F_{ov}\{V_{GS}, \psi_{ov_0}\} = 0 \quad (15.67)$$

$$F_{ov}\{V_{GS} - V_{DS}, \Psi_{ov_L}\} = 0 \quad (15.68)$$

The oxide voltages in the gate/source overlap  $V_{ov_0}$  and the gate/drain overlap  $V_{ov_L}$  are given by:

$$V_{ov_0} = V_{ov}\{V_{GS}, \Psi_{ov_0}\} \quad (15.69)$$

$$V_{ov_L} = V_{ov}\{V_{GS} - V_{DS}, \Psi_{ov_L}\} \quad (15.70)$$

### Gate Current Equations

The tunnelling probability is given by:

$$P_{tun}\{V_{ox}, \chi_B, B\} = \begin{cases} \exp\left(-B \cdot \frac{[1 - (1 - V_{ox}/\chi_B)^{3/2}]}{V_{ox}}\right) & \text{for: } V_{ox} < \chi_B \\ \exp(-B/V_{ox}) & \text{for: } V_{ox} \geq \chi_B \end{cases} \quad (15.71)$$

### Source/Drain Gate Overlap Current:

The gate tunnelling currents in both gate/source and gate/drain overlap are given by:

$$P_{ov}\{V_{ov}\} = P_{tun}\{V_{ov}, \chi_{B_{inv}}, B_{inv}\} \quad (15.72)$$

$$I_{Gov}\{V_{GX}, V_{ov}\} = I_{GOV} \cdot V_{GX} \cdot V_{ov} \cdot [P_{ov}\{V_{ov}\} - P_{ov}\{-V_{ov}\}] \quad (15.73)$$

$$I_{Gov_0} = I_{Gov}\{V_{GS}, V_{ov_0}\} \quad (15.74)$$

$$I_{Gov_L} = I_{Gov}\{V_{GS} - V_{DS}, V_{ov_L}\} \quad (15.75)$$

### Intrinsic Gate Current

The gate tunnelling current in accumulation:

$$P_{acc} = P_{tun}\{-\bar{V}_{ov}, \chi_{B_{acc}}, B_{acc}\} \quad (15.76)$$

$$I_{GB} = \begin{cases} -I_{GACC} \cdot (V_{GS} + V_{SB}) \cdot \bar{V}_{ox} \cdot P_{acc} & \text{for: } \bar{V}_{ox} \leq 0 \\ 0 & \text{for: } \bar{V}_{ox} > 0 \end{cases} \quad (15.77)$$

The tunnelling current in inversion (i.e.,  $V_{GB}^* > 0$ ), including quantum-mechanical barrier lowering  $\Delta\chi_B$ :

$$\Delta\chi_B = QM_{\psi} \cdot (\bar{V}_{inv}/3 + \bar{V}_{ox} - \bar{V}_{inv})^{2/3} \quad (15.78)$$

$$\chi_{B_{eff}} = \chi_{B_{inv}} - \Delta\chi_B \quad (15.79)$$

$$B_{eff} = B_{inv} \cdot (\chi_{B_{eff}}/\chi_{B_{inv}})^{3/2} \quad (15.80)$$

$$P_{inv} = P_{tun}\{\bar{V}_{ox}, \chi_{B_{eff}}, B_{eff}\} \quad (15.81)$$

$$r_B = \frac{3}{8} \cdot \frac{B_{eff}}{\chi_{B_{eff}}^2} \cdot \frac{\bar{\xi}_{ox}}{\Phi_T} \quad (15.82)$$

$$r^* = \frac{\bar{\xi}}{\phi_T \cdot \bar{V}_{inv}^*} \quad (15.83)$$

$$r_{ox} = \frac{\bar{\xi}_{ox}}{\phi_T \cdot \bar{V}_{ox}} \quad (15.84)$$

$$P_{GC} = 1 + \frac{r_B^2 + 4 \cdot r_B \cdot r^* + 2 \cdot r_B \cdot r_{ox} + 2 \cdot r^{*2} + 4 \cdot r_{ox} \cdot r^*}{24} \cdot \Delta\psi^2 \quad (15.85)$$

$$\bar{I}_{GC} = I_{GINV} \cdot G_{\Delta L} \cdot \left( V_{GS} - \frac{1}{2} V_{DS_x} \right) \cdot P_{inv} \quad (15.86)$$

The total intrinsic gate current  $I_{GC}$  :

$$I_{GC} = \bar{I}_{GC} \cdot \bar{V}_{inv} \cdot P_{GC} \quad (15.87)$$

$$P_{GS} = [r_B + r_{ox}] \cdot \frac{\Delta\psi}{12} \quad (15.88)$$

$$I_{GS} = \frac{1}{2} \cdot I_{GC} + \left( P_{GS} \cdot \bar{V}_{inv} + \frac{V_{inv_0} - V_{inv_L}}{12} \right) \cdot \bar{I}_{GC} + I_{Gov_0} \quad (15.89)$$

$$I_{GD} = I_{GC} - I_{GS} + I_{Gov_0} + I_{Gov_L} \quad (15.90)$$

**Gate-Induced Drain/Source Leakage Current:**

$$V_{tov}\{V_{ov}, V\} = \sqrt{V_{ov}^2 + C_{GIDL}^2 \cdot V^2} \quad (15.91)$$

$$I_{gixl}\{V_{ov}, V\} = A_{GIDL} \cdot V \cdot V_{tov}\{V_{ov}, V\}^2 \cdot \exp\left(-\frac{B_{GIDL_T}}{V_{tov}\{V_{ov}, V\}}\right) \quad (15.92)$$

$$I_{gisl} = I_{gixl}\{V_{ov_0}, V_{SB}\} \quad (15.93)$$

$$I_{gidl} = I_{gixl}\{V_{ov_L}, V_{DS} + V_{SB}\} \quad (15.94)$$

### Basic Charge Equations

#### Bias-Dependent Overlap Capacitance:

$$Q_{ov_0} = C_{GSO} \cdot V_{ov_0} \quad (15.95)$$

$$Q_{ov_L} = C_{GDO} \cdot V_{ov_L} \quad (15.96)$$

#### Intrinsic Charges:

$$C_{OX_{eff}} = \frac{C_{OX} \cdot G_{\Delta L}}{1 + QM_{tox} \cdot \left[\frac{V_{eff}}{\eta_{mob_T}}\right]^{-1/3}} \quad (15.97)$$

$$\Delta V_{inv} = (V_{inv_0} - V_{inv_L}) \cdot \left(1 - \frac{G_R}{G_{tot}}\right) \quad (15.98)$$

$$F_j = \frac{1}{2} \cdot \frac{\Delta V_{inv}}{\bar{V}_{inv}^*} \quad (15.99)$$

$$Q_S = -\frac{C_{OX_{eff}}}{2} \cdot \left[ \bar{V}_{inv} + \frac{\Delta V_{inv}}{6} \cdot \left( F_j - \frac{F_j^2}{5} + 1 \right) \right] \quad (15.100)$$

$$Q_D = -\frac{C_{OX_{eff}}}{2} \cdot \left[ \bar{V}_{inv} + \frac{\Delta V_{inv}}{6} \cdot \left( F_j + \frac{F_j^2}{5} - 1 \right) \right] \quad (15.101)$$

$$Q_G = C_{OX_{eff}} \cdot \left[ \bar{V}_{ox} + \frac{\Delta V_{inv}}{6} \cdot F_j \cdot \frac{\bar{\xi}_{ox}}{\bar{\xi}} \right] \quad (15.102)$$

$$Q_B = -[Q_S + Q_D + Q_G] \quad (15.103)$$

### Noise Equations

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

$$G_{eff} = 1 - \frac{G_R}{G_{tot}} \quad (15.104)$$

$$x_{sat}^2 = \begin{cases} \theta_{sat_T}^2 \cdot \Delta \psi^2 \cdot G_{eff}^2 & \text{for NMOS} \\ \frac{\theta_{sat_T}^2 \cdot \Delta \psi^2 \cdot G_{eff}^2}{\sqrt{1 + \theta_{sat_T}^2 \cdot \Delta \psi^2 \cdot G_{eff}^2}} & \text{for PMOS} \end{cases} \quad (15.105)$$

$$G_{vsat_R} = \frac{G_{mob} + \sqrt{G_{mob}^2 + 2 \cdot x_{sat}^2}}{2} \quad (15.106)$$

$$t_1 = \frac{\bar{V}_{inv}}{\bar{V}_{inv}^*} \quad (15.107)$$

$$t_2 = \frac{F_j^2}{36} \quad (15.108)$$

$$t_{sat} = \frac{x_{sat}^2}{G_{vsat_R}^2} \quad (15.109)$$

$$g_{ideal} = \frac{\beta_T \cdot \bar{V}_{inv}^*}{G_{vsat_R} \cdot G_{\Delta L}} \quad (15.110)$$

$$S_{th} = N_{T_T} \cdot G_{eff}^2 \cdot g_{ideal} \cdot \max\{t_1 + 12 \cdot t_2 \cdot (1 - 2 \cdot t_{sat} - 2 \cdot t_{sat}^2), 0\} \quad (15.111)$$

$$C_{G_{eff}} = C_{OX_{eff}} \cdot \frac{\bar{\xi}_{ox}}{\phi_T} \cdot \frac{G_{vsat_R} \cdot G_{\Delta L}}{G_{mob}} \quad (15.112)$$

$$m_{ig} = \frac{1}{g_{ideal}} \cdot \left[ \frac{t_1}{12} - t_1 \cdot t_2 - \frac{t_2}{5} + 12 \cdot t_2^2 \right. \\ \left. + t_{sat} \cdot \left( \frac{t_1}{12} + 3 \cdot t_1 \cdot t_2 - \frac{9 \cdot t_2}{5} - 36 \cdot t_2^2 \right) \right. \\ \left. + t_{sat}^2 \cdot \left( \frac{t_1}{12} + 4 \cdot t_1 \cdot t_2 - \frac{17 \cdot t_2}{5} - 24 \cdot t_2^2 \right) \right] \quad (15.113)$$

$$m_{igh} = G_{eff} \cdot \sqrt{t_2} \cdot \left[ 1 - 12 \cdot t_2 + t_{sat} \cdot \left( \frac{1}{2} - t_1 + 30 \cdot t_2 \right) + t_{sat}^2 \cdot \left( \frac{3}{8} - \frac{3 \cdot t_1}{2} + \frac{51 \cdot t_2}{2} \right) \right] \quad (15.114)$$

$$S_{ig} = N_{T_T} \cdot (2 \cdot \pi \cdot f \cdot C_{G_{eff}})^2 \cdot m_{ig} \quad (15.115)$$

$$S_{igth} = j \cdot N_{T_T} \cdot 2 \cdot \pi \cdot f \cdot C_{G_{eff}} \cdot m_{igth} \quad (15.116)$$

$$\text{for GATENOISE}=1: \begin{cases} g_{ideal} = \frac{\beta_T \cdot \bar{V}_{inv}}{G_{mob} \cdot G_{\Delta L}} \\ S_{th} = N_{T_T} \cdot G_{eff}^2 \cdot g_{ideal} / \sqrt{1 + t_{sat} + t_{sat}^2} \\ S_{ig} = 0 \\ S_{igth} = 0 \end{cases} \quad (15.117)$$

$$N_0 = \frac{\epsilon_{ox}}{q \cdot t_{ox}} \cdot \left( \bar{V}_{inv} + \frac{\Delta V_{inv}}{2} \right) \quad (15.118)$$

$$N_L = \frac{\epsilon_{ox}}{q \cdot t_{ox}} \cdot \left( \bar{V}_{inv} + \frac{\Delta V_{inv}}{2} \right) \quad (15.119)$$

$$N^* = \frac{\epsilon_{ox}}{q \cdot t_{ox}} \cdot \bar{\xi} \quad (15.120)$$

$$\begin{aligned}
S_{fl} = & \frac{q \cdot \phi_T^2 \cdot t_{ox} \cdot \beta_T \cdot I_{DS}}{f \cdot \epsilon_{ox} \cdot G_{vsat} \cdot N^*} \cdot [(N_{FA} - N^* \cdot N_{FB} + N^{*2} \cdot N_{FC}) \cdot \ln\left(\frac{N_0 + N^*}{N_L + N^*}\right) \\
& + (N_{FB} - N^* \cdot N_{FC}) \cdot (N_0 - N_L) + \frac{N_{FC}}{2} \cdot (N_0^2 - N_L^2)] \\
& + \frac{\phi_T \cdot I_{DS}^2}{f} \cdot (1 - G_{\Delta L}) \cdot \left[ \frac{N_{FA} + N_{FB} \cdot N_L + N_{FC} \cdot N_L^2}{(N_L + N^{*2})} \right]
\end{aligned}$$

## 15.3 Symbols, parameters and constants

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

### 15.3.1 Glossary of used symbols

All parameters which refer to the reference transistor and/or the reference temperature have a symbol with the subscript R and a programming name ending with R. All characters 0 (zero) in subscripts of parameters are represented by the capital letter O in the programming name, because they are often distinguishable with great difficulty! Scaling parameters are indicated by  $S$  with a subscript where the variables on which the parameter depends, precede a semicolon whereas the parameter succeeds it, e.g.  $S_{T;\theta_{sr}}$

Note that since the list of parameters for an individual transistor (i.e. the so-called miniset parameters) and the list of physical constants can be found in sections titled *Parameters of the electrical model on page 97* and *Model constants on page 108*, respectively, they will not be repeated here.

#### List of numerical constants

| Constant | Prog. Name   | Value |
|----------|--------------|-------|
| $A$      | LN_MINDOUBLE | -800  |

#### List of circuit simulator variables

| Symbol | Prog. Name | Units           | Description  |
|--------|------------|-----------------|--|
| $L$    | L          | m               | Drawn channel length in the lay-out of the actual transistor |
| $W$    | W          | m               | Drawn channel width in the lay-out of the actual transistor  |
| $T_A$  | TA         | °C              | Ambient circuit temperature                                  |
| $f$    | F          | s <sup>-1</sup> | Operation frequency  |

## External Electrical Variables

The definitions of the external electrical variables are illustrated in Figure 69.

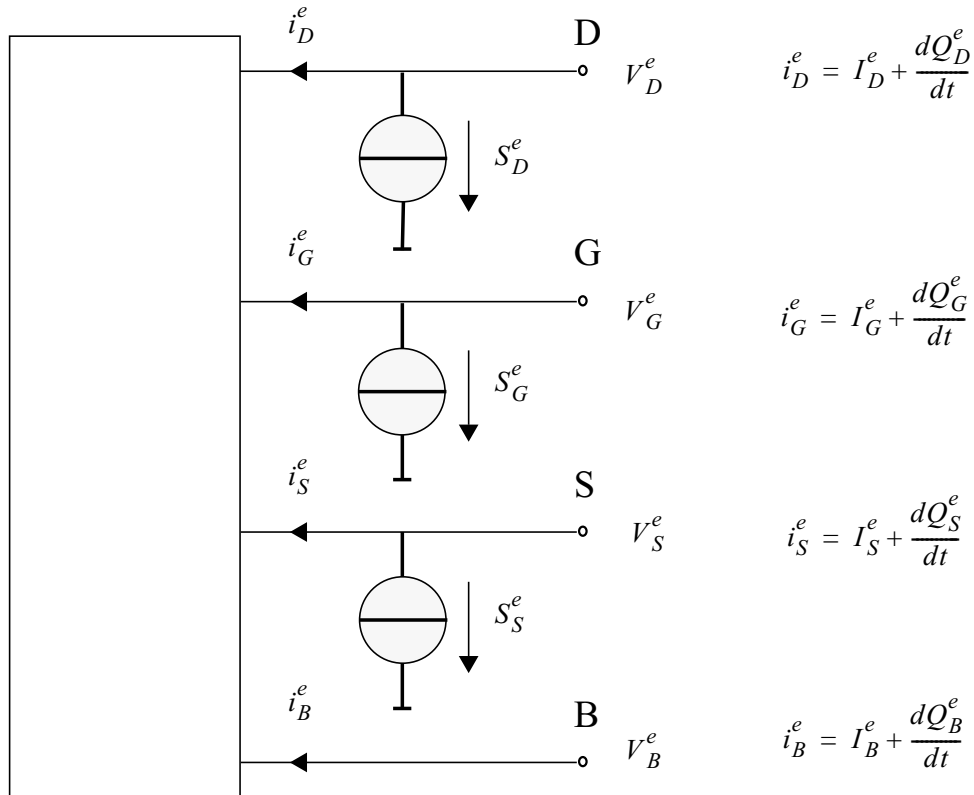


Figure 69: Definition of the external electrical quantities and variables.

| Variable | Prog. Name | Units | Description                          |
|----------|------------|-------|--------------------------------------|
| $V_D^e$  | VDE        | V     | Potential applied to the drain node  |
| $V_G^e$  | VGE        | V     | Potential applied to the gate node   |
| $V_S^e$  | VSE        | V     | Potential applied to the source node |
| $V_B^e$  | VBE        | V     | Potential applied to the bulk node   |

| Variable   | Prog. Name | Units            | Description  |
|------------|------------|------------------|--|
| $I_D^e$    | IDE        | A                | DC current into the drain  |
| $I_G^e$    | IGE        | A                | DC current into the gate   |
| $I_S^e$    | ISE        | A                | DC current into the source   |
| $I_B^e$    | IBE        | A                | DC current into the bulk   |
| $Q_D^e$    | QDE        | C                | Charge in the device attributed to the drain node                      |
| $Q_G^e$    | QGE        | C                | Charge in the device attributed to the gate node                       |
| $Q_S^e$    | QSE        | C                | Charge in the device attributed to the source node                     |
| $Q_B^e$    | QBE        | C                | Charge in the device attributed to the bulk node                       |
| $S_D^e$    | SDE        | A <sup>2</sup> s | Spectral density of the noise current into the drain                   |
| $S_G^e$    | SGE        | A <sup>2</sup> s | Spectral density of the noise current into the gate                    |
| $S_S^e$    | SSE        | A <sup>2</sup> s | Spectral density of the noise current into the source                  |
| $S_{DG}^e$ | SDGE       | A <sup>2</sup> s | Cross spectral density between the drain and the gate noise currents   |
| $S_{GS}^e$ | SGSE       | A <sup>2</sup> s | Cross spectral density between the gate and the source noise currents  |
| $S_{SD}^e$ | SSDE       | A <sup>2</sup> s | Cross spectral density between the source and the drain noise currents |

**Internal Electrical Variables**

| <b>Variable</b> | <b>Progr. Name</b> | <b>Units</b> | <b>Description</b>   |
|-----------------|--------------------|--------------|--|
| $V_{DS}$        | VDS                | V            | Drain-to-source voltage applied to the equivalent n-MOST                             |
| $V_{GS}$        | VGS                | V            | Gate-to-source voltage applied to the equivalent n-MOST                              |
| $V_{SB}$        | VSB                | V            | Source-to-bulk voltage applied to the equivalent n-MOST                              |
| $I_{DS}$        | IDS                | A            | DC current through the channel flowing from drain to source                          |
| $I_{AVL}$       | IAVL               | A            | DC current flowing from drain to bulk due to the weak-avalanche effect               |
| $I_{GS}$        | IGS                | A            | DC current flowing from gate to source due to the direct tunnelling effect           |
| $I_{GD}$        | IGD                | A            | DC current flowing from gate to drain due to the direct tunnelling effect            |
| $I_{GB}$        | IGB                | A            | DC current flowing from gate to bulk due to the direct tunnelling effect             |
| $I_{GISL}$      | IGISL              | A            | DC current flowing from source to bulk due to the gate-induced source leakage effect |
| $I_{GIDL}$      | IGIDL              | A            | DC current flowing from drain to bulk due to the gate-induced source leakage effect  |
| $Q_D$           | QD                 | C            | Charge in the equivalent n-MOST attributed to the drain node                         |
| $Q_G$           | QG                 | C            | Charge in the equivalent n-MOST attributed to the gate node                          |
| $Q_S$           | QS                 | C            | Charge in the equivalent n-MOST attributed to the source node                        |
| $Q_B$           | QB                 | C            | Charge in the equivalent n-MOST attributed to the bulk node                          |
| $Q_{ov0}$       | QOVO               | C            | Extrinsic charge in the equivalent n-MOST attributed to the gate-source overlap      |

---

|            |       |         |  |
|------------|-------|---------|--|
| $Q_{ovL}$  | QOVL  | C       | Extrinsic charge in the equivalent n-MOST attributed to the gate-drain overlap                               |
| $S_{th}$   | STH   | $A^2_s$ | Spectral density of the thermal-noise current of the channel   |
| $S_{fl}$   | SFL   | $A^2_s$ | Spectral density of the flicker-noise current of the channel   |
| $S_{ig}$   | SIG   | $A^2_s$ | Spectral density of the noise current induced in the gate  |
| $S_{igth}$ | SIGTH | $A^2_s$ | Cross spectral density of the noise current induced in the gate and the thermal-noise current of the channel |

### 15.3.2 Parameters

In MOS Model 11, level 1102, parameter binning has been facilitated by adding a second, separate set of geometry scaling rules. Consequently, besides the physical geometrical scaling rules there is also a set of binning geometrical scaling rules. The physical geometry scaling rules of Level 1102 (see the sections titled *Parameters for physical geometry scaling on page 43* and *Calculation of Geometry-Dependent Parameters using the Physical Scaling Rules on page 113*), 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 this 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 Level 1102 are not straightforwardly applicable to binning strategies, since they may result in discontinuities in parameter values at the bin boundaries. Consequently, special binning geometrical scaling relations have been developed (see the sections titled *Parameters for Binning Geometrical Scaling on page 62* and *Calculation of Geometry-Dependent Parameters using the Binning Scaling Rules on page 118*), which guarantee continuity in the model parameters at the bin boundaries. It should be noted that using the source code of the Modelkit on the Philips' website (which can be found at [http://www.semiconductors.philips.com/Philips\\_Models](http://www.semiconductors.philips.com/Philips_Models))

1. the physical geometry scaling rules can be selected by using Level 11020, while
2. the binning geometry scaling rules can be selected by using Level 11021.

#### Parameters for physical geometry scaling

- These parameters correspond to the geometrical model (MN, MP, MOS 11020).

| Symbol                      | Progr. Name | Units | Description  |
|-----------------------------|-------------|-------|--|
| -                           | LEVEL       | -     | Must be 11020  |
| -                           | PARAMCHK    | -     | Level of clip warning info *)  |
| $\Delta L_{PS}$             | LVAR        | m     | Difference between the actual and the programmed poly-silicon gate length                                |
| $\Delta L_{\text{overlap}}$ | LAP         | m     | Effective channel length reduction per side due to the lateral diffusion of the source/drain dopant ions |
| $\Delta W_{OD}$             | WVAR        | m     | Difference between the actual and the programmed field-oxide opening                                     |

| Symbol                     | Progr. Name | Units             | Description  |
|----------------------------|-------------|-------------------|--|
| $\Delta W_{\text{narrow}}$ | WOT         | m                 | Effective reduction of the channel width per side due to the lateral diffusion of the channel-stop dopant ions |
| $T_R$                      | TR          | °C                | Reference temperature  |
| $V_{FB}$                   | VFB         | V                 | Flat-band voltage at the reference temperature   |
| $S_{T;V_{FB}}$             | STVFB       | $\text{VK}^{-1}$  | Coefficient of the temperature dependence of $V_{FB}$  |
| $k_{0R}$                   | KOR         | $\text{V}^{1/2}$  | Body-effect factor for an infinite square transistor   |
| $S_{L;k_0}$                | SLKO        | -                 | Coefficient of the length dependence of $k_0$  |
| $S_{L2;k_0}$               | SL2KO       | -                 | Second coefficient of the length dependence of $k_0$   |
| $S_{L3;k_0}$               | SL3KO       | -                 | Third coefficient of the length dependence of $k_0$  |
| -                          | SL3KOEXP    | -                 | Exponent belonging to the third coefficient of the length dependence of $k_0$                                  |
| $S_{W;k_0}$                | SWKO        | -                 | Coefficient of the width dependence of $k_0$   |
| $1/k_p$                    | KPINV       | $\text{V}^{-1/2}$ | Inverse of body-effect factor of the polysilicon gate  |
| $\phi_{BR}$                | PHIBR       | V                 | Surface potential at the onset of strong inversion at the reference temperature                                |
| $S_{T;\phi_B}$             | STPHIB      | $\text{VK}^{-1}$  | Coefficient of the temperature dependence of $\phi_B$  |
| $S_{L;\phi_B}$             | SLPHIB      | -                 | Coefficient of the length dependence of $\phi_B$   |
| $S_{L2;\phi_B}$            | SL2PHIB     | -                 | Second coefficient of the length dependence of $\phi_B$  |
| $S_{W;\phi_B}$             | SWPHIB      | -                 | Coefficient of the width dependence of $\phi_B$  |
| $\beta_{\text{sq}}$        | BETSQ       | $\text{AV}^{-2}$  | Gain factor for an infinite square transistor at the reference temperature                                     |

| Symbol               | Progr. Name | Units           | Description  |
|----------------------|-------------|-----------------|--|
| $\eta_{\beta R}$     | ETABETR     | -               | Exponent of the temperature dependence of the gain factor of an infinite square transistor   |
| $S_{L;\eta_{\beta}}$ | SLETABET    | -               | Coefficient of the length dependence of $\eta_{\beta R}$   |
| $f_{\beta,1}$        | FBET1       | -               | Relative mobility decrease due to first lateral profile  |
| $L_{P,1}$            | LP1         | m               | Characteristic length of first lateral profile   |
| $f_{\beta,2}$        | FBET2       | -               | Relative mobility decrease due to second lateral profile   |
| $L_{P,2}$            | LP2         | m               | Characteristic length of second lateral profile  |
| $\theta_{srR}$       | THESRR      | V <sup>-1</sup> | Coefficient of the mobility reduction due to surface roughness scattering for an infinite square transistor at the reference temperature |
| $\eta_{sr}$          | ETASR       | -               | Exponent of the temperature dependence of $\theta_{sr}$  |
| $S_{W;\theta_{sr}}$  | SWTHESR     | -               | Coefficient of the width dependence of $\theta_{sr}$   |
| $\theta_{phR}$       | THEPHR      | V <sup>-1</sup> | Coefficient of the mobility reduction due to phonon scattering for an infinite square transistor at the reference temperature            |
| $\eta_{ph}$          | ETAPH       | -               | Exponent of the temperature dependence of $\theta_{ph}$ for the reference transistor   |
| $S_{W;\theta_{ph}}$  | SWTHEPH     | -               | Coefficient of the width dependence of $\theta_{ph}$   |
| $\eta_{mobR}$        | ETAMOB      | -               | Effective field parameter for dependence on depletion/ inversion charge for an infinite square transistor                                |
| $S_{T;\eta_{mob}}$   | STETAMOB    | K <sup>-1</sup> | Coefficient of the temperature dependence of $\eta_{mob}$  |

| Symbol             | Progr. Name | Units    | Description  |
|--------------------|-------------|----------|--|
| $S_{W;\eta_{mob}}$ | SWETAMOB    | -        | Coefficient of the width dependence of $\eta_{mob}$  |
| $\nu$              | NU          | -        | Exponent of the field dependence of the mobility model at the reference temperature  |
| $\nu_{EXP}$        | NUEXP       | -        | Exponent of the temperature dependence of parameter $\nu$  |
| $C_S$              | CS          | -        | Coefficient of Coulomb scattering  |
| $C_{sR}$           | CSR         | -        | Prefactor of scaling rule for $C_S$  |
| $S_{L;C_s}$        | SLCS        | -        | Coefficient of the length dependence of $C_S$  |
| $C_{sEXP}$         | CSEXP       | -        | Exponent of the length dependence of $C_S$   |
| $S_{W;C_s}$        | SWCS        | -        | Coefficient of the width dependence of $C_S$   |
| $\eta_{C_s}$       | ETACS       | -        | Exponent of the temperature dependence of $C_S$  |
| $\theta_{RR}$      | THERR       | $V^{-1}$ | Coefficient of the series resistance per unit length for an infinitely wide transistor   |
| $\eta_R$           | ETAR        | -        | Exponent of the temperature dependence of $\theta_R$   |
| $S_{W;\theta_R}$   | SWTHER      | -        | Coefficient of the width dependence of $\theta_R$  |
| $\theta_{R1}$      | THER1       | V        | Numerator of the gate voltage dependent part of series resistance  |
| $\theta_{R2}$      | THER2       | V        | Denominator of the gate voltage dependent part of series resistance  |
| $\theta_{satR}$    | THESATR     | $V^{-1}$ | Velocity saturation parameter due to optical/acoustic phonon scattering for an infinite square transistor at the reference temperature |
| $\eta_{sat}$       | ETASAT      | -        | Exponent of the temperature dependence of $\theta_{sat}$   |

| Symbol               | Progr. Name | Units             | Description  |
|----------------------|-------------|-------------------|--|
| $S_{L;\theta_{sat}}$ | SLTHESAT    | -                 | Coefficient of the length dependence of $\theta_{sat}$   |
| $\theta_{satEXP}$    | THESATEXP   | -                 | Exponent of the length dependence of $\theta_{sat}$  |
| $S_{W;\theta_{sat}}$ | SWTHESAT    | -                 | Coefficient of the width dependence of $\theta_{sat}$  |
| $\theta_{ThR}$       | THETHR      | V <sup>-3</sup>   | Coefficient of self-heating per unit length for an infinitely wide transistor at the reference temperature |
| $\theta_{ThEXP}$     | THETHEXP    | -                 | Exponent of the length dependence of $\theta_{Th}$   |
| $S_{W;\theta_{Th}}$  | SWTHETH     | -                 | Coefficient of the width dependence of $\theta_{Th}$   |
| $\sigma_{dibl0}$     | SDIBLO      | V <sup>-1/2</sup> | Drain-induced barrier-lowering parameter per unit length   |
| $\sigma_{diblEXP}$   | SDIBLEXP    | -                 | Exponent of the length dependence of $\sigma_{dibl}$   |
| $m_{00}$             | MOO         | -                 | Parameter for short-channel subthreshold slope   |
| $m_{0R}$             | MOR         | -                 | Parameter for short-channel subthreshold slope per unit length   |
| $m_{0EXP}$           | MOEXP       | -                 | Exponent of the length dependence of $m_0$   |
| $\sigma_{sfR}$       | SSFR        | V <sup>-1/2</sup> | Static feedback parameter for an infinite square transistor  |
| $S_{L;\sigma_{sf}}$  | SLSSF       | -                 | Coefficient of the length dependence of $\sigma_{sf}$  |
| $S_{W;\sigma_{sf}}$  | SWSSF       | -                 | Coefficient of the width dependence of $\sigma_{sf}$   |
| $\alpha_R$           | ALPR        | -                 | Factor of the channel length modulation for an infinite square transistor                                  |
| $S_{L;\alpha}$       | SLALP       | -                 | Coefficient of the length dependence of $\alpha$   |
| $\alpha_{EXP}$       | ALPEXP      | -                 | Exponent of the length dependence of $\alpha$  |
| $S_{W;\alpha}$       | SWALP       | -                 | Coefficient of the width dependence of $\alpha$  |
| $V_P$                | VP          | V                 | Characteristic voltage of the channel length modulation  |

| Symbol      | Progr. Name | Units            | Description   |
|-------------|-------------|------------------|---|
| $L_{min}$   | LMIN        | m                | Minimum effective channel length in technology, used for calculation of smoothing factor $m$            |
| $a_{1R}$    | A1R         | -                | Factor of the weak-avalanche current for an infinite square transistor at the reference temperature     |
| $S_{T;a_1}$ | STA1        | K <sup>-1</sup>  | Coefficient of the temperature dependence of $a_1$  |
| $S_{L;a_1}$ | SLA1        | -                | Coefficient of the length dependence of $a_1$   |
| $S_{W;a_1}$ | SWA1        | -                | Coefficient of the width dependence of $a_1$  |
| $a_{2R}$    | A2R         | V                | Exponent of the weak-avalanche current for an infinite square transistor                                |
| $S_{L;a_2}$ | SLA2        | -                | Coefficient of the length dependence of $a_2$   |
| $S_{W;a_2}$ | SWA2        | -                | Coefficient of the width dependence of $a_2$  |
| $a_{3R}$    | A3R         | -                | Factor of the drain-source voltage above which weak-avalanche occurs, for an infinite square transistor |
| $S_{L;a_3}$ | SLA3        | -                | Coefficient of the length dependence of $a_3$   |
| $S_{W;a_3}$ | SWA3        | -                | Coefficient of the width dependence of $a_3$  |
| $I_{GINVR}$ | IGINVR      | AV <sup>-2</sup> | Gain factor for intrinsic gate tunnelling current in inversion for a channel area of $1\mu m^2$         |
| $B_{inv}$   | BINV        | V                | Probability factor for intrinsic gate tunnelling current in inversion                                   |
| $I_{GACCR}$ | IGACCR      | AV <sup>-2</sup> | Gain factor for intrinsic gate tunnelling current in accumulation for a channel area of $1\mu m^2$      |
| $B_{acc}$   | BACC        | V                | Probability factor for intrinsic gate tunnelling current in accumulation                                |

| Symbol        | Progr. Name | Units          | Description  |
|---------------|-------------|----------------|--|
| $V_{FBov}$    | VFBOV       | V              | Flat-band voltage for the source/drain overlap extensions                                    |
| $k_{ov}$      | KOV         | $V^{1/2}$      | Body-effect factor for the source/drain overlap extensions                                   |
| $I_{GOVR}$    | IGOVR       | $AV^{-2}$      | Gain factor for source/drain overlap gate tunnelling current for a channel width of $1\mu m$ |
| $A_{GIDLR}$   | AGIDLR      | $AV^{-3}$      | Gain factor for gate-induced drain leakage current for a channel width of $1\mu m$           |
| $B_{GIDL}$    | BGIDL       | V              | Probability factor for gate-induced drain leakage current at the reference temperature       |
| $S_{T;BGIDL}$ | STBGIDL     | $VK^{-1}$      | Coefficient of the temperature dependence of BGIDL   |
| $C_{GIDL}$    | CGIDL       | -              | Factor for the lateral field dependence of the gate-induced drain leakage current            |
| $t_{ox}$      | TOX         | m              | Thickness of the gate-oxide layer.   |
| $C_{ol}$      | COL         | F              | Gate overlap capacitance for a channel width of $1\mu m$                                     |
| -             | GATENOISE   | -              | Flag for in/exclusion of induced gate thermal noise  |
| $N_T$         | NT          | J              | Coefficient of the thermal noise at the reference temperature                                |
| $N_{FAR}$     | NFAR        | $V^{-1}m^{-4}$ | First coefficient of the flicker noise for a channel area of $1\mu m^2$                      |
| $N_{FBR}$     | NFBR        | $V^{-1}m^{-2}$ | Second coefficient of the flicker noise for a channel area of $1\mu m^2$                     |
| $N_{FCR}$     | NFCR        | $V^{-1}$       | Third coefficient of the flicker noise for a channel area of $1\mu m^2$                      |
| $\Delta T_A$  | DTA         | K              | Temperature offset of the device with respect to $T_A$                                       |
| $RG0$         | RGO         | $\Omega$       | Gate Resistance  |

| <b>Symbol</b> | <b>Progr. Name</b> | <b>Units</b>         | <b>Description</b>                               |
|---------------|--------------------|----------------------|--|
| <i>RINT</i>   | RINT               | $\Omega \text{ m}^2$ | Contact resistance between silicide and poly     |
| <i>RVPOLY</i> | RVPOLY             | $\Omega \text{ m}^2$ | Vertical poly resistance                         |
| <i>RSHG</i>   | RSHG               | $\Omega/\square$     | Gate electrode diffusion sheet resistance        |
| <i>DLSIL</i>  | DLSIL              | m                    | Silicide extension over the physical gate length |

The additional parameters for the model including self-heating (see section 15.6 on page 156) are listed in the table below.

| <b>Symbol</b> | <b>Progr. Name</b> | <b>Units</b>                | <b>Description</b>                                |
|---------------|--------------------|-----------------------------|---|
| $R_{Th}$      | RTH                | $^{\circ}\text{C}/\text{W}$ | Thermal resistance                                |
| $C_{Th}$      | CTH                | $\text{J}/^{\circ}\text{C}$ | Thermal capacitance                               |
| $A_{TH}$      | ATH                | -                           | Temperature coefficient of the thermal resistance |

The instance parameters are listed in the table below.

| <b>Symbol</b> | <b>Progr. Name</b> | <b>Units</b> | <b>Description</b>   |
|---------------|--------------------|--------------|--|
| <i>L</i>      | L                  | m            | Drawn channel length in the lay-out of the actual transistor |
| <i>W</i>      | W                  | m            | Drawn channel width in the lay-out of the actual transistor  |
| $N_{MULT}$    | MULT               | -            | Number of devices in parallel                                |
| <i>NF</i>     | NF                 | -            | Number of fingers  |
| <i>NGCON</i>  | NGCON              | -            | Number of gate contacts                                      |
| <i>XGW</i>    | XGW                | m            | Distance from the gate contact to the channel edge           |
| -             | PRINT-SCALED       | -            | Flag to add scaled parameters to the OP output               |

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

\*) See Appendix D for the definition of PARAMCHK.

**Default and clipping values (physical geometrical model)**

The default values and clipping values as used for the parameters of the physical geometrical MOS model, level 1102 (n-channel) are listed below.

| <b>Parameter</b> | <b>Units</b>      | <b>Default</b>         | <b>Clip low</b> | <b>Clip high</b> |
|------------------|-------------------|------------------------|-----------------|------------------|
| <i>LEVEL</i>     | -                 | 11020                  | -               | -                |
| <i>PARAMCHK</i>  | -                 | 0                      | -               | -                |
| <i>LVAR</i>      | m                 | 0.000                  | -               | -                |
| <i>LAP</i>       | m                 | $4.0 \times 10^{-8}$   | -               | -                |
| <i>WVAR</i>      | m                 | 0.000                  | -               | -                |
| <i>WOT</i>       | m                 | 0.000                  | -               | -                |
| <i>TR</i>        | °C                | 21.0                   | -273.0          | -                |
| <i>VFB</i>       | V                 | -1.050                 | -               | -                |
| <i>STVFB</i>     | VK <sup>-1</sup>  | $0.5 \times 10^{-3}$   | -               | -                |
| <i>KOR</i>       | V <sup>1/2</sup>  | 0.500                  | -               | -                |
| <i>SLKO</i>      | -                 | 0.000                  | -               | -                |
| <i>SL2KO</i>     | -                 | 0.000                  | -               | -                |
| <i>SL3KO</i>     | -                 | 0.000                  | -               | -                |
| <i>SL3KOEXP</i>  | -                 | 1.000                  | -               | -                |
| <i>SWKO</i>      | -                 | 0.000                  | -               | -                |
| <i>KPINV</i>     | V <sup>-1/2</sup> | 0.000                  | -               | -                |
| <i>PHIBR</i>     | V                 | 0.950                  | -               | -                |
| <i>STPHIB</i>    | VK <sup>-1</sup>  | $-8.5 \times 10^{-4}$  | -               | -                |
| <i>SLPHIB</i>    | -                 | 0.000                  | -               | -                |
| <i>SL2PHIB</i>   | -                 | 0.000                  | -               | -                |
| <i>SWPHIB</i>    | -                 | 0.000                  | -               | -                |
| <i>BETSQ</i>     | AV <sup>-2</sup>  | $3.709 \times 10^{-4}$ | -               | -                |
| <i>ETABETR</i>   | -                 | 1.300                  | -               | -                |

| <b>Parameter</b> | <b>Units</b>    | <b>Default</b>        | <b>Clip low</b>       | <b>Clip high</b> |
|------------------|-----------------|-----------------------|-----------------------|------------------|
| <i>SLETABET</i>  | -               | 0.000                 | -                     | -                |
| <i>FBET1</i>     | -               | 0.000                 | -                     | -                |
| <i>LP1</i>       | m               | $0.8 \times 10^{-6}$  | $1.0 \times 10^{-10}$ | -                |
| <i>FBET2</i>     | -               | 0.000                 | -                     | -                |
| <i>LP2</i>       | m               | $0.8 \times 10^{-6}$  | $1.0 \times 10^{-10}$ | -                |
| <i>THESRR</i>    | V <sup>-1</sup> | 0.400                 | -                     | -                |
| <i>ETASR</i>     | -               | 0.650                 | -                     | -                |
| <i>SWTHESR</i>   | -               | 0.000                 | -                     | -                |
| <i>THEPHR</i>    | V <sup>-1</sup> | $1.29 \times 10^{-2}$ | -                     | -                |
| <i>ETAPH</i>     | -               | 1.350                 | -                     | -                |
| <i>SWTHEPH</i>   | -               | 0.000                 | -                     | -                |
| <i>ETAMOBR</i>   | -               | 1.40                  | -                     | -                |
| <i>STETAMOB</i>  | K <sup>-1</sup> | 0.000                 | -                     | -                |
| <i>SWETAMOB</i>  | -               | 0.000                 | -                     | -                |
| <i>NU</i>        | -               | 2.000                 | 1.000                 | 100              |
| <i>NUEXP</i>     | -               | 5.250                 | -                     | -                |
| <i>CS</i>        | -               | 0                     | 0                     | -                |
| <i>CSR</i>       | -               | 0.000                 | -                     | -                |
| <i>SLCS</i>      | -               | 0.000                 | -                     | -                |
| <i>CSEXP</i>     | -               | 1.000                 | 0                     | -                |
| <i>SWCS</i>      | -               | 0.000                 | -                     | -                |
| <i>ETACS</i>     | -               | 0.000                 | -                     | -                |
| <i>THERR</i>     | V <sup>-1</sup> | 0.155                 | $1.0 \times 10^{-10}$ | -                |
| <i>ETAR</i>      | -               | 0.950                 | -                     | -                |
| <i>SWTHER</i>    | -               | 0.000                 | -                     | -                |
| <i>THER1</i>     | V               | 0.000                 | -                     | -                |

| <b>Parameter</b> | <b>Units</b>      | <b>Default</b>          | <b>Clip low</b>         | <b>Clip high</b>       |
|------------------|-------------------|-------------------------|-------------------------|------------------------|
| <i>THER2</i>     | V                 | 1.000                   | -                       | -                      |
| <i>THESATR</i>   | V <sup>-1</sup>   | 0.500                   | -                       | -                      |
| <i>ETASAT</i>    | -                 | 1.040                   | -                       | -                      |
| <i>SLTHESAT</i>  | -                 | 1.000                   | -                       | -                      |
| <i>THESATEXP</i> | -                 | 1.000                   | 0.000                   | -                      |
| <i>SWTHESAT</i>  | -                 | 0.000                   | -                       | -                      |
| <i>THETHR</i>    | V <sup>-3</sup>   | 1.0 × 10 <sup>-3</sup>  | -                       | -                      |
| <i>THETHEXP</i>  | -                 | 1.000                   | 0.000                   | -                      |
| <i>SWTHETH</i>   | -                 | 0.000                   | -                       | -                      |
| <i>SDIBLO</i>    | V <sup>-1/2</sup> | 1.0 × 10 <sup>-4</sup>  | -                       | -                      |
| <i>SDIBLEXP</i>  | -                 | 1.350                   | -                       | -                      |
| <i>MOO</i>       | -                 | 0.000                   | -                       | -                      |
| <i>MOR</i>       | -                 | 0.000                   | -                       | -                      |
| <i>MOEXP</i>     | -                 | 1.340                   | -                       | -                      |
| <i>SSFR</i>      | V <sup>-1/2</sup> | 6.25 × 10 <sup>-3</sup> | -                       | -                      |
| <i>SLSSF</i>     | -                 | 1.000                   | -                       | -                      |
| <i>SWSSF</i>     | -                 | 0.000                   | -                       | -                      |
| <i>ALPR</i>      | -                 | 1.0 × 10 <sup>-2</sup>  | -                       | -                      |
| <i>SLALP</i>     | -                 | 1.000                   | -                       | -                      |
| <i>ALPEXP</i>    | -                 | 1.000                   | 0.000                   | -                      |
| <i>SWALP</i>     | -                 | 0.000                   | -                       | -                      |
| <i>VP</i>        | V                 | 5.0 × 10 <sup>-2</sup>  | -                       | -                      |
| <i>LMIN</i>      | m                 | 1.5 × 10 <sup>-7</sup>  | 1.0 × 10 <sup>-10</sup> | 2.5 × 10 <sup>-6</sup> |
| <i>AIR</i>       | -                 | 6.000                   | -                       | -                      |
| <i>STAI</i>      | K <sup>-1</sup>   | 0.000                   | -                       | -                      |
| <i>SLAI</i>      | -                 | 0.000                   | -                       | -                      |

| <b>Parameter</b> | <b>Units</b>   | <b>Default</b>          | <b>Clip low</b>       | <b>Clip high</b> |
|------------------|----------------|-------------------------|-----------------------|------------------|
| <i>SWA1</i>      | -              | 0.000                   | -                     | -                |
| <i>A2R</i>       | V              | 38.00                   | -                     | -                |
| <i>SLA2</i>      | -              | 0.000                   | -                     | -                |
| <i>SWA2</i>      | -              | 0.000                   | -                     | -                |
| <i>A3R</i>       | -              | 1.000                   | -                     | -                |
| <i>SLA3</i>      | -              | 0.000                   | -                     | -                |
| <i>SWA3</i>      | -              | 0.000                   | -                     | -                |
| <i>IGINVR</i>    | $AV^{-2}$      | 0.000                   | 0.000                 | -                |
| <i>BINV</i>      | V              | 48.00                   | 0.000                 | -                |
| <i>IGACCR</i>    | $AV^{-2}$      | 0.000                   | 0.000                 | -                |
| <i>BACC</i>      | V              | 48.00                   | 0.000                 | -                |
| <i>VFBOV</i>     | V              | 0.000                   | -                     | -                |
| <i>KOV</i>       | $V^{1/2}$      | 2.500                   | $1.0 \times 10^{-12}$ | -                |
| <i>IGOVR</i>     | $AV^{-2}$      | 0.000                   | 0.000                 | -                |
| <i>AGIDLR</i>    | $AV^{-3}$      | 0.000                   | 0.000                 | -                |
| <i>BGIDL</i>     | V              | 41.00                   | 0.000                 | -                |
| <i>STBGIDL</i>   | $VK^{-1}$      | $-3.638 \times 10^{-4}$ | -                     | -                |
| <i>CGIDL</i>     | -              | 0.000                   | 0.000                 | -                |
| <i>TOX</i>       | m              | $3.2 \times 10^{-9}$    | $1.0 \times 10^{-12}$ | -                |
| <i>COL</i>       | F              | $3.2 \times 10^{-16}$   | -                     | -                |
| <i>GATENOISE</i> | -              | 0.000                   | 0.000                 | 1.000            |
| <i>NT</i>        | J              | $1.624 \times 10^{-20}$ | 0.000                 | -                |
| <i>NFAR</i>      | $V^{-1}m^{-4}$ | $1.573 \times 10^{23}$  | -                     | -                |
| <i>NFBR</i>      | $V^{-1}m^{-2}$ | $4.752 \times 10^9$     | -                     | -                |
| <i>NFCR</i>      | $V^{-1}$       | 0.000                   | -                     | -                |

| Parameter     | Units                | Default | Clip low | Clip high |
|---------------|----------------------|---------|----------|-----------|
| <i>DTA</i>    | K                    | 0.000   | -        | -         |
| <i>RGO</i>    | $\Omega$             | 0.0     | -        | -         |
| <i>RINT</i>   | $\Omega \text{ m}^2$ | 0.0     | 0.0      | -         |
| <i>RVPOLY</i> | $\Omega \text{ m}^2$ | 0.0     | 0.0      | -         |
| <i>RSHG</i>   | $\Omega/\square$     | 0.0     | 0.0      | -         |
| <i>DLSIL</i>  | m                    | 0.0     | -        | -         |

The additional values and clipping values of the additional parameters for the (**n-channel**) model including self-heating (see section 15.6 on page 156) are listed in the table below.

| Parameter  | Units                       | Default              | Clip low | Clip high |
|------------|-----------------------------|----------------------|----------|-----------|
| <i>RTH</i> | $^{\circ}\text{C}/\text{W}$ | 300.0                | 0.000    | -         |
| <i>CTH</i> | $\text{J}/^{\circ}\text{C}$ | $3.0 \times 10^{-9}$ | 0.000    | -         |
| <i>ATH</i> | -                           | 0.0                  | -        | -         |

The instance parameters are listed in the table below.

| Parameter           | Units | Default                | Clip low | Clip high |
|---------------------|-------|------------------------|----------|-----------|
| <i>L</i>            | m     | $2.000 \times 10^{-6}$ | -        | -         |
| <i>W</i>            | m     | $1.000 \times 10^{-5}$ | -        | -         |
| <i>MULT</i>         | -     | 1.000                  | 0.000    | -         |
| <i>NF</i>           | -     | 1.0                    | 1.0      | -         |
| <i>NGCON</i>        | -     | 1.0                    | 1.0      | 2.0       |
| <i>XGW</i>          | m     | $1.0 \times 10^{-7}$   | -        | -         |
| <i>PRINT-SCALED</i> | -     | 0                      | -        | -         |

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

The default values and clipping values as used for the parameters of the physical geometrical MOS model, level 1102 (p-channel) are listed below.

| <b>Parameter</b> | <b>Units</b>      | <b>Default</b>         | <b>Clip low</b> | <b>Clip high</b> |
|------------------|-------------------|------------------------|-----------------|------------------|
| <i>LEVEL</i>     | -                 | 11020                  | -               | -                |
| <i>PARAMCHK</i>  | -                 | 0                      | -               | -                |
| <i>LVAR</i>      | m                 | 0.000                  | -               | -                |
| <i>LAP</i>       | m                 | $4.0 \times 10^{-8}$   | -               | -                |
| <i>WVAR</i>      | m                 | 0.000                  | -               | -                |
| <i>WOT</i>       | m                 | 0.000                  | -               | -                |
| <i>TR</i>        | °C                | 21.0                   | -273.0          | -                |
| <i>VFB</i>       | V                 | -1.050                 | -               | -                |
| <i>STVFB</i>     | VK <sup>-1</sup>  | $0.5 \times 10^{-3}$   | -               | -                |
| <i>KOR</i>       | V <sup>1/2</sup>  | 0.500                  | -               | -                |
| <i>SLKO</i>      | -                 | 0.000                  | -               | -                |
| <i>SL2KO</i>     | -                 | 0.000                  | -               | -                |
| <i>SL3KO</i>     | -                 | 0.000                  | -               | -                |
| <i>SL3KOEXP</i>  | -                 | 1.000                  | -               | -                |
| <i>SWKO</i>      | -                 | 0.000                  | -               | -                |
| <i>KPINV</i>     | V <sup>-1/2</sup> | 0.000                  | -               | -                |
| <i>PHIBR</i>     | V                 | 0.950                  | -               | -                |
| <i>STPHIB</i>    | VK <sup>-1</sup>  | $-8.5 \times 10^{-4}$  | -               | -                |
| <i>SLPHIB</i>    | -                 | 0.000                  | -               | -                |
| <i>SL2PHIB</i>   | -                 | 0.000                  | -               | -                |
| <i>SWPHIB</i>    | -                 | 0.000                  | -               | -                |
| <i>BETSQ</i>     | AV <sup>-2</sup>  | $1.150 \times 10^{-4}$ | -               | -                |
| <i>ETABETR</i>   | -                 | 0.500                  | -               | -                |
| <i>SLETABET</i>  | -                 | 0.000                  | -               | -                |

| <b>Parameter</b> | <b>Units</b>    | <b>Default</b>       | <b>Clip low</b>       | <b>Clip high</b> |
|------------------|-----------------|----------------------|-----------------------|------------------|
| <i>FBET1</i>     | -               | 0.000                | -                     | -                |
| <i>LP1</i>       | m               | $0.8 \times 10^{-6}$ | $1.0 \times 10^{-10}$ | -                |
| <i>FBET2</i>     | -               | 0.000                | -                     | -                |
| <i>LP2</i>       | m               | $0.8 \times 10^{-6}$ | $1.0 \times 10^{-10}$ | -                |
| <i>THESRR</i>    | V <sup>-1</sup> | 0.730                | -                     | -                |
| <i>ETASR</i>     | -               | 0500                 | -                     | -                |
| <i>SWTHESR</i>   | -               | 0.000                | -                     | -                |
| <i>THEPHR</i>    | V <sup>-1</sup> | $1.0 \times 10^{-3}$ | -                     | -                |
| <i>ETAPH</i>     | -               | 3.750                | -                     | -                |
| <i>SWTHEPH</i>   | -               | 0.000                | -                     | -                |
| <i>ETAMOBR</i>   | -               | 3.000                | -                     | -                |
| <i>STETAMOB</i>  | K <sup>-1</sup> | 0.000                | -                     | -                |
| <i>SWETAMOB</i>  | -               | 0.000                | -                     | -                |
| <i>NU</i>        | -               | 2.000                | 1.000                 | 100              |
| <i>NUEXP</i>     | -               | 3.230                | -                     | -                |
| <i>CS</i>        | -               | 0                    | 0                     | -                |
| <i>CSR</i>       | -               | 0.000                | -                     | -                |
| <i>SLCS</i>      | -               | 0.000                | -                     | -                |
| <i>CSEXP</i>     | -               | 1.000                | 0                     | -                |
| <i>SWCS</i>      | -               | 0.000                | -                     | -                |
| <i>ETACS</i>     | -               | 0.000                | -                     | -                |
| <i>THERR</i>     | V <sup>-1</sup> | 0.080                | $1.0 \times 10^{-10}$ | -                |
| <i>ETAR</i>      | -               | 0.400                | -                     | -                |
| <i>SWTHER</i>    | -               | 0.000                | -                     | -                |
| <i>THER1</i>     | V               | 0.000                | -                     | -                |
| <i>THER2</i>     | V               | 1.000                | -                     | -                |

| <b>Parameter</b> | <b>Units</b>      | <b>Default</b>          | <b>Clip low</b>         | <b>Clip high</b>       |
|------------------|-------------------|-------------------------|-------------------------|------------------------|
| <i>THESATR</i>   | V <sup>-1</sup>   | 0.200                   | -                       | -                      |
| <i>ETASAT</i>    | -                 | 0.860                   | -                       | -                      |
| <i>SLTHESAT</i>  | -                 | 1.000                   | -                       | -                      |
| <i>THESATEXP</i> | -                 | 1.000                   | 0.000                   | -                      |
| <i>SWTHESAT</i>  | -                 | 0.000                   | -                       | -                      |
| <i>THETHR</i>    | V <sup>-3</sup>   | 0.5 × 10 <sup>-3</sup>  | -                       | -                      |
| <i>THETHEXP</i>  | -                 | 1.000                   | 0.000                   | -                      |
| <i>SWTHETH</i>   | -                 | 0.000                   | -                       | -                      |
| <i>SDIBLO</i>    | V <sup>-1/2</sup> | 1.0 × 10 <sup>-4</sup>  | -                       | -                      |
| <i>SDIBLEXP</i>  | -                 | 1.350                   | -                       | -                      |
| <i>MOO</i>       | -                 | 0.000                   | -                       | -                      |
| <i>MOR</i>       | -                 | 0.000                   | -                       | -                      |
| <i>MOEXP</i>     | -                 | 1.340                   | -                       | -                      |
| <i>SSFR</i>      | V <sup>-1/2</sup> | 6.25 × 10 <sup>-3</sup> | -                       | -                      |
| <i>SLSSF</i>     | -                 | 1.000                   | -                       | -                      |
| <i>SWSSF</i>     | -                 | 0.000                   | -                       | -                      |
| <i>ALPR</i>      | -                 | 1.0 × 10 <sup>-2</sup>  | -                       | -                      |
| <i>SLALP</i>     | -                 | 1.000                   | -                       | -                      |
| <i>ALPEXP</i>    | -                 | 1.000                   | 0.000                   | -                      |
| <i>SWALP</i>     | -                 | 0.000                   | -                       | -                      |
| <i>VP</i>        | V                 | 5.0 × 10 <sup>-2</sup>  | -                       | -                      |
| <i>LMIN</i>      | m                 | 1.5 × 10 <sup>-7</sup>  | 1.0 × 10 <sup>-10</sup> | 2.5 × 10 <sup>-6</sup> |
| <i>AIR</i>       | -                 | 6.000                   | -                       | -                      |
| <i>STAI</i>      | K <sup>-1</sup>   | 0.000                   | -                       | -                      |
| <i>SLAI</i>      | -                 | 0.000                   | -                       | -                      |
| <i>SWAI</i>      | -                 | 0.000                   | -                       | -                      |

| <b>Parameter</b> | <b>Units</b>                    | <b>Default</b>            | <b>Clip low</b>         | <b>Clip high</b> |
|------------------|---------------------------------|---------------------------|-------------------------|------------------|
| <i>A2R</i>       | V                               | 38.00                     | -                       | -                |
| <i>SLA2</i>      | -                               | 0.000                     | -                       | -                |
| <i>SWA2</i>      | -                               | 0.000                     | -                       | -                |
| <i>A3R</i>       | -                               | 1.000                     | -                       | -                |
| <i>SLA3</i>      | -                               | 0.000                     | -                       | -                |
| <i>SWA3</i>      | -                               | 0.000                     | -                       | -                |
| <i>IGINVR</i>    | AV <sup>-2</sup>                | 0.000                     | 0.000                   | -                |
| <i>BINV</i>      | V                               | 87.50                     | 0.000                   | -                |
| <i>IGACCR</i>    | AV <sup>-2</sup>                | 0.000                     | 0.000                   | -                |
| <i>BACC</i>      | V                               | 48.00                     | 0.000                   | -                |
| <i>VFBOV</i>     | V                               | 0.000                     | -                       | -                |
| <i>KOV</i>       | V <sup>1/2</sup>                | 2.500                     | 1.0 × 10 <sup>-12</sup> | -                |
| <i>IGOVR</i>     | AV <sup>-2</sup>                | 0.000                     | 0.000                   | -                |
| <i>AGIDLR</i>    | AV <sup>-3</sup>                | 0.000                     | 0.000                   | -                |
| <i>BGIDL</i>     | V                               | 41.00                     | 0.000                   | -                |
| <i>STBGIDL</i>   | VK <sup>-1</sup>                | -3.638X10 <sup>-4</sup>   | -                       | -                |
| <i>CGIDL</i>     | -                               | 0.000                     | 0.000                   | -                |
| <i>TOX</i>       | m                               | 3.2 × 10 <sup>-9</sup>    | 1.0 × 10 <sup>-12</sup> | -                |
| <i>COL</i>       | F                               | 3.2 × 10 <sup>-16</sup>   | -                       | -                |
| <i>GATENOISE</i> | -                               | 0.000                     | 0.000                   | 1.000            |
| <i>NT</i>        | J                               | 1.656 × 10 <sup>-20</sup> | 0.000                   | -                |
| <i>NFAR</i>      | V <sup>-1</sup> m <sup>-4</sup> | 3.825 × 10 <sup>24</sup>  | -                       | -                |
| <i>NFBR</i>      | V <sup>-1</sup> m <sup>-2</sup> | 1.015 × 10 <sup>9</sup>   | -                       | -                |
| <i>NFCR</i>      | V <sup>-1</sup>                 | 7.300 × 10 <sup>-8</sup>  | -                       | -                |
| <i>DTA</i>       | K                               | 0.000                     | -                       | -                |

| Parameter     | Units                | Default | Clip low | Clip high |
|---------------|----------------------|---------|----------|-----------|
| <i>RGO</i>    | $\Omega$             | 0.0     | -        | -         |
| <i>RINT</i>   | $\Omega \text{ m}^2$ | 0.0     | 0.0      | -         |
| <i>RVPOLY</i> | $\Omega \text{ m}^2$ | 0.0     | 0.0      | -         |
| <i>RSHG</i>   | $\Omega/\square$     | 0.0     | 0.0      | -         |
| <i>DLSIL</i>  | m                    | 0.0     | -        | -         |

The additional values and clipping values of the additional parameters for the (**p-channel**) model including self-heating (see section 15.6 on page 156) are listed in the table below.

| Parameter  | Units                       | Default              | Clip low | Clip high |
|------------|-----------------------------|----------------------|----------|-----------|
| <i>RTH</i> | $^{\circ}\text{C}/\text{W}$ | 300.0                | 0.000    | -         |
| <i>CTH</i> | $\text{J}/^{\circ}\text{C}$ | $3.0 \times 10^{-9}$ | 0.000    | -         |
| <i>ATH</i> | -                           | 0.0                  | -        | -         |

The instance parameters are listed in the table below.

| Parameter           | Units | Default                | Clip low | Clip high |
|---------------------|-------|------------------------|----------|-----------|
| <i>L</i>            | m     | $2.000 \times 10^{-6}$ | -        | -         |
| <i>W</i>            | m     | $1.000 \times 10^{-5}$ | -        | -         |
| <i>MULT</i>         | -     | 1.000                  | 0.000    | -         |
| <i>NF</i>           | -     | 1.0                    | 1.0      | -         |
| <i>NGCON</i>        | -     | 1.0                    | 1.0      | 2.0       |
| <i>XGW</i>          | m     | $1.0 \times 10^{-7}$   | -        | -         |
| <i>PRINT-SCALED</i> | -     | 0                      | -        | -         |

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

## Parameters for Binning Geometrical Scaling

These parameters correspond to the geometrical model (MN, MP, MOS 11021), for binning geometrical scaling of the model. Note that for each bin ( $W_{min}, W_{max}, L_{min}, L_{max}$ ), there is a separate parameter set, which is valid for  $(W, L)$  values with  $W_{min} \leq W \leq W_{max}$  and  $L_{min} \leq L \leq L_{max}$ .

| Symbol               | Progr. Name | Units      | Description  |
|----------------------|-------------|------------|--|
| -                    | LEVEL       | -          | Must be 11021  |
| -                    | PARAMCHK    | -          | Level of clip warning info   |
| $\Delta L_{PS}$      | LVAR        | m          | Difference between the actual and the programmed poly-silicon gate length                                      |
| $\Delta L_{overlap}$ | LAP         | m          | Effective channel length reduction per side due to the lateral diffusion of the source/drain dopant ions       |
| $\Delta W_{OD}$      | WVAR        | m          | Difference between the actual and the programmed field-oxide opening   |
| $\Delta W_{narrow}$  | WOT         | m          | Effective reduction of the channel width per side due to the lateral diffusion of the channel-stop dopant ions |
| $T_R$                | TR          | °C         | Reference temperature  |
| $V_{FB}$             | VFB         | V          | Flat-band voltage for all the transistors in the bin at the reference temperature                              |
| $P_{0;k_0}$          | POKO        | $V^{1/2}$  | Coefficient for the geometry independent part of $k_0$   |
| $P_{L;k_0}$          | PLKO        | $V^{1/2}$  | Coefficient for the length dependence of $k_0$   |
| $P_{W;k_0}$          | PWKO        | $V^{1/2}$  | Coefficient for the width dependence of $k_0$  |
| $P_{LW;k_0}$         | PLWKO       | $V^{1/2}$  | Coefficient for the length times width dependence of $k_0$   |
| $1/k_P$              | KPINV       | $V^{-1/2}$ | Inverse of the body-effect factor of the poly-silicon gate   |

| Symbol               | Progr. Name | Units     | Description  |
|----------------------|-------------|-----------|--|
| $P_{0;\phi_B}$       | POPHIB      | V         | Coefficient for the geometry independent part of $\phi_B$          |
| $P_{L;\phi_B}$       | PLPHIB      | V         | Coefficient for the length dependence of $\phi_B$                  |
| $P_{W;\phi_B}$       | PWPHIB      | V         | Coefficient for the width dependence of $\phi_B$                   |
| $P_{LW;\phi_B}$      | PLWPHIB     | V         | Coefficient for the length times width dependence of $\phi_B$      |
| $P_{0;\beta}$        | POBET       | $AV^{-2}$ | Coefficient for the geometry independent part of $\beta$           |
| $P_{L;\beta}$        | PLBET       | $AV^{-2}$ | Coefficient for the length dependence of $\beta$                   |
| $P_{W;\beta}$        | PWBET       | $AV^{-2}$ | Coefficient for the width dependence of $\beta$                    |
| $P_{LW;\beta}$       | PLWBET      | $AV^{-2}$ | Coefficient for the width over length dependence of $\beta$        |
| $P_{0;\theta_{sr}}$  | POTHESTR    | $V^{-1}$  | Coefficient for the geometry independent part of $\theta_{sr}$     |
| $P_{L;\theta_{sr}}$  | PLTHESTR    | $V^{-1}$  | Coefficient for the length dependence of $\theta_{sr}$             |
| $P_{W;\theta_{sr}}$  | PWTHESTR    | $V^{-1}$  | Coefficient for the width dependence of $\theta_{sr}$              |
| $P_{LW;\theta_{sr}}$ | PLWTHESTR   | $V^{-1}$  | Coefficient for the length times width dependence of $\theta_{sr}$ |
| $P_{0;\theta_{ph}}$  | POTHEPH     | $V^{-1}$  | Coefficient for the geometry independent part of $\theta_{ph}$     |
| $P_{L;\theta_{ph}}$  | PLTHEPH     | $V^{-1}$  | Coefficient for the length dependence of $\theta_{ph}$             |

| Symbol               | Progr. Name | Units    | Description  |
|----------------------|-------------|----------|--|
| $P_{W;\theta_{ph}}$  | PWTHEPH     | $V^{-1}$ | Coefficient for the width dependence of $\theta_{ph}$              |
| $P_{LW;\theta_{ph}}$ | PLWTHEPH    | $V^{-1}$ | Coefficient for the length times width dependence of $\theta_{ph}$ |
| $P_{0;\eta_{mob}}$   | POETAMOB    | -        | Coefficient for the geometry independent part of $\eta_{mob}$      |
| $P_{L;\eta_{mob}}$   | PLETAMOB    | -        | Coefficient for the length dependence of $\eta_{mob}$              |
| $P_{W;\eta_{mob}}$   | PWETAMOB    | -        | Coefficient for the width dependence of $\eta_{mob}$               |
| $P_{LW;\eta_{mob}}$  | PLWETAMOB   | -        | Coefficient for the length times width dependence of $\eta_{mob}$  |
| $P_{0;C_s}$          | POCS        | -        | Coefficient for the geometry independent part of $C_s$             |
| $P_{L;C_s}$          | PLCS        | -        | Coefficient for the length dependence of $C_s$                     |
| $P_{W;C_s}$          | PWCS        | -        | Coefficient for the width dependence of $C_s$                      |
| $P_{LW;C_s}$         | PLWCS       | -        | Coefficient for the length times width dependence of $C_s$         |
| $P_{0;\theta_R}$     | POTHER      | $V^{-1}$ | Coefficient for the geometry independent part of $\theta_R$        |
| $P_{L;\theta_R}$     | PLTHER      | $V^{-1}$ | Coefficient for the length dependence of $\theta_R$                |
| $P_{W;\theta_R}$     | PWTHER      | $V^{-1}$ | Coefficient for the width dependence of $\theta_R$                 |
| $P_{LW;\theta_R}$    | PLWTHER     | $V^{-1}$ | Coefficient for the length times width dependence of $\theta_R$    |

| Symbol                 | Progr. Name | Units      | Description  |
|------------------------|-------------|------------|--|
| $\theta_{R1}$          | THER1       | V          | Numerator of the gate voltage dependent part of series resistance for all the transistors in the bin   |
| $\theta_{R2}$          | THER2       | V          | Denominator of the gate voltage dependent part of series resistance for all the transistors in the bin |
| $P_{0;\theta_{sat}}$   | POTHE SAT   | $V^{-1}$   | Coefficient for the geometry independent part of $\theta_{sat}$  |
| $P_{L;\theta_{sat}}$   | PLTHE SAT   | $V^{-1}$   | Coefficient for the length dependence of $\theta_{sat}$  |
| $P_{W;\theta_{sat}}$   | PWTHE SAT   | $V^{-1}$   | Coefficient for the width dependence of $\theta_{sat}$   |
| $P_{LW;\theta_{sat}}$  | PLWTHE SAT  | $V^{-1}$   | Coefficient for the length times width dependence of $\theta_{sat}$                                    |
| $P_{0;\theta_{Th}}$    | POTHE TH    | $V^{-3}$   | Coefficient for the geometry independent part of $\theta_{Th}$   |
| $P_{L;\theta_{Th}}$    | PLTHE TH    | $V^{-3}$   | Coefficient for the length dependence of $\theta_{Th}$   |
| $P_{W;\theta_{Th}}$    | PWTHE TH    | $V^{-3}$   | Coefficient for the width dependence of $\theta_{Th}$  |
| $P_{LW;\theta_{Th}}$   | PLWTHE TH   | $V^{-3}$   | Coefficient for the length times width dependence of $\theta_{Th}$                                     |
| $P_{0;\sigma_{dibl}}$  | POSDIBL     | $V^{-1/2}$ | Coefficient for the geometry independent part of $\sigma_{dibl}$                                       |
| $P_{L;\sigma_{dibl}}$  | PLSDIBL     | $V^{-1/2}$ | Coefficient for the length dependence of $\sigma_{dibl}$   |
| $P_{W;\sigma_{dibl}}$  | PWSDIBL     | $V^{-1/2}$ | Coefficient for the width dependence of $\sigma_{dibl}$  |
| $P_{LW;\sigma_{dibl}}$ | PLWSDIBL    | $V^{-1/2}$ | Coefficient for the length times width dependence of $\sigma_{dibl}$                                   |

| Symbol               | Progr. Name | Units      | Description  |
|----------------------|-------------|------------|--|
| $P_{0;m_0}$          | POMO        | -          | Coefficient for the geometry independent part of $m_0$             |
| $P_{L;m_0}$          | PLMO        | -          | Coefficient for the length dependence of $m_0$                     |
| $P_{W;m_0}$          | PWMO        | -          | Coefficient for the width dependence of $m_0$                      |
| $P_{LW;m_0}$         | PLWMO       | -          | Coefficient for the length times width dependence of $m_0$         |
| $P_{0;\sigma_{sf}}$  | POSSF       | $V^{-1/2}$ | Coefficient for the geometry independent part of $\sigma_{sf}$     |
| $P_{L;\sigma_{sf}}$  | PLSSF       | $V^{-1/2}$ | Coefficient for the length dependence of $\sigma_{sf}$             |
| $P_{W;\sigma_{sf}}$  | PWSSF       | $V^{-1/2}$ | Coefficient for the width dependence of $\sigma_{sf}$              |
| $P_{LW;\sigma_{sf}}$ | PLWSSF      | $V^{-1/2}$ | Coefficient for the length times width dependence of $\sigma_{sf}$ |
| $P_{0;\alpha}$       | POALP       | -          | Coefficient for the geometry independent part of $\alpha$          |
| $P_{L;\alpha}$       | PLALP       | -          | Coefficient for the length dependence of $\alpha$                  |
| $P_{W;\alpha}$       | PWALP       | -          | Coefficient for the width dependence of $\alpha$                   |
| $P_{LW;\alpha}$      | PLWALP      | -          | Coefficient for the length times width dependence of $\alpha$      |
| $V_P$                | VP          | V          | Characteristic voltage of the channel length modulation            |
| $P_{0;m}$            | POMEXP      | -          | Coefficient for the geometry independent part of $1/m$             |
| $P_{L;m}$            | PLMEXP      | -          | Coefficient for the length dependence of $1/m$                     |

| <b>Symbol</b> | <b>Progr. Name</b> | <b>Units</b> | <b>Description</b>   |
|---------------|--------------------|--------------|--|
| $P_{W;m}$     | PWMEXP             | -            | Coefficient for the width dependence of $1/m$              |
| $P_{LW;m}$    | PLWMEXP            | -            | Coefficient for the length times width dependence of $1/m$ |
| $P_{0;a_1}$   | POA1               | -            | Coefficient for the geometry independent part of $a_1$     |
| $P_{L;a_1}$   | PLA1               | -            | Coefficient for the length dependence of $a_1$             |
| $P_{W;a_1}$   | PWA1               | -            | Coefficient for the width dependence of $a_1$              |
| $P_{LW;a_1}$  | PLWA1              | -            | Coefficient for the length times width dependence of $a_1$ |
| $P_{0;a_2}$   | POA2               | V            | Coefficient for the geometry independent part of $a_2$     |
| $P_{L;a_2}$   | PLA2               | V            | Coefficient for the length dependence of $a_2$             |
| $P_{W;a_2}$   | PWA2               | V            | Coefficient for the width dependence of $a_2$              |
| $P_{LW;a_2}$  | PLWA2              | V            | Coefficient for the length times width dependence of $a_2$ |
| $P_{0;a_3}$   | POA3               | -            | Coefficient for the geometry independent part of $a_3$     |
| $P_{L;a_3}$   | PLA3               | -            | Coefficient for the length dependence of $a_3$             |
| $P_{W;a_3}$   | PWA3               | -            | Coefficient for the width dependence of $a_3$              |
| $P_{LW;a_3}$  | PLWA3              | -            | Coefficient for the length times width dependence of $a_3$ |

| Symbol            | Progr. Name | Units     | Description   |
|-------------------|-------------|-----------|---|
| $P_{0;I_{GINV}}$  | POIGINV     | $AV^{-2}$ | Coefficient for the geometry independent part of $I_{GINV}$     |
| $P_{L;I_{GINV}}$  | PLIGINV     | $AV^{-2}$ | Coefficient for the length dependence of $I_{GINV}$             |
| $P_{W;I_{GINV}}$  | PWIGINV     | $AV^{-2}$ | Coefficient for the width dependence of $I_{GINV}$              |
| $P_{LW;I_{GINV}}$ | PLWIGINV    | $AV^{-2}$ | Coefficient for the length times width dependence of $I_{GINV}$ |
| $P_{0;B_{inv}}$   | POBINV      | V         | Coefficient for the geometry independent part of $B_{inv}$      |
| $P_{L;B_{inv}}$   | PLBINV      | V         | Coefficient for the length dependence of $B_{inv}$              |
| $P_{W;B_{inv}}$   | PWBINV      | V         | Coefficient for the width dependence of $B_{inv}$               |
| $P_{LW;B_{inv}}$  | PLWBINV     | V         | Coefficient for the length times width dependence of $B_{inv}$  |
| $P_{0;I_{GACC}}$  | POIGACC     | $AV^{-2}$ | Coefficient for the geometry independent part of $I_{GACC}$     |
| $P_{L;I_{GACC}}$  | PLIGACC     | $AV^{-2}$ | Coefficient for the length dependence of $I_{GACC}$             |
| $P_{W;I_{GACC}}$  | PWIGACC     | $AV^{-2}$ | Coefficient for the width dependence of $I_{GACC}$              |
| $P_{LW;I_{GACC}}$ | PLWIGACC    | $AV^{-2}$ | Coefficient for the length times width dependence of $I_{GACC}$ |
| $P_{0;B_{acc}}$   | POBACC      | V         | Coefficient for the geometry independent part of $B_{acc}$      |
| $P_{L;B_{acc}}$   | PLBACC      | V         | Coefficient for the length dependence of $B_{acc}$              |

| Symbol            | Progr. Name | Units     | Description  |
|-------------------|-------------|-----------|--|
| $P_{W;B_{acc}}$   | PWBACC      | V         | Coefficient for the width dependence of $B_{acc}$              |
| $P_{LW;B_{acc}}$  | PLWBACC     | V         | Coefficient for the length times width dependence of $B_{acc}$ |
| $V_{FBov}$        | VFBOV       | V         | Flat-band voltage for the source/drain overlap extensions      |
| $k_{ov}$          | KOV         | $V^{1/2}$ | Bodu-effect factor for the source/drain overlap extensions     |
| $P_{0;I_{GOV}}$   | POIGOV      | $AV^{-2}$ | Coefficient for the geometry independent part of $I_{GOV}$     |
| $P_{L;I_{GOV}}$   | PLIGOV      | $AV^{-2}$ | Coefficient for the length dependence of $I_{GOV}$             |
| $P_{W;I_{GOV}}$   | PWIGOV      | $AV^{-2}$ | Coefficient for the width dependence of $I_{GOV}$              |
| $P_{LW;I_{GOV}}$  | PLWIGOV     | $AV^{-2}$ | Coefficient for the length times width dependence of $I_{GOV}$ |
| $P_{0;A_{GIDL}}$  | POAGIDL     | $AV^{-3}$ | Coefficient for the geometry independent part of $A_{GIDL}$    |
| $P_{L;A_{GIDL}}$  | PLAGIDL     | $AV^{-3}$ | Coefficient for the length dependence of $A_{GIDL}$            |
| $P_{W;A_{GIDL}}$  | PWAGIDL     | $AV^{-3}$ | Coefficient for the width dependence of $A_{GIDL}$             |
| $P_{LW;A_{GIDL}}$ | PLWAGIDL    | $AV^{-3}$ | Coefficient for the width over length dependence of $A_{GIDL}$ |
| $P_{0;B_{GIDL}}$  | POBGIDL     | V         | Coefficient for the geometry independent part of $B_{GIDL}$    |
| $P_{L;B_{GIDL}}$  | PLBGIDL     | V         | Coefficient for the length dependence of $B_{GIDL}$            |

| Symbol            | Progr. Name | Units | Description   |
|-------------------|-------------|-------|---|
| $P_{W;B_{GIDL}}$  | PWBGIDL     | V     | Coefficient for the width dependence of $B_{GIDL}$              |
| $P_{LW;B_{GIDL}}$ | PLWBGIDL    | V     | Coefficient for the length times width dependence of $B_{GIDL}$ |
| $P_{0;C_{GIDL}}$  | POCGIDL     | -     | Coefficient for the geometry independent part of $C_{GIDL}$     |
| $P_{L;C_{GIDL}}$  | PLCGIDL     | -     | Coefficient for the length dependence of $C_{GIDL}$             |
| $P_{W;C_{GIDL}}$  | PWCGIDL     | -     | Coefficient for the width dependence of $C_{GIDL}$              |
| $P_{LW;C_{GIDL}}$ | PLWCGIDL    | -     | Coefficient for the length times width dependence of $C_{GIDL}$ |
| $t_{ox}$          | TOX         | m     | Thickness of the gate oxide layer                               |
| $P_{0;C_{ox}}$    | POCOX       | F     | Coefficient for the geometry independent part of $C_{ox}$       |
| $P_{L;C_{ox}}$    | PLCOX       | F     | Coefficient for the length dependence of $C_{ox}$               |
| $P_{W;C_{ox}}$    | PWCOX       | F     | Coefficient for the width dependence of $C_{ox}$                |
| $P_{LW;C_{ox}}$   | PLWCOX      | F     | Coefficient for the length times width dependence of $C_{ox}$   |
| $P_{0;C_{GDO}}$   | POCGDO      | F     | Coefficient for the geometry independent part of $C_{GDO}$      |
| $P_{L;C_{GDO}}$   | PLCGDO      | F     | Coefficient for the length dependence of $C_{GDO}$              |
| $P_{W;C_{GDO}}$   | PWCGDO      | F     | Coefficient for the width dependence of $C_{GDO}$               |
| $P_{LW;C_{GDO}}$  | PLWCGDO     | F     | Coefficient for the width over length dependence of $C_{GDO}$   |

| Symbol           | Progr. Name | Units          | Description   |
|------------------|-------------|----------------|---|
| $P_{0;C_{GSO}}$  | POCGSO      | F              | Coefficient for the geometry independent part of $C_{GSO}$    |
| $P_{L;C_{GSO}}$  | PLCGSO      | F              | Coefficient for the length dependence of $C_{GSO}$            |
| $P_{W;C_{GSO}}$  | PWCGSO      | F              | Coefficient for the width dependence of $C_{GSO}$             |
| $P_{LW;C_{GSO}}$ | PLWCGSO     | F              | Coefficient for the width over length dependence of $C_{GSO}$ |
| -                | GATENOISE   |                | Flag for in/exclusion of induced gate thermal noise           |
| $N_T$            | NT          | J              | Coefficient of the thermal noise at the reference temperature |
| $P_{0;N_{FA}}$   | PONFA       | $V^{-1}m^{-4}$ | Coefficient for the geometry independent part of $N_{FA}$     |
| $P_{L;N_{FA}}$   | PLNFA       | $V^{-1}m^{-4}$ | Coefficient for the length dependence of $N_{FA}$             |
| $P_{W;N_{FA}}$   | PWNFA       | $V^{-1}m^{-4}$ | Coefficient for the width dependence of $N_{FA}$              |
| $P_{LW;N_{FA}}$  | PLWNFA      | $V^{-1}m^{-4}$ | Coefficient for the length times width dependence of $N_{FA}$ |
| $P_{0;N_{FB}}$   | PONFB       | $V^{-1}m^{-2}$ | Coefficient for the geometry independent part of $N_{FB}$     |
| $P_{L;N_{FB}}$   | PLNFB       | $V^{-1}m^{-2}$ | Coefficient for the length dependence of $N_{FB}$             |
| $P_{W;N_{FB}}$   | PWNFB       | $V^{-1}m^{-2}$ | Coefficient for the width dependence of $N_{FB}$              |
| $P_{LW;N_{FB}}$  | PLWNFB      | $V^{-1}m^{-2}$ | Coefficient for the length times width dependence of $N_{FB}$ |

| Symbol               | Progr. Name | Units     | Description   |
|----------------------|-------------|-----------|---|
| $P_{0;N_{FC}}$       | PONFC       | $V^{-1}$  | Coefficient for the geometry independent part of $N_{FC}$           |
| $P_{L;N_{FC}}$       | PLNFC       | $V^{-1}$  | Coefficient for the length dependence of $N_{FC}$                   |
| $P_{W;N_{FC}}$       | PWNFC       | $V^{-1}$  | Coefficient for the width dependence of $N_{FC}$                    |
| $P_{LW;N_{FC}}$      | PLWNFC      | $V^{-1}$  | Coefficient for the length times width dependence of $N_{FC}$       |
| $P_{0;T;V_{FB}}$     | POTVFB      | $VK^{-1}$ | Coefficient for the geometry independent part of $S_{T;V_{FB}}$     |
| $P_{L;T;V_{FB}}$     | PLTVFB      | $VK^{-1}$ | Coefficient for the length dependence of $S_{T;V_{FB}}$             |
| $P_{W;T;V_{FB}}$     | PWTVFB      | $VK^{-1}$ | Coefficient for the width dependence of $S_{T;V_{FB}}$              |
| $P_{LW;T;V_{FB}}$    | PLWTVFB     | $VK^{-1}$ | Coefficient for the length times width dependence of $S_{T;V_{FB}}$ |
| $P_{0;T;\phi_B}$     | POTPHIB     | $VK^{-1}$ | Coefficient for the geometry independent part of $S_{T;\phi_B}$     |
| $P_{L;T;\phi_B}$     | PLTPHIB     | $VK^{-1}$ | Coefficient for the length dependence of $S_{T;\phi_B}$             |
| $P_{W;T;\phi_B}$     | PWTPHIB     | $VK^{-1}$ | Coefficient for the width dependence of $S_{T;\phi_B}$              |
| $P_{LW;T;\phi_B}$    | PLWTPHIB    | $VK^{-1}$ | Coefficient for the length times width dependence of $S_{T;\phi_B}$ |
| $P_{0;T;\eta_\beta}$ | POTETABET   | -         | Coefficient for the geometry independent part of $\eta_\beta$       |
| $P_{L;T;\eta_\beta}$ | PLTETABET   | -         | Coefficient for the length dependence of $\eta_\beta$               |

| Symbol                  | Progr. Name | Units    | Description   |
|-------------------------|-------------|----------|---|
| $P_{W;T;\eta_{\beta}}$  | PWTETABET   | -        | Coefficient for the width dependence of $\eta_{\beta}$                  |
| $P_{LW;T;\eta_{\beta}}$ | PLWTETABET  | -        | Coefficient for the length times width dependence of $\eta_{\beta}$     |
| $P_{0;T;\eta_{sr}}$     | POTETASR    | -        | Coefficient for the geometry independent part of $\eta_{sr}$            |
| $P_{L;T;\eta_{sr}}$     | PLTETASR    | -        | Coefficient for the length dependence of $\eta_{sr}$                    |
| $P_{W;T;\eta_{sr}}$     | PWTETASR    | -        | Coefficient for the width dependence of $\eta_{sr}$                     |
| $P_{LW;T;\eta_{sr}}$    | PLWETASR    | -        | Coefficient for the length times width dependence of $\eta_{sr}$        |
| $P_{0;T;\eta_{ph}}$     | POTETAPH    | -        | Coefficient for the geometry independent part of $\eta_{ph}$            |
| $P_{L;T;\eta_{ph}}$     | PLTETAPH    | -        | Coefficient for the length dependence of $\eta_{ph}$                    |
| $P_{W;T;\eta_{ph}}$     | PWTETAPH    | -        | Coefficient for the width dependence of $\eta_{ph}$                     |
| $P_{LW;T;\eta_{ph}}$    | PLWETAPH    | -        | Coefficient for the length times width dependence of $\eta_{ph}$        |
| $P_{0;T;\eta_{mob}}$    | POTETAMOB   | $K^{-1}$ | Coefficient for the geometry independent part of $S_{T;\eta_{mob}}$     |
| $P_{L;T;\eta_{mob}}$    | PLTETAMOB   | $K^{-1}$ | Coefficient for the length dependence of $S_{T;\eta_{mob}}$             |
| $P_{W;T;\eta_{mob}}$    | PWTETAMOB   | $K^{-1}$ | Coefficient for the width dependence of $S_{T;\eta_{mob}}$              |
| $P_{LW;T;\eta_{mob}}$   | PLWTETAMOB  | $K^{-1}$ | Coefficient for the length times width dependence of $S_{T;\eta_{mob}}$ |

| Symbol                | Progr. Name | Units | Description   |
|-----------------------|-------------|-------|---|
| $\nu$                 | NU          | -     | Exponent of the field dependence of the mobility model at the reference temperature |
| $P_{0;T;\nu_{exp}}$   | POTNUEXP    | -     | Coefficient for the geometry independent part of $\nu_{exp}$                        |
| $P_{L;T;\nu_{exp}}$   | PLTNUEXP    | -     | Coefficient for the length dependence of $\nu_{exp}$                                |
| $P_{W;T;\nu_{exp}}$   | PWTNUEXP    | -     | Coefficient for the width dependence of $\nu_{exp}$                                 |
| $P_{LW;T;\nu_{exp}}$  | PLWTNUEXP   | -     | Coefficient for the length times width dependence of $\nu_{exp}$                    |
| $P_{0;T;\eta_{C_s}}$  | POTETACS    | -     | Coefficient for the geometry independent part of $\eta_{C_s}$                       |
| $P_{L;T;\eta_{C_s}}$  | PLTETACS    | -     | Coefficient for the length dependence of $\eta_{C_s}$                               |
| $P_{W;T;\eta_{C_s}}$  | PWTETACS    | -     | Coefficient for the width dependence of $\eta_{C_s}$                                |
| $P_{LW;T;\eta_{C_s}}$ | PLWTETACS   | -     | Coefficient for the length times width dependence of $\eta_{C_s}$                   |
| $P_{0;T;\eta_R}$      | POTETAR     | -     | Coefficient for the geometry independent part of $\eta_R$                           |
| $P_{L;T;\eta_R}$      | PLTETAR     | -     | Coefficient for the length dependence of $\eta_R$                                   |
| $P_{W;T;\eta_R}$      | PWTETAR     | -     | Coefficient for the width dependence of $\eta_R$                                    |
| $P_{LW;T;\eta_R}$     | PLWTETAR    | -     | Coefficient for the length times width dependence of $\eta_R$                       |
| $P_{0;T;\eta_{sat}}$  | POTETASAT   | -     | Coefficient for the geometry independent part of $\eta_{sat}$                       |

| Symbol                | Progr. Name | Units            | Description   |
|-----------------------|-------------|------------------|---|
| $P_{L;T;\eta_{sat}}$  | PLTETASAT   | -                | Coefficient for the length dependence of $\eta_{sat}$                 |
| $P_{W;T;\eta_{sat}}$  | PWTETASAT   | -                | Coefficient for the width dependence of $\eta_{sat}$                  |
| $P_{LW;T;\eta_{sat}}$ | PLWTETASAT  | -                | Coefficient for the length times width dependence of $\eta_{sat}$     |
| $P_{0;T;a_1}$         | POTA1       | K <sup>-1</sup>  | Coefficient for the geometry independent part of $S_{T;a_1}$          |
| $P_{L;T;a_1}$         | PLTA1       | K <sup>-1</sup>  | Coefficient for the length dependence of $S_{T;a_1}$                  |
| $P_{W;T;a_1}$         | PWTA1       | K <sup>-1</sup>  | Coefficient for the width dependence of $S_{T;a_1}$                   |
| $P_{LW;T;a_1}$        | PLWTA1      | K <sup>-1</sup>  | Coefficient for the length times width dependence of $S_{T;a_1}$      |
| $P_{0;T;B_{GIDL}}$    | POTBGIDL    | VK <sup>-1</sup> | Coefficient for the geometry independent part of $S_{T;B_{GIDL}}$     |
| $P_{L;T;B_{GIDL}}$    | PLTBGIDL    | VK <sup>-1</sup> | Coefficient for the length dependence of $S_{T;B_{GIDL}}$             |
| $P_{W;T;B_{GIDL}}$    | PWTBGIDL    | VK <sup>-1</sup> | Coefficient for the width dependence of $S_{T;B_{GIDL}}$              |
| $P_{LW;T;B_{GIDL}}$   | PLWTBGIDL   | VK <sup>-1</sup> | Coefficient for the length times width dependence of $S_{T;B_{GIDL}}$ |
| $\Delta T_A$          | DTA         | K                | Temperature offset of the device with respect to $T_A$                |
| $l_{min}$             | LMIN        | m                | Minimum length of the bin   |
| $l_{max}$             | LMAX        | m                | Maximum length of the bin   |
| $w_{min}$             | WMIN        | m                | Minimum width of the bin  |
| $w_{max}$             | WMAX        | m                | Maximum width of the bin  |

| <b>Symbol</b> | <b>Progr. Name</b> | <b>Units</b>         | <b>Description</b>                               |
|---------------|--------------------|----------------------|--|
| <i>RG0</i>    | RGO                | $\Omega$             | Gate Resistance                                  |
| <i>RINT</i>   | RINT               | $\Omega \text{ m}^2$ | Contact resistance between silicide and poly     |
| <i>RVPOLY</i> | RVPOLY             | $\Omega \text{ m}^2$ | Vertical poly resistance                         |
| <i>RSHG</i>   | RSHG               | $\Omega/\square$     | Gate electrode diffusion sheet resistance        |
| <i>DLSIL</i>  | DLSIL              | m                    | Silicide extension over the physical gate length |

The additional parameters for the model including self-heating (see section 15.6 on page 156) are listed in the table below.

| <b>Symbol</b> | <b>Progr. Name</b> | <b>Units</b>                | <b>Description</b>                                |
|---------------|--------------------|-----------------------------|---|
| $R_{TH}$      | RTH                | $^{\circ}\text{C}/\text{W}$ | Thermal resistance                                |
| $C_{TH}$      | CTH                | $\text{J}/^{\circ}\text{C}$ | Thermal capacitance                               |
| $A_{TH}$      | ATH                | -                           | Temperature coefficient of the thermal resistance |

The instance parameters are listed in the table below.

| <b>Symbol</b> | <b>Progr. Name</b> | <b>Units</b> | <b>Description</b>   |
|---------------|--------------------|--------------|--|
| <i>L</i>      | L                  | m            | Drawn channel length in the lay-out of the actual transistor |
| <i>W</i>      | W                  | m            | Drawn channel width in the lay-out of the actual transistor  |
| <i>NMULT</i>  | MULT               | -            | Number of devices in parallel                                |
| <i>NF</i>     | NF                 | -            | Number of fingers  |
| <i>NGCON</i>  | NGCON              | -            | Number of gate contacts                                      |
| <i>XGW</i>    | XGW                | m            | Distance from the gate contact to the channel edge           |
| -             | PRINTSCALED        | -            | Flag to add scaled parameters to the OP output               |

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

### Default and clipping values (binning geometrical model)

The default values and clipping values for the parameters of the binning geometrical scaling rules of MOS model, level 1102 (n-channel) are listed below.

| <b>Parameter</b> | <b>Units</b> | <b>Default</b>         | <b>Clip low</b> | <b>Clip high</b> |
|------------------|--------------|------------------------|-----------------|------------------|
| <i>LEVEL</i>     | -            | 11021                  | -               | -                |
| <i>PARAMCHK</i>  | -            | 0                      | -               | -                |
| <i>LVAR</i>      | m            | 0.000                  | -               | -                |
| <i>LAP</i>       | m            | $4.0 \times 10^{-8}$   | -               | -                |
| <i>WVAR</i>      | m            | 0.000                  | -               | -                |
| <i>WOT</i>       | m            | 0.000                  | -               | -                |
| <i>TR</i>        | °C           | 21.0                   | -273.0          | -                |
| <i>VFB</i>       | V            | -1.050                 | -               | -                |
| <i>POKO</i>      | $V^{1/2}$    | 0.500                  | -               | -                |
| <i>PLKO</i>      | $V^{1/2}$    | 0.000                  | -               | -                |
| <i>PWKO</i>      | $V^{1/2}$    | 0.000                  | -               | -                |
| <i>PLWKO</i>     | $V^{1/2}$    | 0.000                  | -               | -                |
| <i>KPINV</i>     | $V^{-1/2}$   | 0.000                  | -               | -                |
| <i>POPHIB</i>    | V            | 0.950                  | -               | -                |
| <i>PLPHIB</i>    | V            | 0.000                  | -               | -                |
| <i>PWPHIB</i>    | v            | 0.000                  | -               | -                |
| <i>PLWPHIB</i>   | V            | 0.000                  | -               | -                |
| <i>POBET</i>     | $AV^{-2}$    | $1.922 \times 10^{-3}$ | -               | -                |
| <i>PLBET</i>     | $AV^{-2}$    | 0.000                  | -               | -                |
| <i>PWBET</i>     | $AV^{-2}$    | 0.000                  | -               | -                |
| <i>PLWBET</i>    | $AV^{-2}$    | 0.000                  | -               | -                |
| <i>POTHSR</i>    | $V^{-1}$     | $3.562 \times 10^{-1}$ | -               | -                |

| <b>Parameter</b> | <b>Units</b>    | <b>Default</b>           | <b>Clip low</b> | <b>Clip high</b> |
|------------------|-----------------|--------------------------|-----------------|------------------|
| <i>PLTHESR</i>   | V <sup>-1</sup> | 0.000                    | -               | -                |
| <i>PWTHESR</i>   | V <sup>-1</sup> | 0.000                    | -               | -                |
| <i>PLWTHESR</i>  | V <sup>-1</sup> | 0.000                    | -               | -                |
| <i>POTHEPH</i>   | V <sup>-1</sup> | 1.290 × 10 <sup>-2</sup> | -               | -                |
| <i>PLTHEPH</i>   | V <sup>-1</sup> | 0.000                    | -               | -                |
| <i>PWTHEPH</i>   | V <sup>-1</sup> | 0.000                    | -               | -                |
| <i>PLWTHEPH</i>  | V <sup>-1</sup> | 0.000                    | -               | -                |
| <i>POETAMOB</i>  | -               | 1.400                    | -               | -                |
| <i>PLETAMOB</i>  | -               | 0.000                    | -               | -                |
| <i>PWETAMOB</i>  | -               | 0.000                    | -               | -                |
| <i>PLWETAMOB</i> | -               | 0.000                    | -               | -                |
| <i>POCS</i>      | -               | 0.00                     | -               | -                |
| <i>PLCS</i>      | -               | 0.000                    | -               | -                |
| <i>PWCS</i>      | -               | 0.000                    | -               | -                |
| <i>PLWCS</i>     | -               | 0.000                    | -               | -                |
| <i>POTHER</i>    | V <sup>-1</sup> | 8.120 × 10 <sup>-2</sup> | -               | -                |
| <i>PLTHER</i>    | V <sup>-1</sup> | 0.000                    | -               | -                |
| <i>PWTHER</i>    | V <sup>-1</sup> | 0.000                    | -               | -                |
| <i>PLWTHER</i>   | V <sup>-1</sup> | 0.000                    | -               | -                |
| <i>THER1</i>     | v               | 0.000                    | -               | -                |
| <i>THER2</i>     | V               | 1.000                    | -               | -                |
| <i>POTHSAT</i>   | V <sup>-1</sup> | 2.513 × 10 <sup>-1</sup> | -               | -                |
| <i>PLTHESAT</i>  | V <sup>-1</sup> | 0.000                    | -               | -                |
| <i>PWTHESAT</i>  | V <sup>-1</sup> | 0.000                    | -               | -                |
| <i>PLWTHESAT</i> | V <sup>-1</sup> | 0.000                    | -               | -                |

| <b>Parameter</b> | <b>Units</b>      | <b>Default</b>           | <b>Clip low</b> | <b>Clip high</b> |
|------------------|-------------------|--------------------------|-----------------|------------------|
| <i>POTHETH</i>   | V <sup>-3</sup>   | 1.0 × 10 <sup>-5</sup>   | -               | -                |
| <i>PLTHETH</i>   | V <sup>-3</sup>   | 0.000                    | -               | -                |
| <i>PWTHETH</i>   | V <sup>-3</sup>   | 0.000                    | -               | -                |
| <i>PLWTHETH</i>  | V <sup>-3</sup>   | 0.000                    | -               | -                |
| <i>POSDIBL</i>   | V <sup>-1/2</sup> | 8.530 × 10 <sup>-4</sup> | -               | -                |
| <i>PLSDIBL</i>   | V <sup>-1/2</sup> | 0.000                    | -               | -                |
| <i>PWSDIBL</i>   | V <sup>-1/2</sup> | 0.000                    | -               | -                |
| <i>PLWSDIBL</i>  | V <sup>-1/2</sup> | 0.000                    | -               | -                |
| <i>POMO</i>      | -                 | 0.000                    | -               | -                |
| <i>PLMO</i>      | -                 | 0.000                    | -               | -                |
| <i>PWMO</i>      | -                 | 0.000                    | -               | -                |
| <i>PLWMO</i>     | -                 | 0.000                    | -               | -                |
| <i>POSSF</i>     | V <sup>-1/2</sup> | 1.200 × 10 <sup>-2</sup> | -               | -                |
| <i>PLSSF</i>     | V <sup>-1/2</sup> | 0.000                    | -               | -                |
| <i>PWSSF</i>     | V <sup>-1/2</sup> | 0.000                    | -               | -                |
| <i>PLWSSF</i>    | V <sup>-1/2</sup> | 0.000                    | -               | -                |
| <i>POALP</i>     | -                 | 2.500 × 10 <sup>-2</sup> | -               | -                |
| <i>PLALP</i>     | -                 | 0.000                    | -               | -                |
| <i>PWALP</i>     | -                 | 0.000                    | -               | -                |
| <i>PLWALP</i>    | -                 | 0.000                    | -               | -                |
| <i>VP</i>        | V                 | 5.000 × 10 <sup>-2</sup> | -               | -                |
| <i>POMEXP</i>    | -                 | 0.200                    | -               | -                |
| <i>PLMEXP</i>    | -                 | 0.000                    | -               | -                |
| <i>PWMEXP</i>    | -                 | 0.000                    | -               | -                |
| <i>PLWMEXP</i>   | -                 | 0.000                    | -               | -                |

| <b>Parameter</b> | <b>Units</b> | <b>Default</b>         | <b>Clip low</b> | <b>Clip high</b> |
|------------------|--------------|------------------------|-----------------|------------------|
| <i>POA1</i>      | -            | 6.022                  | -               | -                |
| <i>PLA1</i>      | -            | 0.000                  | -               | -                |
| <i>PWA1</i>      | -            | 0.000                  | -               | -                |
| <i>PLWA1</i>     | -            | 0.000                  | -               | -                |
| <i>POA2</i>      | V            | $3.802 \times 10^1$    | -               | -                |
| <i>PLA2</i>      | V            | 0.000                  | -               | -                |
| <i>PWA2</i>      | V            | 0.000                  | -               | -                |
| <i>PLWA2</i>     | V            | 0.000                  | -               | -                |
| <i>POA3</i>      | -            | $6.407 \times 10^{-1}$ | -               | -                |
| <i>PLA3</i>      | -            | 0.000                  | -               | -                |
| <i>PWA3</i>      | -            | 0.000                  | -               | -                |
| <i>PLWA3</i>     | -            | 0.000                  | -               | -                |
| <i>POIGINV</i>   | $AV^{-2}$    | 0.000                  | -               | -                |
| <i>PLIGINV</i>   | $AV^{-2}$    | 0.000                  | -               | -                |
| <i>PWIGINV</i>   | $AV^{-2}$    | 0.000                  | -               | -                |
| <i>PLWIGINV</i>  | $AV^{-2}$    | 0.000                  | -               | -                |
| <i>POBINV</i>    | V            | $4.800 \times 10^1$    | -               | -                |
| <i>PLBINV</i>    | V            | 0.000                  | -               | -                |
| <i>PWBINV</i>    | V            | 0.000                  | -               | -                |
| <i>PLWBINV</i>   | V            | 0.000                  | -               | -                |
| <i>POIGACC</i>   | $AV^{-2}$    | 0.000                  | -               | -                |
| <i>PLIGACC</i>   | $AV^{-2}$    | 0.000                  | -               | -                |
| <i>PWIGACC</i>   | $AV^{-2}$    | 0.000                  | -               | -                |
| <i>PLWIGACC</i>  | $AV^{-2}$    | 0.000                  | -               | -                |
| <i>POBACC</i>    | V            | $4.800 \times 10^1$    | -               | -                |

| <b>Parameter</b> | <b>Units</b>     | <b>Default</b>            | <b>Clip low</b>         | <b>Clip high</b> |
|------------------|------------------|---------------------------|-------------------------|------------------|
| <i>PLBACC</i>    | V                | 0.000                     | -                       | -                |
| <i>PWBACC</i>    | V                | 0.000                     | -                       | -                |
| <i>PLWBACC</i>   | V                | 0.000                     | -                       | -                |
| <i>VFBOV</i>     | V                | 0.000                     | -                       | -                |
| <i>KOV</i>       | V <sup>1/2</sup> | 2.500                     | 1.0 × 10 <sup>-12</sup> | -                |
| <i>POIGOV</i>    | AV <sup>-2</sup> | 0.000                     | -                       | -                |
| <i>PLIGOV</i>    | AV <sup>-2</sup> | 0.000                     | -                       | -                |
| <i>PWIGOV</i>    | AV <sup>-2</sup> | 0.000                     | -                       | -                |
| <i>PLWIGOV</i>   | AV <sup>-2</sup> | 0.000                     | -                       | -                |
| <i>POAGIDL</i>   | AV <sup>-3</sup> | 0.000                     | -                       | -                |
| <i>PLAGIDL</i>   | AV <sup>-3</sup> | 0.000                     | -                       | -                |
| <i>PWAGIDL</i>   | AV <sup>-3</sup> | 0.000                     | -                       | -                |
| <i>PLWAGIDL</i>  | AV <sup>-3</sup> | 0.000                     | -                       | -                |
| <i>POBGIDL</i>   | V                | 4.100 × 10 <sup>+1</sup>  | -                       | -                |
| <i>PLBGIDL</i>   | V                | 0.000                     | -                       | -                |
| <i>PWBGIDL</i>   | V                | 0.000                     | -                       | -                |
| <i>PLWBGIDL</i>  | V                | 0.000                     | -                       | -                |
| <i>POCGIDL</i>   | -                | 0.000                     | -                       | -                |
| <i>PLCGIDL</i>   | -                | 0.000                     | -                       | -                |
| <i>PWCGIDL</i>   | -                | 0.000                     | -                       | -                |
| <i>PLWCCGIDL</i> | -                | 0.000                     | -                       | -                |
| <i>TOX</i>       | m                | 3.200 × 10 <sup>-9</sup>  | 1.0 × 10 <sup>-12</sup> | -                |
| <i>POCOX</i>     | F                | 2.980 × 10 <sup>-14</sup> | -                       | -                |
| <i>PLCOX</i>     | F                | 0.000                     | -                       | -                |
| <i>PWCOX</i>     | F                | 0.000                     | -                       | -                |

| <b>Parameter</b> | <b>Units</b>   | <b>Default</b>          | <b>Clip low</b> | <b>Clip high</b> |
|------------------|----------------|-------------------------|-----------------|------------------|
| <i>PLWCOX</i>    | F              | 0.000                   | -               | -                |
| <i>POCGDO</i>    | F              | $6.392 \times 10^{-15}$ | -               | -                |
| <i>PLCGDO</i>    | F              | 0.000                   | -               | -                |
| <i>PWCGDO</i>    | F              | 0.000                   | -               | -                |
| <i>PLWCGDO</i>   | F              | 0.000                   | -               | -                |
| <i>POCGSO</i>    | F              | $6.392 \times 10^{-15}$ | -               | -                |
| <i>PLCGSO</i>    | F              | 0.000                   | -               | -                |
| <i>PWCGSO</i>    | F              | 0.000                   | -               | -                |
| <i>PLWCGSO</i>   | F              | 0.000                   | -               | -                |
| <i>GATENOISE</i> | -              | 0.000                   | 0.000           | 1.000            |
| <i>NT</i>        | J              | $1.624 \times 10^{-20}$ | 0.000           | -                |
| <i>PONFA</i>     | $V^{-1}m^{-4}$ | $8.323 \times 10^{22}$  | -               | -                |
| <i>PLNFA</i>     | $V^{-1}m^{-4}$ | 0.000                   | -               | -                |
| <i>PWNFA</i>     | $V^{-1}m^{-4}$ | 0.000                   | -               | -                |
| <i>PLWNFA</i>    | $V^{-1}m^{-4}$ | 0.000                   | -               | -                |
| <i>PONFB</i>     | $V^{-1}m^{-2}$ | $2.514 \times 10^7$     | -               | -                |
| <i>PLNFB</i>     | $V^{-1}m^{-2}$ | 0.000                   | -               | -                |
| <i>PWNFB</i>     | $V^{-1}m^{-2}$ | 0.000                   | -               | -                |
| <i>PLWNFB</i>    | $V^{-1}m^{-2}$ | 0.000                   | -               | -                |
| <i>PONFC</i>     | $V^{-1}$       | 0.000                   | -               | -                |
| <i>PLNFC</i>     | $V^{-1}$       | 0.000                   | -               | -                |
| <i>PWNFC</i>     | $V^{-1}$       | 0.000                   | -               | -                |
| <i>PLWNFC</i>    | $V^{-1}$       | 0.000                   | -               | -                |
| <i>POTVFB</i>    | $VK^{-1}$      | $5.000 \times 10^{-4}$  | -               | -                |

| <b>Parameter</b>  | <b>Units</b>     | <b>Default</b>            | <b>Clip low</b> | <b>Clip high</b> |
|-------------------|------------------|---------------------------|-----------------|------------------|
| <i>PLTVFB</i>     | VK <sup>-1</sup> | 0.000                     | -               | -                |
| <i>PWTVFB</i>     | VK <sup>-1</sup> | 0.000                     | -               | -                |
| <i>PLWTVFB</i>    | VK <sup>-1</sup> | 0.000                     | -               | -                |
| <i>POTPHIB</i>    | VK <sup>-1</sup> | -8.500 × 10 <sup>-4</sup> | -               | -                |
| <i>PLTPHIB</i>    | VK <sup>-1</sup> | 0.000                     | -               | -                |
| <i>PWTPHIB</i>    | VK <sup>-1</sup> | 0.000                     | -               | -                |
| <i>PLWTPHIB</i>   | VK <sup>-1</sup> | 0.000                     | -               | -                |
| <i>POTETABET</i>  | -                | 1.300                     | -               | -                |
| <i>PLTETABET</i>  | -                | 0.000                     | -               | -                |
| <i>PWTETABET</i>  | -                | 0.000                     | -               | -                |
| <i>PLWTETABET</i> | -                | 0.000                     | -               | -                |
| <i>POTETASR</i>   | -                | 0.650                     | -               | -                |
| <i>PLTETASR</i>   | -                | 0.000                     | -               | -                |
| <i>PWTETASR</i>   | -                | 0.000                     | -               | -                |
| <i>PLWETASR</i>   | -                | 0.000                     | -               | -                |
| <i>POTETAPH</i>   | -                | 1.350                     | -               | -                |
| <i>PLTETAPH</i>   | -                | 0.000                     | -               | -                |
| <i>PWTETAPH</i>   | -                | 0.000                     | -               | -                |
| <i>PLWETAPH</i>   | -                | 0.000                     | -               | -                |
| <i>POTETAMOB</i>  | K <sup>-1</sup>  | 0.000                     | -               | -                |
| <i>PLTETAMOB</i>  | K <sup>-1</sup>  | 0.000                     | -               | -                |
| <i>PWTETAMOB</i>  | K <sup>-1</sup>  | 0.000                     | -               | -                |
| <i>PLWTETAMOB</i> | K <sup>-1</sup>  | 0.000                     | -               | -                |
| <i>NU</i>         | -                | 2.000                     | 1.000           | 100              |
| <i>POTNUEXP</i>   | -                | 5.250                     | -               | -                |

| <b>Parameter</b>  | <b>Units</b>     | <b>Default</b>          | <b>Clip low</b> | <b>Clip high</b> |
|-------------------|------------------|-------------------------|-----------------|------------------|
| <i>PLTNUEXP</i>   | -                | 0.000                   | -               | -                |
| <i>PWTNUEXP</i>   | -                | 0.000                   | -               | -                |
| <i>PLWTNUEXP</i>  | -                | 0.000                   | -               | -                |
| <i>POTETACS</i>   | -                | 0.000                   | -               | -                |
| <i>PLTETACS</i>   | -                | 0.000                   | -               | -                |
| <i>PWTETACS</i>   | -                | 0.000                   | -               | -                |
| <i>PLWTETACS</i>  | -                | 0.000                   | -               | -                |
| <i>POTETAR</i>    | -                | 0.950                   | -               | -                |
| <i>PLTETAR</i>    | -                | 0.000                   | -               | -                |
| <i>PWTETAR</i>    | -                | 0.000                   | -               | -                |
| <i>PLWTETAR</i>   | -                | 0.000                   | -               | -                |
| <i>POTETASAT</i>  | -                | 1.040                   | -               | -                |
| <i>PLTETASAT</i>  | -                | 0.000                   | -               | -                |
| <i>PWTETASAT</i>  | -                | 0.000                   | -               | -                |
| <i>PLWTETASAT</i> | -                | 0.000                   | -               | -                |
| <i>POTAI</i>      | K <sup>-1</sup>  | 0.000                   | -               | -                |
| <i>PLTAI</i>      | K <sup>-1</sup>  | 0.000                   | -               | -                |
| <i>PWTAI</i>      | K <sup>-1</sup>  | 0.000                   | -               | -                |
| <i>PLWTAI</i>     | K <sup>-1</sup>  | 0.000                   | -               | -                |
| <i>POTBGIDL</i>   | VK <sup>-1</sup> | -3.638x10 <sup>-4</sup> | -               | -                |
| <i>PLTBGIDL</i>   | VK <sup>-1</sup> | 0.000                   | -               | -                |
| <i>PWTBGIDL</i>   | VK <sup>-1</sup> | 0.000                   | -               | -                |
| <i>PLWTBGIDL</i>  | VK <sup>-1</sup> | 0.000                   | -               | -                |
| <i>DTA</i>        | K                | 0.000                   | -               | -                |
| <i>LMIN</i>       | m                | 0.000                   | -               | -                |
| <i>LMAX</i>       | m                | 1.000                   | -               | -                |

| <b>Parameter</b> | <b>Units</b>         | <b>Default</b> | <b>Clip low</b> | <b>Clip high</b> |
|------------------|----------------------|----------------|-----------------|------------------|
| <i>WMIN</i>      | m                    | 0.000          | -               | -                |
| <i>WMAX</i>      | m                    | 1.000          | -               | -                |
| <i>RGO</i>       | $\Omega$             | 0.0            | -               | -                |
| <i>RINT</i>      | $\Omega \text{ m}^2$ | 0.0            | 0.0             | -                |
| <i>RVPOLY</i>    | $\Omega \text{ m}^2$ | 0.0            | 0.0             | -                |
| <i>RSHG</i>      | $\Omega/\square$     | 0.0            | 0.0             | -                |
| <i>DLSIL</i>     | m                    | 0.0            | -               | -                |

The additional values and clipping values of the additional parameters for the (**n-channel**) model including self-heating (see section 15.6 on page 156) are listed in the table below.

| <b>Parameter</b> | <b>Units</b>                | <b>Default</b>       | <b>Clip low</b> | <b>Clip high</b> |
|------------------|-----------------------------|----------------------|-----------------|------------------|
| <i>RTH</i>       | $^{\circ}\text{C}/\text{W}$ | 300.0                | 0.000           | -                |
| <i>CTH</i>       | $\text{J}/^{\circ}\text{C}$ | $3.0 \times 10^{-9}$ | 0.000           | -                |
| <i>ATH</i>       | -                           | 0.0                  | -               | -                |

The instance parameters are listed in the table below.

| <b>Parameter</b>    | <b>Units</b> | <b>Default</b>         | <b>Clip low</b> | <b>Clip high</b> |
|---------------------|--------------|------------------------|-----------------|------------------|
| <i>L</i>            | m            | $2.000 \times 10^{-6}$ | -               | -                |
| <i>W</i>            | m            | $1.000 \times 10^{-5}$ | -               | -                |
| <i>MULT</i>         | -            | 1.000                  | 0.000           | -                |
| <i>NF</i>           | -            | 1.0                    | 1.0             | -                |
| <i>NGCON</i>        | -            | 1.0                    | 1.0             | 2.0              |
| <i>XGW</i>          | m            | $1.0 \times 10^{-7}$   | -               | -                |
| <i>PRINT-SCALED</i> | -            | 0                      | -               | -                |

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

The default values and clipping values for the parameters of the binning geometrical scaling rules of MOS model, level 1102 (p-channel) are listed below.

| <b>Parameter</b> | <b>Units</b> | <b>Default</b>         | <b>Clip low</b> | <b>Clip high</b> |
|------------------|--------------|------------------------|-----------------|------------------|
| <i>LEVEL</i>     | -            | 11021                  | -               | -                |
| <i>PARAMCHK</i>  | -            | 0                      | -               | -                |
| <i>LVAR</i>      | m            | 0.000                  | -               | -                |
| <i>LAP</i>       | m            | $4.0 \times 10^{-8}$   | -               | -                |
| <i>WVAR</i>      | m            | 0.000                  | -               | -                |
| <i>WOT</i>       | m            | 0.000                  | -               | -                |
| <i>TR</i>        | °C           | 21.0                   | -273.0          | -                |
| <i>VFB</i>       | V            | -1.050                 | -               | -                |
| <i>POKO</i>      | $V^{1/2}$    | 0.500                  | -               | -                |
| <i>PLKO</i>      | $V^{1/2}$    | 0.000                  | -               | -                |
| <i>PWKO</i>      | $V^{1/2}$    | 0.000                  | -               | -                |
| <i>PLWKO</i>     | $V^{1/2}$    | 0.000                  | -               | -                |
| <i>KPINV</i>     | $V^{-1/2}$   | 0.000                  | -               | -                |
| <i>POPHIB</i>    | V            | 0.950                  | -               | -                |
| <i>PLPHIB</i>    | V            | 0.000                  | -               | -                |
| <i>PWPHIB</i>    | V            | 0.000                  | -               | -                |
| <i>PLWPHIB</i>   | V            | 0.000                  | -               | -                |
| <i>POBET</i>     | $AV^{-2}$    | $3.814 \times 10^{-4}$ | -               | -                |
| <i>PLBET</i>     | $AV^{-2}$    | 0.000                  | -               | -                |
| <i>PWBET</i>     | $AV^{-2}$    | 0.000                  | -               | -                |
| <i>PLWBET</i>    | $AV^{-2}$    | 0.000                  | -               | -                |
| <i>POTHSR</i>    | $V^{-1}$     | $7.300 \times 10^{-1}$ | -               | -                |
| <i>PLTHSR</i>    | $V^{-1}$     | 0.000                  | -               | -                |

| <b>Parameter</b>  | <b>Units</b>    | <b>Default</b>           | <b>Clip low</b> | <b>Clip high</b> |
|-------------------|-----------------|--------------------------|-----------------|------------------|
| <i>PWTHESR</i>    | V <sup>-1</sup> | 0.000                    | -               | -                |
| <i>PLWTHESR</i>   | V <sup>-1</sup> | 0.000                    | -               | -                |
| <i>POTHEPH</i>    | V <sup>-1</sup> | 1.000 × 10 <sup>-3</sup> | -               | -                |
| <i>PLTHEPH</i>    | V <sup>-1</sup> | 0.000                    | -               | -                |
| <i>PWTHEPH</i>    | V <sup>-1</sup> | 0.000                    | -               | -                |
| <i>PLWTHEPH</i>   | V <sup>-1</sup> | 0.000                    | -               | -                |
| <i>POETAMOB</i>   | -               | 3.000                    | -               | -                |
| <i>PLETAMOB</i>   | -               | 0.000                    | -               | -                |
| <i>PWETAMOB</i>   | -               | 0.000                    | -               | -                |
| <i>PLWETAMOB</i>  | -               | 0.000                    | -               | -                |
| <i>POCS</i>       | -               | 0.00                     | -               | -                |
| <i>PLCS</i>       | -               | 0.000                    | -               | -                |
| <i>PWCS</i>       | -               | 0.000                    | -               | -                |
| <i>PLWCS</i>      | -               | 0.000                    | -               | -                |
| <i>POTHER</i>     | V <sup>-1</sup> | 7.900 × 10 <sup>-2</sup> | -               | -                |
| <i>PLTHER</i>     | V <sup>-1</sup> | 0.000                    | -               | -                |
| <i>PWTHER</i>     | V <sup>-1</sup> | 0.000                    | -               | -                |
| <i>PLWTHER</i>    | V <sup>-1</sup> | 0.000                    | -               | -                |
| <i>THER1</i>      | v               | 0.000                    | -               | -                |
| <i>THER2</i>      | V               | 1.000                    | -               | -                |
| <i>POTHE SAT</i>  | V <sup>-1</sup> | 1.728 × 10 <sup>-1</sup> | -               | -                |
| <i>PLTHE SAT</i>  | V <sup>-1</sup> | 0.000                    | -               | -                |
| <i>PWTHE SAT</i>  | V <sup>-1</sup> | 0.000                    | -               | -                |
| <i>PLWTHE SAT</i> | V <sup>-1</sup> | 0.000                    | -               | -                |
| <i>POTHE TH</i>   | V <sup>-3</sup> | 0.000                    | -               | -                |

| <b>Parameter</b> | <b>Units</b>      | <b>Default</b>         | <b>Clip low</b> | <b>Clip high</b> |
|------------------|-------------------|------------------------|-----------------|------------------|
| <i>PLTHETH</i>   | V <sup>-3</sup>   | 0.000                  | -               | -                |
| <i>PWTHETH</i>   | V <sup>-3</sup>   | 0.000                  | -               | -                |
| <i>PLWTHETH</i>  | V <sup>-3</sup>   | 0.000                  | -               | -                |
| <i>POSDIBL</i>   | V <sup>-1/2</sup> | $3.551 \times 10^{-5}$ | -               | -                |
| <i>PLSDIBL</i>   | V <sup>-1/2</sup> | 0.000                  | -               | -                |
| <i>PWSDIBL</i>   | V <sup>-1/2</sup> | 0.000                  | -               | -                |
| <i>PLWSDIBL</i>  | V <sup>-1/2</sup> | 0.000                  | -               | -                |
| <i>POMO</i>      | -                 | 0.000                  | -               | -                |
| <i>PLMO</i>      | -                 | 0.000                  | -               | -                |
| <i>PWMO</i>      | -                 | 0.000                  | -               | -                |
| <i>PLWMO</i>     | -                 | 0.000                  | -               | -                |
| <i>POSSF</i>     | V <sup>-1/2</sup> | $1.000 \times 10^{-2}$ | -               | -                |
| <i>PLSSF</i>     | V <sup>-1/2</sup> | 0.000                  | -               | -                |
| <i>PWSSF</i>     | V <sup>-1/2</sup> | 0.000                  | -               | -                |
| <i>PLWSSF</i>    | V <sup>-1/2</sup> | 0.000                  | -               | -                |
| <i>POALP</i>     | -                 | $2.500 \times 10^{-2}$ | -               | -                |
| <i>PLALP</i>     | -                 | 0.000                  | -               | -                |
| <i>PWALP</i>     | -                 | 0.000                  | -               | -                |
| <i>PLWALP</i>    | -                 | 0.000                  | -               | -                |
| <i>VP</i>        | V                 | $5.000 \times 10^{-2}$ | -               | -                |
| <i>POMEXP</i>    | -                 | 0.200                  | -               | -                |
| <i>PLMEXP</i>    | -                 | 0.000                  | -               | -                |
| <i>PWMEXP</i>    | -                 | 0.000                  | -               | -                |
| <i>PLWMEXP</i>   | -                 | 0.000                  | -               | -                |
| <i>POA1</i>      | -                 | 6.858                  | -               | -                |

| <b>Parameter</b> | <b>Units</b>     | <b>Default</b>         | <b>Clip low</b> | <b>Clip high</b> |
|------------------|------------------|------------------------|-----------------|------------------|
| <i>PLA1</i>      | -                | 0.000                  | -               | -                |
| <i>PWA1</i>      | -                | 0.000                  | -               | -                |
| <i>PLWA1</i>     | -                | 0.000                  | -               | -                |
| <i>POA2</i>      | V                | $5.732 \times 10^1$    | -               | -                |
| <i>PLA2</i>      | V                | 0.000                  | -               | -                |
| <i>PWA2</i>      | V                | 0.000                  | -               | -                |
| <i>PLWA2</i>     | V                | 0.000                  | -               | -                |
| <i>POA3</i>      | -                | $4.254 \times 10^{-1}$ | -               | -                |
| <i>PLA3</i>      | -                | 0.000                  | -               | -                |
| <i>PWA3</i>      | -                | 0.000                  | -               | -                |
| <i>PLWA3</i>     | -                | 0.000                  | -               | -                |
| <i>POIGINV</i>   | AV <sup>-2</sup> | 0.000                  | -               | -                |
| <i>PLIGINV</i>   | AV <sup>-2</sup> | 0.000                  | -               | -                |
| <i>PWIGINV</i>   | AV <sup>-2</sup> | 0.000                  | -               | -                |
| <i>PLWIGINV</i>  | AV <sup>-2</sup> | 0.000                  | -               | -                |
| <i>POBINV</i>    | V                | 87.50                  | -               | -                |
| <i>PLBINV</i>    | V                | 0.000                  | -               | -                |
| <i>PWBINV</i>    | V                | 0.000                  | -               | -                |
| <i>PLWBINV</i>   | V                | 0.000                  | -               | -                |
| <i>POIGACC</i>   | AV <sup>-2</sup> | 0.000                  | -               | -                |
| <i>PLIGACC</i>   | AV <sup>-2</sup> | 0.000                  | -               | -                |
| <i>PWIGACC</i>   | AV <sup>-2</sup> | 0.000                  | -               | -                |
| <i>PLWIGACC</i>  | AV <sup>-2</sup> | 0.000                  | -               | -                |
| <i>POBACC</i>    | V                | 48.00                  | -               | -                |
| <i>PLBACC</i>    | V                | 0.000                  | -               | -                |

| <b>Parameter</b> | <b>Units</b>     | <b>Default</b>           | <b>Clip low</b> | <b>Clip high</b> |
|------------------|------------------|--------------------------|-----------------|------------------|
| <i>PWBACC</i>    | V                | 0.000                    | -               | -                |
| <i>PLWBACC</i>   | V                | 0.000                    | -               | -                |
| <i>VFBOV</i>     | V                | 0.000                    | -               | -                |
| <i>KOV</i>       | V <sup>1/2</sup> | 2.500                    | 1e-12           | -                |
| <i>POIGOV</i>    | AV <sup>-2</sup> | 0.000                    | -               | -                |
| <i>PLIGOV</i>    | AV <sup>-2</sup> | 0.000                    | -               | -                |
| <i>PWIGOV</i>    | AV <sup>-2</sup> | 0.000                    | -               | -                |
| <i>PLWIGOV</i>   | AV <sup>-2</sup> | 0.000                    | -               | -                |
| <i>POAGIDL</i>   | AV <sup>-3</sup> | 0.000                    | -               | -                |
| <i>PLAGIDL</i>   | AV <sup>-3</sup> | 0.000                    | -               | -                |
| <i>PWAGIDL</i>   | AV <sup>-3</sup> | 0.000                    | -               | -                |
| <i>PLWAGIDL</i>  | AV <sup>-3</sup> | 0.000                    | -               | -                |
| <i>POBGIDL</i>   | V                | 4.100 x10 <sup>+1</sup>  | -               | -                |
| <i>PLBGIDL</i>   | V                | 0.000                    | -               | -                |
| <i>PWBGIDL</i>   | V                | 0.000                    | -               | -                |
| <i>PLWBGIDL</i>  | V                | 0.000                    | -               | -                |
| <i>POCGIDL</i>   | -                | 0.000                    | -               | -                |
| <i>PLCGIDL</i>   | -                | 0.000                    | -               | -                |
| <i>PWCGIDL</i>   | -                | 0.000                    | -               | -                |
| <i>PLWCCGIDL</i> | -                | 0.000                    | -               | -                |
| <i>TOX</i>       | m                | 3.200 ×10 <sup>-9</sup>  | 1e-12           | -                |
| <i>POCOX</i>     | F                | 2.717 ×10 <sup>-14</sup> | -               | -                |
| <i>PLCOX</i>     | F                | 0.000                    | -               | -                |
| <i>PWCOX</i>     | F                | 0.000                    | -               | -                |
| <i>PLWCOX</i>    | F                | 0.000                    | -               | -                |

| <b>Parameter</b> | <b>Units</b>   | <b>Default</b>          | <b>Clip low</b> | <b>Clip high</b> |
|------------------|----------------|-------------------------|-----------------|------------------|
| <i>POCGDO</i>    | F              | $6.358 \times 10^{-15}$ | -               | -                |
| <i>PLCGDO</i>    | F              | 0.000                   | -               | -                |
| <i>PWCGDO</i>    | F              | 0.000                   | -               | -                |
| <i>PLWCGDO</i>   | F              | 0.000                   | -               | -                |
| <i>POCGSO</i>    | F              | $6.358 \times 10^{-15}$ | -               | -                |
| <i>PLCGSO</i>    | F              | 0.000                   | -               | -                |
| <i>PWCGSO</i>    | F              | 0.000                   | -               | -                |
| <i>PLWCGSO</i>   | F              | 0.000                   | -               | -                |
| <i>GATENOISE</i> | -              | 0.000                   | 0.000           | 1.000            |
| <i>NT</i>        | J              | $1.656 \times 10^{-20}$ | 0               | -                |
| <i>PONFA</i>     | $V^{-1}m^{-4}$ | $1.900 \times 10^{22}$  | -               | -                |
| <i>PLNFA</i>     | $V^{-1}m^{-4}$ | 0.000                   | -               | -                |
| <i>PWNFA</i>     | $V^{-1}m^{-4}$ | 0.000                   | -               | -                |
| <i>PLWNFA</i>    | $V^{-1}m^{-4}$ | 0.000                   | -               | -                |
| <i>PONFB</i>     | $V^{-1}m^{-2}$ | $5.043 \times 10^6$     | -               | -                |
| <i>PLNFB</i>     | $V^{-1}m^{-2}$ | 0.000                   | -               | -                |
| <i>PWNFB</i>     | $V^{-1}m^{-2}$ | 0.000                   | -               | -                |
| <i>PLWNFB</i>    | $V^{-1}m^{-2}$ | 0.000                   | -               | -                |
| <i>PONFC</i>     | $V^{-1}$       | $3.627 \times 10^{-10}$ | -               | -                |
| <i>PLNFC</i>     | $V^{-1}$       | 0.000                   | -               | -                |
| <i>PWNFC</i>     | $V^{-1}$       | 0.000                   | -               | -                |
| <i>PLWNFC</i>    | $V^{-1}$       | 0.000                   | -               | -                |
| <i>POTVFB</i>    | $VK^{-1}$      | $0.5 \times 10^{-3}$    | -               | -                |
| <i>PLTVFB</i>    | $VK^{-1}$      | 0.000                   | -               | -                |

| <b>Parameter</b>  | <b>Units</b>     | <b>Default</b>          | <b>Clip low</b> | <b>Clip high</b> |
|-------------------|------------------|-------------------------|-----------------|------------------|
| <i>PWTVFB</i>     | VK <sup>-1</sup> | 0.000                   | -               | -                |
| <i>PLWTVFB</i>    | VK <sup>-1</sup> | 0.000                   | -               | -                |
| <i>POTPHIB</i>    | VK <sup>-1</sup> | -8.5 × 10 <sup>-4</sup> | -               | -                |
| <i>PLTPHIB</i>    | VK <sup>-1</sup> | 0.000                   | -               | -                |
| <i>PWTPHIB</i>    | VK <sup>-1</sup> | 0.000                   | -               | -                |
| <i>PLWTPHIB</i>   | VK <sup>-1</sup> | 0.000                   | -               | -                |
| <i>POTETABET</i>  | -                | 0.500                   | -               | -                |
| <i>PLTETABET</i>  | -                | 0.000                   | -               | -                |
| <i>PWTETABET</i>  | -                | 0.000                   | -               | -                |
| <i>PLWTETABET</i> | -                | 0.000                   | -               | -                |
| <i>POTETASR</i>   | -                | 0.500                   | -               | -                |
| <i>PLTETASR</i>   | -                | 0.000                   | -               | -                |
| <i>PWTETASR</i>   | -                | 0.000                   | -               | -                |
| <i>PLWTETASR</i>  | -                | 0.000                   | -               | -                |
| <i>POTETAPH</i>   | -                | 3.750                   | -               | -                |
| <i>PLTETAPH</i>   | -                | 0.000                   | -               | -                |
| <i>PWTETAPH</i>   | -                | 0.000                   | -               | -                |
| <i>PLWTETAPH</i>  | -                | 0.000                   | -               | -                |
| <i>POTETAMOB</i>  | K <sup>-1</sup>  | 0.000                   | -               | -                |
| <i>PLTETAMOB</i>  | K <sup>-1</sup>  | 0.000                   | -               | -                |
| <i>PWTETAMOB</i>  | K <sup>-1</sup>  | 0.000                   | -               | -                |
| <i>PLWTETAMOB</i> | K <sup>-1</sup>  | 0.000                   | -               | -                |
| <i>NU</i>         | -                | 2.000                   | 1               | 100              |
| <i>POTNUEXP</i>   | -                | 3.230                   | -               | -                |
| <i>PLTNUEXP</i>   | -                | 0.000                   | -               | -                |

| <b>Parameter</b>  | <b>Units</b>     | <b>Default</b>          | <b>Clip low</b> | <b>Clip high</b> |
|-------------------|------------------|-------------------------|-----------------|------------------|
| <i>PWTNUEXP</i>   | -                | 0.000                   | -               | -                |
| <i>PLWTNUEXP</i>  | -                | 0.000                   | -               | -                |
| <i>POTETACS</i>   | -                | 0.000                   | -               | -                |
| <i>PLTETACS</i>   | -                | 0.000                   | -               | -                |
| <i>PWTETACS</i>   | -                | 0.000                   | -               | -                |
| <i>PLWTETACS</i>  | -                | 0.000                   | -               | -                |
| <i>POTETAR</i>    | -                | 0.400                   | -               | -                |
| <i>PLTETAR</i>    | -                | 0.000                   | -               | -                |
| <i>PWTETAR</i>    | -                | 0.000                   | -               | -                |
| <i>PLWTETAR</i>   | -                | 0.000                   | -               | -                |
| <i>POTETASAT</i>  | -                | 0.860                   | -               | -                |
| <i>PLTETASAT</i>  | -                | 0.000                   | -               | -                |
| <i>PWTETASAT</i>  | -                | 0.000                   | -               | -                |
| <i>PLWTETASAT</i> | -                | 0.000                   | -               | -                |
| <i>POTAI</i>      | K <sup>-1</sup>  | 0.000                   | -               | -                |
| <i>PLTAI</i>      | K <sup>-1</sup>  | 0.000                   | -               | -                |
| <i>PWTAI</i>      | K <sup>-1</sup>  | 0.000                   | -               | -                |
| <i>PLWTAI</i>     | K <sup>-1</sup>  | 0.000                   | -               | -                |
| <i>POTBGIDL</i>   | VK <sup>-1</sup> | -3.638x10 <sup>-4</sup> | -               | -                |
| <i>PLTBGIDL</i>   | VK <sup>-1</sup> | 0.000                   | -               | -                |
| <i>PWTBGIDL</i>   | VK <sup>-1</sup> | 0.000                   | -               | -                |
| <i>PLWTBGIDL</i>  | VK <sup>-1</sup> | 0.000                   | -               | -                |
| <i>DTA</i>        | K                | 0.000                   | -               | -                |
| <i>LMIN</i>       | m                | 0.000                   | -               | -                |
| <i>LMAX</i>       | m                | 1.000                   | -               | -                |
| <i>WMIN</i>       | m                | 0.000                   | -               | -                |

| Parameter     | Units                | Default | Clip low | Clip high |
|---------------|----------------------|---------|----------|-----------|
| <i>WMAX</i>   | m                    | 1.000   | -        | -         |
| <i>RGO</i>    | $\Omega$             | 0.0     | -        | -         |
| <i>RINT</i>   | $\Omega \text{ m}^2$ | 0.0     | 0.0      | -         |
| <i>RVPOLY</i> | $\Omega \text{ m}^2$ | 0.0     | 0.0      | -         |
| <i>RSHG</i>   | $\Omega/\square$     | 0.0     | 0.0      | -         |
| <i>DLSIL</i>  | m                    | 0.0     | -        | -         |

The additional values and clipping values of the additional parameters for the (**p-channel**) model including self-heating (see section 15.6 on page 156) are listed in the table below.

| Parameter  | Units                       | Default              | Clip low | Clip high |
|------------|-----------------------------|----------------------|----------|-----------|
| <i>RTH</i> | $^{\circ}\text{C}/\text{W}$ | 300.0                | 0.000    | -         |
| <i>CTH</i> | $\text{J}/^{\circ}\text{C}$ | $3.0 \times 10^{-9}$ | 0.000    | -         |
| <i>ATH</i> | -                           | 0.0                  | -        | -         |

The instance parameters are listed in the table below.

| Parameter           | Units | Default                | Clip low | Clip high |
|---------------------|-------|------------------------|----------|-----------|
| <i>L</i>            | m     | $2.000 \times 10^{-6}$ | -        | -         |
| <i>W</i>            | m     | $1.000 \times 10^{-5}$ | -        | -         |
| <i>MULT</i>         | -     | 1.000                  | 0.000    | -         |
| <i>NF</i>           | -     | 1.0                    | 1.0      | -         |
| <i>NGCON</i>        | -     | 1.0                    | 1.0      | 2.0       |
| <i>XGW</i>          | m     | $1.0 \times 10^{-7}$   | -        | -         |
| <i>PRINT-SCALED</i> | -     | 0                      | -        | -         |

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

### Parameters of the electrical model

These parameters correspond to the electrical model (MNE, MPE, MOS1102e).

| Parameter      | Progr. Name | Units             | Description  |
|----------------|-------------|-------------------|--|
| -              | LEVEL       | -                 | Must be 1102   |
| -              | PARAMCHK    | -                 | Level of clip warning info   |
| $T_R$          | TR          | °C                | Reference temperature  |
| $V_{FB}$       | VFB         | V                 | Flat-band voltage for the actual transistor at the reference temperature   |
| $S_{T;V_{FB}}$ | STVFB       | VK <sup>-1</sup>  | Coefficient of the temperature dependence of $V_{FB}$  |
| $k_0$          | K0          | V <sup>1/2</sup>  | Body-effect factor for the actual transistor   |
| $1/kp$         | KPINV       | V <sup>-1/2</sup> | Inverse of body-effect of the poly-silicon gate for the actual transistor  |
| $\phi_B$       | PHIB        | V                 | Surface potential at the onset of strong inversion for the actual transistor at the reference temperature                        |
| $S_{T;\phi_B}$ | STPHIB      | VK <sup>-1</sup>  | Coefficient of the temperature dependence of $\phi_B$  |
| $\beta$        | BET         | AV <sup>-2</sup>  | Gain factor for the actual transistor at the reference temperature   |
| $\eta_\beta$   | ETABET      | -                 | Exponent of the temperature dependence of the gain factor  |
| $\theta_{sr}$  | THESR       | V <sup>-1</sup>   | Coefficient of the mobility reduction due to surface roughness scattering for the actual transistor at the reference temperature |
| $\eta_{sr}$    | ETASR       | -                 | Exponent of the temperature dependence of $\theta_{sr}$  |
| $\theta_{ph}$  | THEPH       | V <sup>-1</sup>   | Coefficient of the mobility reduction due to phonon scattering for the actual transistor at the reference temperature            |
| $\eta_{ph}$    | ETAPH       | -                 | Exponent of the temperature dependence of $\theta_{ph}$  |

| Parameter          | Progr. Name | Units             | Description  |
|--------------------|-------------|-------------------|--|
| $\eta_{mob}$       | ETAMOB      | -                 | Effective field parameter for dependence on depletion/ inversion charge for the actual transistor at the reference temperature       |
| $S_{T;\eta_{mob}}$ | STETAMOB    | K <sup>-1</sup>   | Coefficient of the temperature dependence of $\eta_{mob}$  |
| $\nu$              | NU          | -                 | Exponent of field dependence of mobility model at the reference temperature  |
| $\nu_{exp}$        | NUEXP       | -                 | Exponent of the temperature dependence of $\nu$  |
| $C_S$              | CS          | -                 | Coulomb scattering parameter for the actual transistor at the reference temperature.   |
| $\eta_{c_s}$       | ETACS       | -                 | Exponent of the temperature dependence of $C_S$  |
| $\theta_R$         | THER        | V <sup>-1</sup>   | Coefficient of the series resistance for the actual transistor at the reference temperature:<br>$\theta_R = 2 \cdot \beta \cdot R_S$ |
| $\eta_R$           | ETAR        | -                 | Exponent of the temperature dependence of $\theta_R$   |
| $\theta_{R1}$      | THER1       | V                 | Numerator of the gate voltage dependent part of series resistance for the actual transistor  |
| $\theta_{R2}$      | THER2       | V                 | Denominator of the gate voltage dependent part of series resistance for the actual transistor  |
| $\theta_{sat}$     | THESAT      | V <sup>-1</sup>   | Velocity saturation parameter due to optical/acoustic phonon scattering for the actual transistor at the reference temperature       |
| $\eta_{sat}$       | ETASAT      | -                 | Exponent of the temperature dependence of $\theta_{sat}$   |
| $\theta_{Th}$      | THETH       | V <sup>-3</sup>   | Coefficient of self-heating for the actual transistor at the reference temperature   |
| $\sigma_{dibl}$    | SDIBL       | V <sup>-1/2</sup> | Drain-induced barrier-lowering parameter for the actual transistor   |

| Parameter     | Progr. Name | Units      | Description  |
|---------------|-------------|------------|--|
| $m_0$         | MO          | -          | Parameter for (short-channel) subthreshold slope for the actual transistor                     |
| $\sigma_{sf}$ | SSF         | $V^{-1/2}$ | Static-feedback parameter for the actual transistor  |
| $\alpha$      | ALP         | -          | Factor of the channel-length modulation for the actual transistor                              |
| $V_P$         | VP          | V          | Characteristic voltage of the channel-length modulation  |
| $m$           | MEXP        | -          | Smoothing factor for the actual transistor   |
| $a_1$         | A1          | -          | Factor of the weak-avalanche current for the actual transistor at the reference temperature    |
| $S_{T;a_1}$   | STA1        | $K^{-1}$   | Coefficient of the temperature dependence of $a_1$   |
| $a_2$         | A2          | V          | Exponent of the weak-avalanche current for the actual transistor                               |
| $a_3$         | A3          | -          | Factor of the drain-source voltage above which weak-avalanche occurs for the actual transistor |
| $I_{GINV}$    | IGINV       | $AV^{-2}$  | Gain factor for intrinsic gate tunnelling current in inversion for the actual transistor       |
| $B_{inv}$     | BINV        | V          | Probability factor for intrinsic gate tunnelling current in inversion                          |
| $I_{GACC}$    | IGACC       | $AV^{-2}$  | Gain factor for intrinsic gate tunnelling current in accumulation for the actual transistor    |
| $B_{acc}$     | BACC        | V          | Probability factor for intrinsic gate tunnelling current in accumulation                       |
| $V_{FBov}$    | VFBOV       | V          | Flat-band voltage for the source/drain overlap extensions                                      |
| $k_{ov}$      | KOV         | $V^{1/2}$  | Body-effect factor for the sourcedrain overlap extensions                                      |
| $I_{GOV}$     | IGOV        | $AV^{-2}$  | Gain factor for source/drain overlap gate tunnelling current for the actual transistor         |

| Parameter        | Progr. Name | Units          | Description  |
|------------------|-------------|----------------|--|
| $A_{GIDL}$       | AGIDL       | $AV^{-3}$      | Gain factor for gate-induced drain leakage current for the actual transistor       |
| $B_{GIDL}$       | BGIDL       | V              | Probability factor for gate-induced leakage current at the reference temperature   |
| $S_{T;B_{GIDL}}$ | STBGIDL     | $VK^{-1}$      | Coefficient of the temperature dependence of $B_{GIDL}$                            |
| $C_{GIDL}$       | CGIDL       | -              | Factor for the lateral field dependence of the gate-induced drain leakage current  |
| $C_{OX}$         | COX         | F              | Oxide capacitance for the intrinsic channel for the actual transistor              |
| $C_{GDO}$        | CGDO        | F              | Oxide capacitance for the gate-drain overlap for the actual transistor             |
| $C_{GSO}$        | CGSO        | F              | Oxide capacitance for the gate-source overlap for the actual transistor            |
| -                | GATENOISE   |                | Flag for in/exclusion of induced gate thermal noise                                |
| $N_T$            | NT          | J              | Coefficient of the thermal noise at the reference temperature                      |
| $N_{FA}$         | NFA         | $V^{-1}m^{-4}$ | First coefficient of the flicker noise for the actual transistor                   |
| $N_{FB}$         | NFB         | $V^{-1}m^{-2}$ | Second coefficient of the flicker noise for the actual transistor                  |
| $N_{FC}$         | NFC         | $V^{-1}$       | Third coefficient of the flicker noise for the actual transistor                   |
| $t_{ox}$         | TOX         | m              | Thickness of the gate-oxide layer  |
| $\Delta T_A$     | DTA         | K              | Temperature offset of the device with respect to ambient circuit temperature $T_A$ |
| $R_G$            | RG          | $\Omega$       | Gate resistance  |

The additional parameters for the model including self-heating (see section 15.6 on page 156) are listed in the table below.

| <b>Symbol</b> | <b>Progr. Name</b> | <b>Units</b> | <b>Description</b>                                |
|---------------|--------------------|--------------|---|
| $R_{TH}$      | RTH                | °C/W         | Thermal resistance                                |
| $C_{TH}$      | CTH                | J/°C         | Thermal capacitance                               |
| $A_{TH}$      | ATH                | -            | Temperature coefficient of the thermal resistance |

The *MULT* parameter is listed in the table below.

| <b>Symbol</b> | <b>Progr. Name</b> | <b>Units</b> | <b>Description</b>                             |
|---------------|--------------------|--------------|--|
| $N_{MULT}$    | MULT               | -            | Number of devices in parallel                  |
| -             | PRINTSCALED        | -            | Flag to add scaled parameters to the OP output |

### 3 Note

The parameter  $t_{ox}$  is used for calculation of the effective oxide thickness (due to quantum-mechanical effects) and the 1/f noise, not for the calculation of  $\beta$  !!!

**Default and clipping values (electrical model)**

The default values and clipping values as used for the parameters of the electrical MOS model, level 1102 (n-channel) are listed below.

| <b>Parameter</b> | <b>Units</b>      | <b>Default</b>          | <b>Clip low</b>       | <b>Clip high</b> |
|------------------|-------------------|-------------------------|-----------------------|------------------|
| <i>LEVEL</i>     | -                 | 1102                    | -                     | -                |
| <i>PARAMCHK</i>  | -                 | 0                       | -                     | -                |
| <i>TR</i>        | °C                | 21.0                    | -273.0                | -                |
| <i>VFB</i>       | V                 | -1.0500                 | -                     | -                |
| <i>STVFB</i>     | VK <sup>-1</sup>  | $0.5 \times 10^{-3}$    | -                     | -                |
| <i>KO</i>        | V <sup>1/2</sup>  | 0.5000                  | $1.0 \times 10^{-12}$ | -                |
| <i>KPINV</i>     | V <sup>-1/2</sup> | 0.000                   | 0.000                 | -                |
| <i>PHIB</i>      | V                 | 0.9500                  | $1.0 \times 10^{-12}$ | -                |
| <i>STPHIB</i>    | VK <sup>-1</sup>  | $-8.5 \times 10^{-4}$   | -                     | -                |
| <i>BET</i>       | AV <sup>-2</sup>  | $1.9215 \times 10^{-3}$ | 0.000                 | -                |
| <i>ETABET</i>    | -                 | 1.300                   | -                     | -                |
| <i>THESR</i>     | V <sup>-1</sup>   | 0.3562                  | $1.0 \times 10^{-12}$ | -                |
| <i>ETASR</i>     | -                 | 0.650                   | -                     | -                |
| <i>THEPH</i>     | V <sup>-1</sup>   | $1.29 \times 10^{-2}$   | $1.0 \times 10^{-12}$ | -                |
| <i>ETAPH</i>     | -                 | 1.350                   | -                     | -                |
| <i>ETAMOB</i>    | -                 | 1.4000                  | 1e-12                 | -                |
| <i>STETAMOB</i>  | K <sup>-1</sup>   | 0.000                   | -                     | -                |
| <i>NU</i>        | -                 | 2.0000                  | 1.000                 | 100              |
| <i>NUEXP</i>     | -                 | 5.250                   | -                     | -                |
| <i>CS</i>        | -                 | 0.0000                  | 0.000                 | -                |
| <i>ETACS</i>     | -                 | 0.0000                  | -                     | -                |
| <i>THER</i>      | V <sup>-1</sup>   | $8.12 \times 10^{-2}$   | 0.000                 | -                |

| <b>Parameter</b> | <b>Units</b>      | <b>Default</b>          | <b>Clip low</b>         | <b>Clip high</b> |
|------------------|-------------------|-------------------------|-------------------------|------------------|
| <i>ETAR</i>      | -                 | 0.950                   | -                       | -                |
| <i>THER1</i>     | V                 | 0.0000                  | 0.000                   | -                |
| <i>THER2</i>     | V                 | 1.0000                  | 0.000                   | -                |
| <i>THESAT</i>    | V <sup>-1</sup>   | 0.2513                  | 0.000                   | -                |
| <i>ETASAT</i>    | -                 | 1.040                   | -                       | -                |
| <i>THETH</i>     | V <sup>-3</sup>   | 1.0 × 10 <sup>-5</sup>  | 0.000                   | -                |
| <i>SDIBL</i>     | V <sup>-1/2</sup> | 8.53 × 10 <sup>-4</sup> | 1.0 × 10 <sup>-12</sup> | -                |
| <i>MO</i>        | V                 | 0.0000                  | 0.000                   | 0.500            |
| <i>SSF</i>       | V <sup>-1/2</sup> | 0.0120                  | 1.0 × 10 <sup>-12</sup> | -                |
| <i>ALP</i>       | -                 | 0.0250                  | 0.000                   | -                |
| <i>VP</i>        | V                 | 0.0500                  | 1.0 × 10 <sup>-12</sup> | -                |
| <i>MEXP</i>      | -                 | 5.0000                  | 1.000                   | -                |
| <i>A1</i>        | -                 | 6.0221                  | 0.000                   | -                |
| <i>STA1</i>      | K <sup>-1</sup>   | 0.000                   | -                       | -                |
| <i>A2</i>        | V                 | 38.017                  | 1.0 × 10 <sup>-12</sup> | -                |
| <i>A3</i>        | -                 | 0.6407                  | 0.000                   | -                |
| <i>IGINV</i>     | AV <sup>-2</sup>  | 0.0000                  | 0.000                   | -                |
| <i>BINV</i>      | V                 | 48.000                  | 0.000                   | -                |
| <i>IGACC</i>     | AV <sup>-2</sup>  | 0.0000                  | 0.000                   | -                |
| <i>BACC</i>      | V                 | 48.000                  | 0.000                   | -                |
| <i>VFBOV</i>     | V                 | 0.0000                  | -                       | -                |
| <i>KOV</i>       | V <sup>1/2</sup>  | 2.5000                  | 1.0 × 10 <sup>-12</sup> | -                |
| <i>IGOV</i>      | AV <sup>-2</sup>  | 0.0000                  | 0.000                   | -                |
| <i>AGIDL</i>     | AV <sup>-3</sup>  | 0.0000                  | 0.000                   | -                |
| <i>BGIDL</i>     | V                 | 41.000                  | 0.000                   | -                |

| <b>Parameter</b> | <b>Units</b>                    | <b>Default</b>           | <b>Clip low</b>        | <b>Clip high</b> |
|------------------|---------------------------------|--------------------------|------------------------|------------------|
| <i>STBGIDL</i>   | VK <sup>-1</sup>                | -3.638 x10 <sup>-4</sup> | -                      | -                |
| <i>CGIDL</i>     | -                               | 0.000                    | 0.000                  | -                |
| <i>COX</i>       | F                               | 2.98 x10 <sup>-14</sup>  | 0.000                  | -                |
| <i>CGDO</i>      | F                               | 6.392 x10 <sup>-15</sup> | 0.000                  | -                |
| <i>CGSO</i>      | F                               | 6.392 x10 <sup>-15</sup> | 0.000                  | -                |
| <i>GATENOISE</i> | -                               | 0.0000                   | 0.000                  | 1.000            |
| <i>NT</i>        | J                               | 1.656 x10 <sup>-20</sup> | 0.000                  | -                |
| <i>NFA</i>       | V <sup>-1</sup> m <sup>-4</sup> | 8.323 x10 <sup>22</sup>  | 0.000                  | -                |
| <i>NFB</i>       | V <sup>-1</sup> m <sup>-2</sup> | 2.514 x10 <sup>7</sup>   | -                      | -                |
| <i>NFC</i>       | V <sup>-1</sup>                 | 0.0000                   | -                      | -                |
| <i>TOX</i>       | m                               | 3.2 x10 <sup>-9</sup>    | 1.0 x10 <sup>-12</sup> | -                |
| <i>DTA</i>       | K                               | 0.000                    | -                      | -                |
| <i>RG</i>        | Ω                               | 0.000                    | 0.000                  | -                |

The default values and clipping values of the additional parameters for the (**n-channel**) model including self-heating (see section 15.6 on page 156) are listed in the table below.

| <b>Parameter</b> | <b>Units</b> | <b>Default</b>       | <b>Clip low</b> | <b>Clip high</b> |
|------------------|--------------|----------------------|-----------------|------------------|
| <i>RTH</i>       | °C/W         | 300.0                | 0.000           | -                |
| <i>CTH</i>       | J/°C         | 3.0x10 <sup>-9</sup> | 0.000           | -                |
| <i>ATH</i>       | -            | 0.0                  | -               | -                |

The *MULT* parameter is listed in the table below.

| <b>Parameter</b>    | <b>Units</b> | <b>Default</b> | <b>Clip low</b> | <b>Clip high</b> |
|---------------------|--------------|----------------|-----------------|------------------|
| <i>MULT</i>         | -            | 1.000          | 0.000           | -                |
| <i>PRINT-SCALED</i> | -            | 0              | -               | -                |

The default values and clipping values as used for the parameters of the electrical MOS model, level 1102 (p-channel) are listed below.

| <b>Parameter</b> | <b>Units</b>      | <b>Default</b>          | <b>Clip low</b>       | <b>Clip high</b> |
|------------------|-------------------|-------------------------|-----------------------|------------------|
| <i>LEVEL</i>     | -                 | 1102                    | -                     | -                |
| <i>PARAMCHK</i>  | -                 | 0                       | -                     | -                |
| <i>TR</i>        | °C                | 21.0                    | -273.0                | -                |
| <i>VFB</i>       | V                 | -1.0500                 | -                     | -                |
| <i>STVFB</i>     | VK <sup>-1</sup>  | $0.5 \times 10^{-3}$    | -                     | -                |
| <i>KO</i>        | V <sup>1/2</sup>  | 0.5000                  | $1.0 \times 10^{-12}$ | -                |
| <i>KPINV</i>     | V <sup>-1/2</sup> | 0.000                   | 0.000                 | -                |
| <i>PHIB</i>      | V                 | 0.9500                  | $1.0 \times 10^{-12}$ | -                |
| <i>STPHIB</i>    | VK <sup>-1</sup>  | $-8.5 \times 10^{-4}$   | -                     | -                |
| <i>BET</i>       | AV <sup>-2</sup>  | $3.8140 \times 10^{-4}$ | 0.0                   | -                |
| <i>ETABET</i>    | -                 | 0.500                   | -                     | -                |
| <i>THESR</i>     | V <sup>-1</sup>   | 0.7300                  | $1.0 \times 10^{-12}$ | -                |
| <i>ETASR</i>     | -                 | 0.500                   | -                     | -                |
| <i>THEPH</i>     | V <sup>-1</sup>   | 0.0010                  | $1.0 \times 10^{-12}$ | -                |
| <i>ETAPH</i>     | -                 | 3.750                   | -                     | -                |
| <i>ETAMOB</i>    | -                 | 3.0000                  | 1e-12                 | -                |
| <i>STETAMOB</i>  | K <sup>-1</sup>   | 0.000                   | -                     | -                |
| <i>NU</i>        | -                 | 2.0000                  | 1.000                 | 100              |
| <i>NUEXP</i>     | -                 | 3.230                   | -                     | -                |
| <i>CS</i>        | -                 | 0.0000                  | 0.000                 | -                |
| <i>ETACS</i>     | -                 | 0.0000                  | -                     | -                |
| <i>THER</i>      | V <sup>-1</sup>   | $7.90 \times 10^{-2}$   | 0.000                 | -                |
| <i>ETAR</i>      | -                 | 0.400                   | -                     | -                |

| <b>Parameter</b> | <b>Units</b>      | <b>Default</b>            | <b>Clip low</b>         | <b>Clip high</b> |
|------------------|-------------------|---------------------------|-------------------------|------------------|
| <i>THER1</i>     | V                 | 0.0000                    | 0.000                   | -                |
| <i>THER2</i>     | V                 | 1.0000                    | 0.000                   | -                |
| <i>THESAT</i>    | V <sup>-1</sup>   | 0.1728                    | 0.000                   | -                |
| <i>ETASAT</i>    | -                 | 0.860                     | -                       | -                |
| <i>THETH</i>     | V <sup>-3</sup>   | 0.000                     | 0.000                   | -                |
| <i>SDIBL</i>     | V <sup>-1/2</sup> | 3.551 × 10 <sup>-5</sup>  | 1.0 × 10 <sup>-12</sup> | -                |
| <i>MO</i>        | V                 | 0.0000                    | 0.000                   | 0.500            |
| <i>SSF</i>       | V <sup>-1/2</sup> | 0.0100                    | 1.0 × 10 <sup>-12</sup> | -                |
| <i>ALP</i>       | -                 | 0.0250                    | 0.000                   | -                |
| <i>VP</i>        | V                 | 0.0500                    | 1.0 × 10 <sup>-12</sup> | -                |
| <i>MEXP</i>      | -                 | 5.0000                    | 1.000                   | -                |
| <i>A1</i>        | -                 | 6.8583                    | 0.000                   | -                |
| <i>STAI</i>      | K <sup>-1</sup>   | 0.000                     | -                       | -                |
| <i>A2</i>        | V                 | 57.324                    | 1.0 × 10 <sup>-12</sup> | -                |
| <i>A3</i>        | -                 | 0.4254                    | 0.000                   | -                |
| <i>IGINV</i>     | AV <sup>-2</sup>  | 0.0000                    | 0.000                   | -                |
| <i>BINV</i>      | V                 | 87.500                    | 0.000                   | -                |
| <i>IGACC</i>     | AV <sup>-2</sup>  | 0.0000                    | 0.000                   | -                |
| <i>BACC</i>      | V                 | 48.000                    | 0.000                   | -                |
| <i>VFBOV</i>     | V                 | 0.0000                    | -                       | -                |
| <i>KOV</i>       | V <sup>1/2</sup>  | 2.5000                    | 1.0 × 10 <sup>-12</sup> | -                |
| <i>IGOV</i>      | AV <sup>-2</sup>  | 0.0000                    | 0.000                   | -                |
| <i>AGIDL</i>     | AV <sup>-3</sup>  | 0.0000                    | 0.000                   | -                |
| <i>BGIDL</i>     | V                 | 41.000                    | 0.000                   | -                |
| <i>STBGIDL</i>   | VK <sup>-1</sup>  | -3.638 × 10 <sup>-4</sup> | -                       | -                |

| <b>Parameter</b> | <b>Units</b>   | <b>Default</b>          | <b>Clip low</b>       | <b>Clip high</b> |
|------------------|----------------|-------------------------|-----------------------|------------------|
| <i>CGIDL</i>     | -              | 0.000                   | 0.000                 | -                |
| <i>COX</i>       | F              | $2.717 \times 10^{-14}$ | 0.000                 | -                |
| <i>CGDO</i>      | F              | $6.358 \times 10^{-15}$ | 0.000                 | -                |
| <i>CGSO</i>      | F              | $6.358 \times 10^{-15}$ | 0.000                 | -                |
| <i>GATENOISE</i> | -              | 0.0000                  | 0.000                 | 1.000            |
| <i>NT</i>        | J              | $1.656 \times 10^{-20}$ | 0.000                 | -                |
| <i>NFA</i>       | $V^{-1}m^{-4}$ | $1.900 \times 10^{22}$  | 0.000                 | -                |
| <i>NFB</i>       | $V^{-1}m^{-2}$ | $5.043 \times 10^6$     | -                     | -                |
| <i>NFC</i>       | $V^{-1}$       | $3.627 \times 10^{-10}$ | -                     | -                |
| <i>TOX</i>       | m              | $3.2 \times 10^{-9}$    | $1.0 \times 10^{-12}$ | -                |
| <i>DTA</i>       | K              | 0.000                   | -                     | -                |
| <i>RG</i>        | $\Omega$       | 0.000                   | 0.000                 | -                |

The default values and clipping values of the additional parameters for the (**p-channel**) model including self-heating (see section 15.6 on page 156) are listed in the table below.

| <b>Parameter</b> | <b>Units</b>  | <b>Default</b>       | <b>Clip low</b> | <b>Clip high</b> |
|------------------|---------------|----------------------|-----------------|------------------|
| <i>RTH</i>       | $^{\circ}C/W$ | 300.0                | 0.000           | -                |
| <i>CTH</i>       | $J/^{\circ}C$ | $3.0 \times 10^{-9}$ | 0.000           | -                |
| <i>ATH</i>       | -             | 0.0                  | -               | -                |

The *MULT* parameter is listed in the table below.

| <b>Parameter</b>    | <b>Units</b> | <b>Default</b> | <b>Clip low</b> | <b>Clip high</b> |
|---------------------|--------------|----------------|-----------------|------------------|
| <i>MULT</i>         | -            | 1.000          | 0.000           | -                |
| <i>PRINT-SCALED</i> | -            | 0              | -               | -                |

### 15.3.3 Model constants

This table gives the symbolic representation, the recommended programming names and the value of the various physical constants used in MOS Model 11.

| Constant        | Progr. Name | Units                               | Description   |
|-----------------|-------------|-------------------------------------|---|
| $T_0$           | TO          | K                                   | Offset for conversion from Celsius to Kelvin temperature scale (273.15)                             |
| $k_B$           | KB          | JK <sup>-1</sup>                    | Boltzmann constant (1.3806226.10 <sup>-23</sup> )   |
| $q$             | Q           | C                                   | Elementary unit charge (1.6021918.10 <sup>-19</sup> )   |
| $\epsilon_{ox}$ | EPSOX       | Fm <sup>-1</sup>                    | Absolute permittivity of the oxide layer (3.453143800.10 <sup>-11</sup> )                           |
| $QM_N$          | QMN         | Vm <sup>4/3</sup> C <sup>-2/3</sup> | Constant of quantum-mechanical behavior of electrons (5.951993.10 <sup>+00</sup> )                  |
| $QM_p$          | QMP         | Vm <sup>4/3</sup> C <sup>-2/3</sup> | Constant of quantum-mechanical behavior of holes (7.448711.10 <sup>+00</sup> )                      |
| $\chi_{BN}$     | CHIBN       | V                                   | Tunnelling barrier height for electrons for Si/SiO <sub>2</sub> -structure (3.1.10 <sup>+00</sup> ) |
| $\chi_{Bp}$     | CHIBP       | V                                   | Tunnelling barrier height for holes for Si/SiO <sub>2</sub> -structure (4.5.10 <sup>+00</sup> )     |

## 15.4 Parameter Scaling

### 15.4.1 Geometrical scaling and temperature scaling

In this section the geometry and temperature scaling rules for the model parameters will be given. The temperature scaling rules have already been given in Section 15.2.2, but they are repeated here for the sake of completeness.

#### Calculation of Transistor Geometry

$$L_E = L - \Delta L = L + \Delta L_{PS} - 2 \cdot \Delta L_{\text{overlap}} \quad (15.121)$$

$$W_E = W - \Delta W = W / NF + \Delta W_{OD} - 2 \cdot \Delta W_{\text{narrow}} \quad (15.122)$$

**WARNING :**  $L_E$  and  $W_E$  after calculation cannot be less than  $1.0 \times 10^{-9}$  !

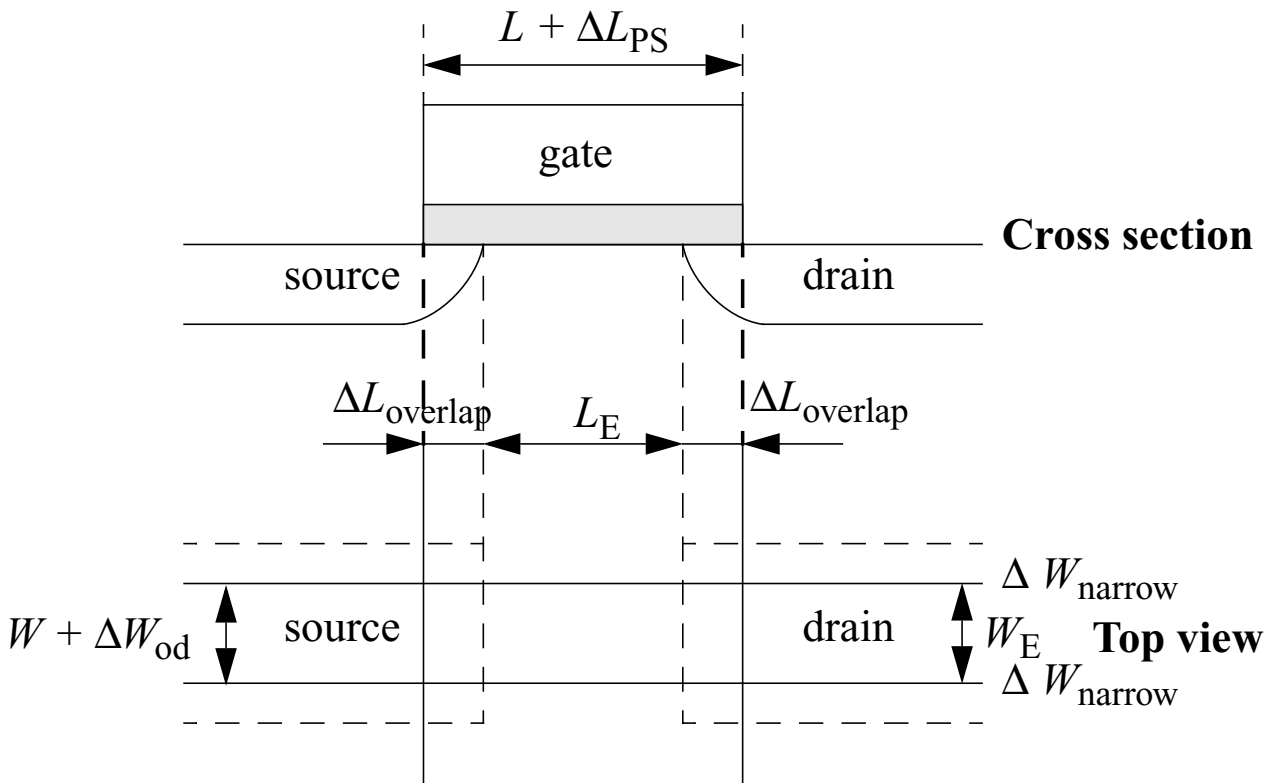


Figure 70: Specification of the dimensions of a MOS transistor

## Calculation of Geometry-Dependent Parameters

In MOS Model 11, Level 1102, parameter binning has been facilitated by adding a second, separate set of geometry scaling rules. Consequently, besides the physical geometrical scaling rules there is also a set of binning geometrical scaling rules. The physical geometry scaling rules of Level 1102 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 this 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 Level 1102 are not straightforwardly applicable to binning strategies, since they may result in discontinuities in parameter values at the bin boundaries. Consequently, special binning geometrical scaling relations have been developed, which guarantee continuity in the model parameters at the bin boundaries.

It should be noted that when using the source code of the Modelkit on the Philips' website (which can be found at [http://www.semiconductors.philips.com/Philips\\_Models](http://www.semiconductors.philips.com/Philips_Models)):

1. The physical geometry scaling rules can be selected by using Level 11020, while
2. The binning geometry scaling rules can be selected by using Level 11021.

Three types of binning geometrical scaling rules can be distinguished:

1. Type I

$$P(W_E, L_E) = P_0 + \frac{L_{EN}}{L_E} \cdot P_L + \frac{W_{EN}}{W_E} \cdot P_W + \frac{L_{EN}}{L_E} \cdot \frac{W_{EN}}{W_E} \cdot P_{LW} \quad (15.123)$$

2. Type II

$$P(W_E, L_E) = P_0 + \frac{L_E}{L_{EN}} \cdot P_L + \frac{W_E}{W_{EN}} \cdot P_W + \frac{L_E}{L_{EN}} \cdot \frac{W_E}{W_{EN}} \cdot P_{LW} \quad (15.124)$$

## 3. Type III

$$P(W_E, L_E) = P_0 + \frac{L_{EN}}{L_E} \cdot P_L + \frac{W_E}{W_{EN}} \cdot P_W + \frac{W_E}{L_E} \cdot P_{LW} \quad (15.125)$$

In these equations  $L_{EN}$  and  $W_{EN}$  are constants. Table 18 below gives a survey of the parameters scaling.

When using the three binning rules given, the scaling parameters for one bin can be directly calculated from the minisets of the four corner devices of the bin. The binning scheme ensures that the minisets are exactly reproduced in the bin corners, and that no humps occur in parameter values accross bin borders. The exact way to calculate binning parameters from minisets is described in Appendix B.

*Table 18: Survey of parameters scaling. The third column indicates if there is a physical geometrical scaling rule for the parameter; the fourth column indicates the type of binning geometrical scaling rule for the parameter.*

| #  | Parameter     | physical scaling | binning  | #  | parameter          | physical scaling | binning |
|----|---------------|------------------|----------|----|--------------------|------------------|---------|
| 0  | $LEVEL$       | no               | no       | 1  | $T_R$              | no               | no      |
| 2  | $V_{FB}$      | no               | no       | 3  | $S_{T;V_{FB}}$     | no               | type I  |
| 4  | $k_0$         | yes              | type I   | 5  | $1/k_P$            | no               | no      |
| 6  | $\phi_B$      | yes              | type I   | 7  | $S_{T;\phi_B}$     | no               | type I  |
| 8  | $\beta$       | yes              | type III | 9  | $\eta_\beta$       | yes              | type I  |
| 10 | $\theta_{sr}$ | yes              | type I   | 11 | $\eta_{sr}$        | no               | type I  |
| 12 | $\theta_{ph}$ | yes              | type I   | 13 | $\eta_{ph}$        | no               | type I  |
| 14 | $\eta_{mob}$  | yes              | type I   | 15 | $S_{T;\eta_{mob}}$ | no               | type I  |

Table 18: Survey of parameters scaling. The third column indicates if there is a physical geometrical scaling rule for the parameter; the fourth column indicates the type of binning geometrical scaling rule for the parameter.

| #  | Parameter      | physical scaling | binning  | #  | parameter       | physical scaling | binning  |
|----|----------------|------------------|----------|----|-----------------|------------------|----------|
| 16 | $\nu$          | no               | no       | 17 | $\nu_{EXP}$     | no               | type I   |
| 18 | $C_s$          | yes              | type I   | 19 | $\eta_{C_s}$    | no               | type I   |
| 20 | $\theta_R$     | yes              | type I   | 21 | $\eta_R$        | no               | type I   |
| 22 | $\theta_{R1}$  | no               | no       | 23 | $\theta_{R2}$   | no               | no       |
| 24 | $\theta_{sat}$ | yes              | type I   | 25 | $\eta_{sat}$    | no               | type I   |
| 26 | $\theta_{Th}$  | yes              | type I   | 27 | $\sigma_{dibl}$ | yes              | type I   |
| 28 | $m_0$          | yes              | type I   | 29 | $\sigma_{sf}$   | yes              | type I   |
| 30 | $\alpha$       | yes              | type I   | 31 | $V_P$           | no               | no       |
| 32 | $m$            | yes              | type I   | 33 | $a_1$           | yes              | type I   |
| 34 | $S_{T;a_1}$    | no               | type I   | 35 | $a_2$           | yes              | type I   |
| 36 | $a_3$          | yes              | type I   | 37 | $I_{GINV}$      | yes              | type II  |
| 38 | $B_{INV}$      | no               | type I   | 39 | $I_{GACC}$      | yes              | type II  |
| 40 | $B_{ACC}$      | no               | type I   | 41 | $V_{RFBov}$     | no               | no       |
| 42 | $k_{ov}$       | no               | no       | 43 | $I_{GOV}$       | yes              | type III |
| 44 | $A_{GIDL}$     | yes              | type III | 45 | $B_{GIDL}$      | yes              | type I   |

Table 18: Survey of parameters scaling. The third column indicates if there is a physical geometrical scaling rule for the parameter; the fourth column indicates the type of binning geometrical scaling rule for the parameter.

| #  | Parameter        | physical scaling | binning  | #  | parameter    | physical scaling | binning  |
|----|------------------|------------------|----------|----|--------------|------------------|----------|
| 46 | $S_{T;B_{GIDL}}$ | yes              | type I   | 47 | $C_{GIDL}$   | yes              | type I   |
| 48 | $C_{ox}$         | yes              | type II  | 49 | $C_{GDO}$    | yes              | type III |
| 50 | $C_{GSO}$        | yes              | type III | 51 | $GATENOISE$  | no               | no       |
| 52 | $N_T$            | no               | no       | 53 | $N_{FA}$     | yes              | type I   |
| 54 | $N_{FB}$         | yes              | type I   | 55 | $N_{FC}$     | yes              | type I   |
| 56 | $t_{ox}$         | no               | no       | 57 | $\Delta T_A$ | no               | no       |
| 58 | $N_{MULT}$       | no               | no       |    |              |                  |          |

### Calculation of Geometry-Dependent Parameters using the Physical Scaling Rules

$$L_{EN} = 10^{-6} \quad (15.126)$$

$$W_{EN} = 10^{-6} \quad (15.127)$$

### Calculation of Threshold-Voltage Parameters

$$klen = 1 + \frac{L_{EN}}{L_E} \cdot S_{L;k_0} + \left(\frac{L_{EN}}{L_E}\right)^2 \cdot S_{L2;k_0} + \left(\frac{L_{EN}}{L_E}\right)^{SL3KOEXP} \cdot S_{L3;k_0}$$

$$kwid = 1 + \frac{W_{EN}}{W_E} \cdot S_{W;k_0}$$

$$k_0 = k_{0R} \cdot klen \cdot kwid \quad (15.128)$$

$$\phi_B = \phi_{BR} \cdot \left[ 1 + \frac{L_{EN}}{L_E} \cdot S_{L;\phi_B} + \left( \frac{L_{EN}}{L_E} \right)^2 \cdot S_{L2;\phi_B} \right] \cdot \left[ 1 + \frac{W_{EN}}{W_E} \cdot S_{W;\phi_B} \right] \quad (15.129)$$

### Calculation of Mobility/Series-Resistance Parameters

$$G_{P,E} = 1 + f_{\beta,1} \cdot \frac{L_{P,1}}{L_E} \cdot \left\{ 1 - \exp\left(-\frac{L_E}{L_{P,1}}\right) \right\} + f_{\beta,2} \cdot \frac{L_{P,2}}{L_E} \cdot \left\{ 1 - \exp\left(-\frac{L_E}{L_{P,2}}\right) \right\} \quad (15.130)$$

$$\beta = \frac{\beta_{sq}}{G_{P,E}} \cdot \frac{W_E}{L_E} \quad (15.131)$$

$$\theta_{sr} = \theta_{srR} \cdot \left[ 1 + \frac{W_{EN}}{W_E} \cdot S_{W;\theta_{sr}} \right] \quad (15.132)$$

$$\theta_{ph} = \theta_{phR} \cdot \left[ 1 + \frac{W_{EN}}{W_E} \cdot S_{W;\theta_{ph}} \right] \quad (15.133)$$

$$\eta_{mob} = \theta_{mobR} \cdot \left[ 1 + \frac{W_{EN}}{W_E} \cdot S_{W;\eta_{mob}} \right] \quad (15.134)$$

$$C_s = C_{sR} \cdot \left[ 1 + \frac{W_{EN}}{W_E} \cdot S_{W;C_s} \right] \cdot \left[ 1 + S_{L;C_s} \cdot \left\{ \left( \frac{L_{EN}}{L_E} \right)^{C_{sEXP}} - 1 \right\} \right] \quad (15.135)$$

$$\theta_R = \theta_{RR} \cdot \left[ 1 + \frac{W_{EN}}{W_E} \cdot S_{W;\theta_R} \right] \cdot \frac{L_{EN}}{L_E} \cdot \frac{1}{G_{P,E}} \quad (15.136)$$

$$\theta_{sat} = \theta_{satR} \cdot \left[ 1 + \frac{W_{EN}}{W_E} \cdot S_{W;\theta_{sat}} \right] \cdot \left[ 1 + S_{L;\theta_{sat}} \cdot \left\{ \left( \frac{L_{EN}}{L_E} \right)^{\theta_{satEXP}} - 1 \right\} \right] \quad (15.137)$$

### Calculation of Conductance Parameters

$$\theta_{Th} = \theta_{ThR} \cdot \left[ 1 + \frac{W_{EN}}{W_E} \cdot S_{W;\theta_{Th}} \right] \cdot \left[ \frac{L_{EN}}{L_E} \right]^{\theta_{ThEXP}} \quad (15.138)$$

$$\sigma_{sf} = \sigma_{sfR} \cdot \left[ 1 + \frac{W_{EN}}{W_E} \cdot S_{W;\sigma_{sf}} \right] \cdot \left[ 1 + \frac{L_{EN}}{L_E} \cdot S_{L;\sigma_{sf}} \right] \quad (15.139)$$

$$\alpha = \alpha_R \cdot \left[ 1 + \frac{W_{EN}}{W_E} \cdot S_{W;\alpha} \right] \cdot \left[ 1 + S_{L;\alpha} \cdot \left\{ \left( \frac{L_{EN}}{L_E} \right)^{\alpha_{EXP}} - 1 \right\} \right] \quad (15.140)$$

### Calculation of Sub-Threshold Parameters

$$\sigma_{dibl} = \sigma_{dibl0} \cdot \left( \frac{L_{EN}}{L_E} \right)^{\sigma_{diblEXP}} \quad (15.141)$$

$$m_0 = m_{00} + m_{0R} \cdot \left( \frac{L_{EN}}{L_E} \right)^{m_{0EXP}} \quad (15.142)$$

**Calculation of Smoothing Parameters**

$$L_{max} = 10 \cdot 10^{-6} \quad (15.143)$$

$$m = \frac{8 \cdot (L_{max} - L_{min})}{L_{max} - 4 \cdot L_{min} + 3 \cdot \frac{L_{max} \cdot L_{min}}{L_E}} \quad (15.144)$$

**Calculation of Weak-Avalanche Parameters**

$$a_1 = a_{1R} \cdot \left[ 1 + \frac{L_{EN}}{L_E} \cdot S_{L;a_1} \right] \cdot \left[ 1 + \frac{W_{EN}}{W_E} \cdot S_{W;a_1} \right] \quad (15.145)$$

$$a_2 = a_{2R} \cdot \left[ 1 + \frac{L_{EN}}{L_E} \cdot S_{L;a_2} \right] \cdot \left[ 1 + \frac{W_{EN}}{W_E} \cdot S_{W;a_2} \right] \quad (15.146)$$

$$a_3 = a_{3R} \cdot \left[ 1 + \frac{L_{EN}}{L_E} \cdot S_{L;a_3} \right] \cdot \left[ 1 + \frac{W_{EN}}{W_E} \cdot S_{W;a_3} \right] \quad (15.147)$$

**Calculation of Gate Current Parameters**

$$I_{GINV} = \frac{W_E \cdot L_E}{W_{EN} \cdot L_{EN}} \cdot I_{GINVR} \quad (15.148)$$

$$I_{GACC} = \frac{W_E \cdot L_E}{W_{EN} \cdot L_{EN}} \cdot I_{GACCR} \quad (15.149)$$

$$I_{GOV} = \frac{W_E}{W_{EN}} \cdot I_{GOVR} \quad (15.150)$$

**Calculation of Gate-Induced Drain Leakage Parameters**

$$A_{GIDL} = \frac{W_E}{W_{EN}} \cdot A_{GIDLR} \quad (15.151)$$

**Calculation of Charge Parameters**

$$C_{OX} = \epsilon_{ox} \cdot \frac{W_E \cdot L_E}{t_{ox}} \quad (15.152)$$

$$C_{GDO} = \frac{W_E}{W_{EN}} \cdot C_{ol} \quad (15.153)$$

$$C_{GSO} = \frac{W_E}{W_{EN}} \cdot C_{ol} \quad (15.154)$$

**Calculation of Noise Parameters**

$$N_{FA} = \frac{W_{EN} \cdot L_{EN}}{W_E \cdot L_E} \cdot N_{FAR} \quad (15.155)$$

$$N_{FB} = \frac{W_{EN} \cdot L_{EN}}{W_E \cdot L_E} \cdot N_{FBR} \quad (15.156)$$

$$N_{FC} = \frac{W_{EN} \cdot L_{EN}}{W_E \cdot L_E} \cdot N_{FCR} \quad (15.157)$$

### Calculation of Mobility/Series-Resistance Temperature-Scaling Coefficients

$$\eta_{\beta} = \eta_{\beta R} + S_{L;\eta_{\beta}} \cdot \frac{L_{EN}}{L_E} \quad (15.158)$$

### Calculation of Geometry-Dependent Parameters using the Binning Scaling Rules

Note that for each bin  $(W_{min}, W_{max}, L_{min}, L_{max})$ , there is a separate parameter set, which is valid for  $(W, L)$  values with  $W_{min} \leq W \leq W_{max}$  and  $L_{min} \leq L \leq L_{max}$ .

$$L_{EN} = 10^{-6} \quad (15.159)$$

$$W_{EN} = 10^{-6} \quad (15.160)$$

### Calculation of Threshold-Voltage Parameters

$$k_0 = P_{0;k_0} + \frac{L_{EN}}{L_E} \cdot P_{L;k_0} + \frac{W_{EN}}{W_E} \cdot P_{W;k_0} + \frac{L_{EN} \cdot W_{EN}}{L_E \cdot W_E} \cdot P_{LW;k_0} \quad (15.161)$$

$$\phi_B = P_{0;\phi_B} + \frac{L_{EN}}{L_E} \cdot P_{L;\phi_B} + \frac{W_{EN}}{W_E} \cdot P_{W;\phi_B} + \frac{L_{EN} \cdot W_{EN}}{L_E \cdot W_E} \cdot P_{LW;\phi_B} \quad (15.162)$$

### Calculation of Mobility/Series-Resistance Parameters

$$\beta = P_{0;\beta} + \frac{L_{EN}}{L_E} \cdot P_{L;\beta} + \frac{W_E}{W_{EN}} \cdot P_{W;\beta} + \frac{W_E}{L_E} \cdot P_{LW;\beta} \quad (15.163)$$

$$\theta_{sr} = P_{0;\theta_{sr}} + \frac{L_{EN}}{L_E} \cdot P_{L;\theta_{sr}} + \frac{W_{EN}}{W_E} \cdot P_{W;\theta_{sr}} + \frac{L_{EN} \cdot W_{EN}}{L_E \cdot W_E} \cdot P_{LW;\theta_{sr}} \quad (15.164)$$

$$\theta_{ph} = P_{0;\theta_{ph}} + \frac{L_{EN}}{L_E} \cdot P_{L;\theta_{ph}} + \frac{W_{EN}}{W_E} \cdot P_{W;\theta_{ph}} + \frac{L_{EN} \cdot W_{EN}}{L_E \cdot W_E} \cdot P_{LW;\theta_{ph}} \quad (15.165)$$

$$\eta_{mob} = P_{0;\eta_{mob}} + \frac{L_{EN}}{L_E} \cdot P_{L;\eta_{mob}} + \frac{W_{EN}}{W_E} \cdot P_{W;\eta_{mob}} + \frac{L_{EN} \cdot W_{EN}}{L_E \cdot W_E} \cdot P_{LW;\eta_{mob}} \quad (15.166)$$

$$C_s = P_{0;C_s} + \frac{L_{EN}}{L_E} \cdot P_{L;C_s} + \frac{W_{EN}}{W_E} \cdot P_{W;C_s} + \frac{L_{EN} \cdot W_{EN}}{L_E \cdot W_E} \cdot P_{LW;C_s} \quad (15.167)$$

$$\theta_R = P_{0;\theta_R} + \frac{L_{EN}}{L_E} \cdot P_{L;\theta_R} + \frac{W_{EN}}{W_E} \cdot P_{W;\theta_R} + \frac{L_{EN} \cdot W_{EN}}{L_E \cdot W_E} \cdot P_{LW;\theta_R} \quad (15.168)$$

$$\theta_{sat} = P_{0;\theta_{sat}} + \frac{L_{EN}}{L_E} \cdot P_{L;\theta_{sat}} + \frac{W_{EN}}{W_E} \cdot P_{W;\theta_{sat}} + \frac{L_{EN} \cdot W_{EN}}{L_E \cdot W_E} \cdot P_{LW;\theta_{sat}} \quad (15.169)$$

### Calculation of Conductance Parameters

$$\theta_{Th} = P_{0;\theta_{Th}} + \frac{L_{EN}}{L_E} \cdot P_{L;\theta_{Th}} + \frac{W_{EN}}{W_E} \cdot P_{W;\theta_{Th}} + \frac{L_{EN} \cdot W_{EN}}{L_E \cdot W_E} \cdot P_{LW;\theta_{Th}} \quad (15.170)$$

$$\sigma_{sf} = P_{0;\sigma_{sf}} + \frac{L_{EN}}{L_E} \cdot P_{L;\sigma_{sf}} + \frac{W_{EN}}{W_E} \cdot P_{W;\sigma_{sf}} + \frac{L_{EN} \cdot W_{EN}}{L_E \cdot W_E} \cdot P_{LW;\sigma_{sf}} \quad (15.171)$$

$$\alpha = P_{0;\alpha} + \frac{L_{EN}}{L_E} \cdot P_{L;\alpha} + \frac{W_{EN}}{W_E} \cdot P_{W;\alpha} + \frac{L_{EN} \cdot W_{EN}}{L_E \cdot W_E} \cdot P_{LW;\alpha} \quad (15.172)$$

**Calculation of Sub-Threshold Parameters**

$$\sigma_{dibl} = P_{0;\sigma_{dibl}} + \frac{L_{EN}}{L_E} \cdot P_{L;\sigma_{dibl}} + \frac{W_{EN}}{W_E} \cdot P_{W;\sigma_{dibl}} + \frac{L_{EN} \cdot W_{EN}}{L_E \cdot W_E} \cdot P_{LW;\sigma_{dibl}} \quad (15.173)$$

$$m_0 = P_{0;m_0} + \frac{L_{EN}}{L_E} \cdot P_{L;m_0} + \frac{W_{EN}}{W_E} \cdot P_{W;m_0} + \frac{L_{EN} \cdot W_{EN}}{L_E \cdot W_E} \cdot P_{LW;m_0} \quad (15.174)$$

**Calculation of Smoothing Parameters**

$$\frac{1}{m} = P_{0;m} + \frac{L_{EN}}{L_E} \cdot P_{L;m} + \frac{W_{EN}}{W_E} \cdot P_{W;m} + \frac{L_{EN} \cdot W_{EN}}{L_E \cdot W_E} \cdot P_{LW;m} \quad (15.175)$$

**Calculation of Weak-Avalanche Parameters**

$$a_1 = P_{0;a_1} + \frac{L_{EN}}{L_E} \cdot P_{L;a_1} + \frac{W_{EN}}{W_E} \cdot P_{W;a_1} + \frac{L_{EN} \cdot W_{EN}}{L_E \cdot W_E} \cdot P_{LW;a_1} \quad (15.176)$$

$$a_2 = P_{0;a_2} + \frac{L_{EN}}{L_E} \cdot P_{L;a_2} + \frac{W_{EN}}{W_E} \cdot P_{W;a_2} + \frac{L_{EN} \cdot W_{EN}}{L_E \cdot W_E} \cdot P_{LW;a_2} \quad (15.177)$$

$$a_3 = P_{0;a_3} + \frac{L_{EN}}{L_E} \cdot P_{L;a_3} + \frac{W_{EN}}{W_E} \cdot P_{W;a_3} + \frac{L_{EN} \cdot W_{EN}}{L_E \cdot W_E} \cdot P_{LW;a_3} \quad (15.178)$$

**Calculation of Gate Current Parameters**

$$I_{GINV} = P_{0;I_{GINV}} + \frac{L_E}{L_{EN}} \cdot P_{L;I_{GINV}} + \frac{W_E}{W_{EN}} \cdot P_{W;I_{GINV}} + \frac{L_E \cdot W_E}{L_{EN} \cdot W_{EN}} \cdot P_{LW;I_{GINV}} \quad (15.179)$$

$$B_{INV} = P_{0;B_{INV}} + \frac{L_{EN}}{L_E} \cdot P_{L;B_{INV}} + \frac{W_{EN}}{W_E} \cdot P_{W;B_{INV}} + \frac{L_{EN} \cdot W_{EN}}{L_E \cdot W_E} \cdot P_{LW;B_{INV}} \quad (15.180)$$

$$I_{GACC} = P_{0;I_{GACC}} + \frac{L_E}{L_{EN}} \cdot P_{L;I_{GACC}} + \frac{W_E}{W_{EN}} \cdot P_{W;I_{GACC}} + \frac{L_E \cdot W_E}{L_{EN} \cdot W_{EN}} \cdot P_{LW;I_{GACC}} \quad (15.181)$$

$$B_{acc} = P_{0;B_{acc}} + \frac{L_{EN}}{L_E} \cdot P_{L;B_{acc}} + \frac{W_{EN}}{W_E} \cdot P_{W;B_{acc}} + \frac{L_{EN} \cdot W_{EN}}{L_E \cdot W_E} \cdot P_{LW;B_{acc}} \quad (15.182)$$

$$I_{GOV} = P_{0;I_{GOV}} + \frac{L_{EN}}{L_E} \cdot P_{L;I_{GOV}} + \frac{W_E}{W_{EN}} \cdot P_{W;I_{GOV}} + \frac{W_E}{L_E} \cdot P_{LW;I_{GOV}} \quad (15.183)$$

### Calculation of Gate-Induced Drain Leakage Parameters

$$A_{GIDL} = P_{0;A_{GIDL}} + \frac{L_{EN}}{L_E} \cdot P_{L;A_{GIDL}} + \frac{W_E}{W_{EN}} \cdot P_{W;A_{GIDL}} + \frac{W_E}{L_E} \cdot P_{LW;A_{GIDL}} \quad (15.184)$$

$$B_{GIDL} = P_{0;B_{GIDL}} + \frac{L_{EN}}{L_E} \cdot P_{L;B_{GIDL}} + \frac{W_{EN}}{W_E} \cdot P_{W;B_{GIDL}} + \frac{L_{EN} \cdot W_{EN}}{L_E \cdot W_E} \cdot P_{LW;B_{GIDL}} \quad (15.185)$$

$$C_{GIDL} = P_{0;C_{GIDL}} + \frac{L_{EN}}{L_E} \cdot P_{L;C_{GIDL}} + \frac{W_{EN}}{W_E} \cdot P_{W;C_{GIDL}} + \frac{L_{EN} \cdot W_{EN}}{L_E \cdot W_E} \cdot P_{LW;C_{GIDL}} \quad (15.186)$$

### Calculation of Charge Parameters

$$C_{OX} = P_{0;C_{ox}} + \frac{L_E}{L_{EN}} \cdot P_{L;C_{ox}} + \frac{W_E}{W_{EN}} \cdot P_{W;C_{ox}} + \frac{L_E \cdot W_E}{L_{EN} \cdot W_{EN}} \cdot P_{LW;C_{ox}} \quad (15.187)$$

$$C_{GDO} = P_{0;C_{GDO}} + \frac{L_{EN}}{L_E} \cdot P_{L;C_{GDO}} + \frac{W_E}{W_{EN}} \cdot P_{W;C_{GDO}} + \frac{W_E}{L_E} \cdot P_{LW;C_{GDO}} \quad (15.188)$$

$$C_{GSO} = P_{0;C_{GSO}} + \frac{L_{EN}}{L_E} \cdot P_{L;C_{GSO}} + \frac{W_E}{W_{EN}} \cdot P_{W;C_{GSO}} + \frac{W_E}{L_E} \cdot P_{LW;C_{GSO}} \quad (15.189)$$

### Calculation of Noise Parameters

$$N_{FA} = P_{0;N_{FA}} + \frac{L_{EN}}{L_E} \cdot P_{L;N_{FA}} + \frac{W_{EN}}{W_E} \cdot P_{W;N_{FA}} + \frac{L_{EN} \cdot W_{EN}}{L_E \cdot W_E} \cdot P_{LW;N_{FA}} \quad (15.190)$$

$$N_{FB} = P_{0;N_{FB}} + \frac{L_{EN}}{L_E} \cdot P_{L;N_{FB}} + \frac{W_{EN}}{W_E} \cdot P_{W;N_{FB}} + \frac{L_{EN} \cdot W_{EN}}{L_E \cdot W_E} \cdot P_{LW;N_{FB}} \quad (15.191)$$

$$N_{FC} = P_{0;N_{FC}} + \frac{L_{EN}}{L_E} \cdot P_{L;N_{FC}} + \frac{W_{EN}}{W_E} \cdot P_{W;N_{FC}} + \frac{L_{EN} \cdot W_{EN}}{L_E \cdot W_E} \cdot P_{LW;N_{FC}} \quad (15.192)$$

### Calculation of Treshold-voltage Temperature-Scaling Coefficients

$$S_{T;V_{FB}} = P_{0;T;V_{FB}} + \frac{L_{EN}}{L_E} \cdot P_{L;T;V_{FB}} + \frac{W_{EN}}{W_E} \cdot P_{W;T;V_{FB}} + \frac{L_{EN} \cdot W_{EN}}{L_E \cdot W_E} \cdot P_{LW;T;V_{FB}}$$

(15.193)

$$S_{T;\phi_B} = P_{0;T;\phi_B} + \frac{L_{EN}}{L_E} \cdot P_{L;T;\phi_B} + \frac{W_{EN}}{W_E} \cdot P_{W;T;\phi_B} + \frac{L_{EN} \cdot W_{EN}}{L_E \cdot W_E} \cdot P_{LW;T;\phi_B}$$

(15.194)

### Calculation of Mobility/Series-Resistance Temperature-Scaling Coefficients

$$\eta_{\beta} = P_{0;T;\eta_{\beta}} + \frac{L_{EN}}{L_E} \cdot P_{L;T;\eta_{\beta}} + \frac{W_{EN}}{W_E} \cdot P_{W;T;\eta_{\beta}} + \frac{L_{EN} \cdot W_{EN}}{L_E \cdot W_E} \cdot P_{LW;T;\eta_{\beta}}$$

(15.195)

$$\eta_{sr} = P_{0;T;\eta_{sr}} + \frac{L_{EN}}{L_E} \cdot P_{L;T;\eta_{sr}} + \frac{W_{EN}}{W_E} \cdot P_{W;T;\eta_{sr}} + \frac{L_{EN} \cdot W_{EN}}{L_E \cdot W_E} \cdot P_{LW;T;\eta_{sr}}$$

(15.196)

$$\eta_{ph} = P_{0;T;\eta_{ph}} + \frac{L_{EN}}{L_E} \cdot P_{L;T;\eta_{ph}} + \frac{W_{EN}}{W_E} \cdot P_{W;T;\eta_{ph}} + \frac{L_{EN} \cdot W_{EN}}{L_E \cdot W_E} \cdot P_{LW;T;\eta_{ph}}$$

(15.197)

$$S_{T;\eta_{mob}} = P_{0;T;\eta_{mob}} + \frac{L_{EN}}{L_E} \cdot P_{L;T;\eta_{mob}} + \frac{W_{EN}}{W_E} \cdot P_{W;T;\eta_{mob}} + \frac{L_{EN} \cdot W_{EN}}{L_E \cdot W_E} \cdot P_{LW;T;\eta_{mob}}$$

(15.198)

$$v_{exp} = P_{0;T;v_{exp}} + \frac{L_{EN}}{L_E} \cdot P_{L;T;v_{exp}} + \frac{W_{EN}}{W_E} \cdot P_{W;T;v_{exp}} + \frac{L_{EN} \cdot W_{EN}}{L_E \cdot W_E} \cdot P_{LW;T;v_{exp}}$$

(15.199)

$$\eta_{C_s} = P_{0;T;\eta_{C_s}} + \frac{L_{EN}}{L_E} \cdot P_{L;T;\eta_{C_s}} + \frac{W_{EN}}{W_E} \cdot P_{W;T;\eta_{C_s}} + \frac{L_{EN} \cdot W_{EN}}{L_E \cdot W_E} \cdot P_{LW;T;\eta_{C_s}}$$

(15.200)

$$\eta_R = P_{0;T;\eta_R} + \frac{L_{EN}}{L_E} \cdot P_{L;T;\eta_R} + \frac{W_{EN}}{W_E} \cdot P_{W;T;\eta_R} + \frac{L_{EN} \cdot W_{EN}}{L_E \cdot W_E} \cdot P_{LW;T;\eta_R}$$

(15.201)

$$\eta_{sat} = P_{0;T;\eta_{sat}} + \frac{L_{EN}}{L_E} \cdot P_{L;T;\eta_{sat}} + \frac{W_{EN}}{W_E} \cdot P_{W;T;\eta_{sat}} + \frac{L_{EN} \cdot W_{EN}}{L_E \cdot W_E} \cdot P_{LW;T;\eta_{sat}}$$

(15.202)

### Calculation of Weak-Avalanche Temperature-Scaling Coefficients

$$S_{T;a_1} = P_{0;T;a_1} + \frac{L_{EN}}{L_E} \cdot P_{L;T;a_1} + \frac{W_{EN}}{W_E} \cdot P_{W;T;a_1} + \frac{L_{EN} \cdot W_{EN}}{L_E \cdot W_E} \cdot P_{LW;T;a_1}$$

(15.203)

### Calculation of Gate-Induced Drain Leakage Temperature-Scaling Coefficients

$$S_{T;B_{GIDL}} = P_{0;T;B_{GIDL}} + \frac{L_{EN}}{L_E} \cdot P_{L;T;B_{GIDL}} + \frac{W_{EN}}{W_E} \cdot P_{W;T;B_{GIDL}} + \frac{L_{EN} \cdot W_{EN}}{L_E \cdot W_E} \cdot P_{LW;T;B_{GIDL}}$$

(15.204)

## Calculation of Temperature-Dependent Parameters

### Calculation of Transistor Temperature

#### 3 Note

Note the addition of the voltage  $V_{dT}$  of the thermal node in order to include self-heating, see Section 15.6.

$$T_{KR} = T_0 + T_R \quad (15.205)$$

$$T_{KD} = T_0 + T_A + \Delta T_A + V_{dT} \quad (15.206)$$

### Calculation of Threshold-Voltage Parameters

$$\phi_T = \frac{k_B \cdot T_{KD}}{q} \quad (15.207)$$

$$V_{FB_T} = V_{FB} + (T_{KD} - T_{KR}) \cdot S_{T;V_{FB}} \quad (15.208)$$

$$\phi_{B_T} = \phi_B + (T_{KD} - T_{KR}) \cdot S_{T;\phi_B} \quad (15.209)$$

### Calculation of Mobility/Series-Resistance Parameters

$$\beta_T = \beta \cdot \left( \frac{T_{KR}}{T_{KD}} \right)^{\eta_\beta} \quad (15.210)$$

$$\theta_{sr_T} = \theta_{sr} \cdot \left( \frac{T_{KR}}{T_{KD}} \right)^{\eta_{sr}} \quad (15.211)$$

$$\theta_{ph_T} = \theta_{ph} \cdot \left( \frac{T_{KD}}{T_{KR}} \right)^{\eta_{ph}} \quad (15.212)$$

$$\eta_{mob_T} = \eta_{mob} \cdot [1 + (T_{KD} - T_{KR}) \cdot S_{T;\eta_{mob}}] \quad (15.213)$$

$$C_{s_T} = C_s \cdot \left( \frac{T_{KR}}{T_{KD}} \right)^{\eta_{C_s}} \quad (15.214)$$

$$v_T = 1 + (v - 1) \cdot (T_{KR}/T_{KD})^{v_{exp}} \quad (15.215)$$

$$\theta_{R_T} = \theta_R \cdot \left( \frac{T_{KR}}{T_{KD}} \right)^{\eta_R} \quad (15.216)$$

$$\theta_{sat_T} = \theta_{sat} \cdot \left( \frac{T_{KR}}{T_{KD}} \right)^{\eta_{sat}} \quad (15.217)$$

### Calculation of Conductance Parameters

$$\theta_{Th_T} = \theta_{Th} \cdot \left( \frac{T_{KR}}{T_{KD}} \right)^{\eta_{\beta}} \quad (15.218)$$

### Calculation of Weak-Avalanche Parameters

$$a_{1_T} = a_1 \cdot [1 + (T_{KD} - T_{KR}) \cdot S_{T;a_1}] \quad (15.219)$$

### Calculation of Gate-Induced Drain Leakage Parameters

$$B_{GIDL_T} = B_{GIDL} \cdot [1 + (T_{KD} - T_{KR}) \cdot S_{T;B_{GIDL}}] \quad (15.220)$$

**Calculation of Noise Parameters**

$$N_{T_T} = \frac{T_{KD}}{T_{KR}} \cdot N_T \quad (15.221)$$

## 15.5 Model Equations

The electrical equations of MOS Model 11 to be implemented are essentially the basic equations of Section 15.2. Since in circuit design equal parallel circuited transistors are frequently applied the specification of one transistor together with a multiplication factor  $NF \cdot N_{MULT}$  in the circuit description is convenient and saves computation time. The general and safe method to implement this mechanism into the model is to evaluate the currents, charges, noise spectral densities and their derivatives with respect to the external voltages and, at the end, to multiply them by  $NF \cdot N_{MULT}$ . In MOS Model 11 it is allowed to circumvent these multiplications for each model evaluation during circuit simulation by adjusting some parameters. In this case the following rules apply:

$$\beta = \beta \cdot NF \cdot N_{MULT}$$

$$I_{GINV} = I_{GINV} \cdot NF \cdot N_{MULT}$$

$$I_{GACC} = I_{GACC} \cdot NF \cdot N_{MULT}$$

$$I_{GOV} = I_{GOV} \cdot NF \cdot N_{MULT}$$

$$A_{GIDL} = A_{GIDL} \cdot NF \cdot N_{MULT}$$

$$C_{OX} = C_{OX} \cdot NF \cdot N_{MULT}$$

$$C_{GDO} = C_{GDO} \cdot NF \cdot N_{MULT}$$

$$C_{GSO} = C_{GSO} \cdot NF \cdot N_{MULT}$$

$$N_{FA} = \frac{N_{FA}}{NF \cdot N_{MULT}}$$

$$N_{FB} = \frac{N_{FB}}{NF \cdot N_{MULT}}$$

$$N_{FC} = \frac{N_{FC}}{NF \cdot N_{MULT}}$$

Although the basic equations, given in Section 15.2, form a complete set of model equations, they are not yet suited for a circuit simulator. Several equations have to be adapted in order to obtain smooth transitions of the characteristics between adjacent regions of operation and to prevent numerical problems during the iteration process for solving the network equations. In the following section a list of numerical adaptations and elucidations is given, followed by the extended set of model equations.

The definition of the hyp-function, which provides for a smooth  $C_\infty$ -continuous clipping, is to be found in Appendix A.

### 15.5.1 Extended Equations

In the following sections a function is denoted by  $F\{\text{variable}, \dots\}$ , where  $F$  denotes the function name and the function variables are enclosed by braces  $\{\}$ . The definition of the hyp-functions can be found in *Appendix A Hyp functions*.

#### Internal Parameters

$$\varepsilon_1 = 1 \cdot 10^{-2}$$

$$\varepsilon_2 = 4 \cdot 10^{-2}$$

$$\varepsilon_3 = 1 \cdot 10^{-4}$$

$$P_D = 1 + (k_0/k_p)^2$$

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

$$\theta_{R_{eff}} = \frac{1}{2} \cdot \theta_{R_T} \cdot \left( 1 + \frac{\theta_{R1}}{1/2 + \theta_{R2}} \right)$$

$$m_{\phi_T} = (1 + m_0) \cdot \phi_T$$

$$Acc = \left. \frac{\partial \psi_s}{\partial V_{GB}} \right|_{V_{GB} = V_{FB_T}} = \frac{1}{1 + k_0 / \sqrt{2} \cdot \phi_T}$$

$$Acc_{ov} = \left. \frac{\partial \psi_{sov}}{\partial V_{GB}} \right|_{V_{GB} = V_{FB_{ov}}} = \frac{1}{1 + k_{ov} / \sqrt{2} \cdot \phi_T}$$

$$QM_{\psi} = \begin{cases} QM_N \cdot (\epsilon_{ox} / t_{ox})^{2/3} & \text{for NMOS} \\ QM_P \cdot (\epsilon_{ox} / t_{ox})^{2/3} & \text{for PMOS} \end{cases}$$

$$QM_{tox} = \frac{2}{5} \cdot QM_{\psi}$$

$$\chi_{B_{inv}} = \begin{cases} \chi_{B_N} & \text{for NMOS} \\ \chi_{B_P} & \text{for PMOS} \end{cases}$$

$$\chi_{B_{acc}} = \chi_{B_N}$$

### Extended Current Equations

$$V_{GB_{eff}} = \text{hyp}_1(V_{GS} + V_{SB} - V_{FB_T}; \epsilon_1) \quad (15.222)$$

$$V_{SB_t} = \text{hyp}_1(V_{SB} + 0.9 \cdot \phi_{B_T}; \epsilon_2) + 0.1 \cdot \phi_{B_T} \quad (15.223)$$

$$\Psi_{sat_0} = \left( \frac{\sqrt{P_D \cdot V_{GB_{eff}} + k_0^2 / 4 - k_0 / 2}}{P_D} \right)^2 \quad (15.224)$$

**Drain induced barrier lowering and Static Feedback**

$$D_{dibl} = \sigma_{dibl} \cdot \sqrt{V_{SB_i}} \quad (15.225)$$

$$D_{sf} = \sigma_{sf} \cdot \sqrt{\text{hyp}_1(\Psi_{sat_0} - V_{SB_i}, \epsilon_2)} \quad (15.226)$$

$$V_{DS_{eff}} = \frac{V_{DS}^4}{(V_{limit}^2 + V_{DS}^2)^{3/2}} \quad (15.227)$$

$$\Delta V_G = \sqrt{D_{dibl}^2 + D_{sf}^2} \cdot V_{DS_{eff}} \quad (15.228)$$

**Effective Gate-Bulk Voltage**

$$V_{GB}^* = V_{GS} + V_{SB} + \Delta V_G - V_{FB_T} \quad (15.229)$$

**Drain Saturation Voltage**

Equations 15.230 to 15.234 are only calculated for  $V_{GB}^* > 0$ :

$$\Psi_{sat_1} = \left( \frac{\sqrt{P_D \cdot V_{GB}^* + k_0^2/4 - k_0/2}}{P_D} \right)^2 \quad (15.230)$$

$$V_{DSAT_{long}} = \Psi_{sat_1} - V_{SB_i} \quad (15.231)$$

$$T_{sat} = \begin{cases} \theta_{sat_T} & \text{for NMOS} \\ \frac{\theta_{sat_T}}{(1 + \theta_{sat_T}^2 \cdot V_{DSAT_{long}}^2)^{1/4}} & \text{for PMOS} \end{cases} \quad (15.232)$$

$$\Delta_{SAT} = \frac{(T_{sat} - \theta_{R_{eff}}) \cdot V_{DSAT_{long}}}{\frac{1}{2} \cdot \left( \sqrt{2} + \sqrt{2 + 2 \cdot T_{sat}^2 \cdot V_{DSAT_{long}}^2} \right) + \theta_{R_{eff}} \cdot V_{DSAT_{long}}} \quad (15.233)$$

$$V_{DSAT_{short}} = V_{DSAT_{long}} \cdot \left[ 1 - \frac{44/45 \cdot \Delta_{SAT}}{1 + \sqrt{1 - \frac{(\sqrt{2} - 1) \cdot T_{sat} - \theta_{R_{eff}} \cdot \Delta_{SAT}}{T_{sat} - \theta_{R_{eff}}}}} \right] \quad (15.234)$$

$$V_{Dsat} = \begin{cases} V_{limit} & \text{for: } V_{GB}^* \leq 0 \\ V_{limit} + \text{hyp}_1\{V_{DSAT_{short}} - V_{limit}, \epsilon_2\} & \text{for: } V_{GB}^* > 0 \end{cases} \quad (15.235)$$

$$V_{DS_x} = \frac{V_{DS}}{[1 + (V_{DS}/V_{DSAT})^{2 \cdot m}]^{\frac{1}{2 \cdot m}}} \quad (15.236)$$

$$V_{DB_i} = V_{DS_x} + \phi_{B_T} \quad (15.237)$$

## Surface Potential

The surface potential  $\psi_s$  is given by the following implicit relation:

$$F\{\psi_s, \phi\} = -V_{ox}\{\psi_s\}^2 + k_0^2 \cdot d\{\psi_s, \phi\} = 0 \quad (15.238)$$

where  $\phi$  can be either  $V_{SB_i}$  or  $V_{DB_i}$ , and:

$$V_{GC}^*\{\psi_s\} = V_{GB}^* - \psi_s \quad (15.239)$$

$$c\{\psi_s\} = \frac{1}{2} + \frac{1}{2} \cdot \sqrt{1 + 4/k_p^2 \cdot hyp_1\{V_{GC}^*\{\psi_s\}, \epsilon_1\}} \quad (15.240)$$

$$V_{ox}\{\psi_s\} = \frac{V_{GC}^*\{\psi_s\}}{c\{\psi_s\}} \quad (15.241)$$

$$\begin{aligned} d\{\psi_s, \phi\} = & \psi_s + \phi_T \cdot \left[ \exp\left(-\frac{\psi_s}{\phi_T}\right) - 1 \right] \\ & + \phi_T \cdot \exp\left(-\frac{\phi}{m_{\phi_T}}\right) \cdot \left[ \exp\left(\frac{\psi_s}{m_{\phi_T}}\right) - \frac{\psi_s}{m_{\phi_T}} - 1 \right] \end{aligned} \quad (15.242)$$

The surface potential is iteratively calculated using a second-order Newton Raphson procedure, where the surface potential  $\psi_{i+1}$  in the  $i + 1^{\text{th}}$  iteration is given in terms of the surface potential  $\psi_i$  in the  $i^{\text{th}}$  iteration by:

$$\psi_{i+1} = \psi_i - \frac{F_i}{F'_i - \frac{1}{2} \cdot F_i \cdot F''_i / F'_i} \quad (15.243)$$

where:

$$F_i = F\{\psi_i, \phi\} = -V_{ox}\{\psi_i\}^2 + k_0^2 \cdot d\{\psi_i, \phi\} \quad (15.244)$$

$$F'_i = \left. \frac{\partial F\{\psi_i, \phi\}}{\partial \psi_s} \right|_{\psi_s = \psi_i} = -2 \cdot V_{ox}\{\psi_i\} \cdot V'_{ox}\{\psi_i\} + k_0^2 \cdot d'\{\psi_i, \phi\} \quad (15.245)$$

$$F''_i = \left. \frac{\partial^2 F\{\psi_i, \phi\}}{\partial \psi_s^2} \right|_{\psi_s = \psi_i} = -2 \cdot V'_{ox}\{\psi_i\}^2 - 2 \cdot V_{ox}\{\psi_i\} \cdot V''_{ox}\{\psi_i\} + k_0^2 \cdot d''\{\psi_i, \phi\} \quad (15.246)$$

The first-order and second-order derivatives are given by:

$$c'\{\psi_s\} = \frac{\partial c\{\psi_s\}}{\partial \psi_s} = -\frac{1}{4} \cdot \frac{4/k_p^2}{2 \cdot c\{\psi_s\} - 1} \cdot \frac{\partial hyp_1\{V_{GC}^*\{\psi_s\}, \epsilon_1\}}{\partial V_{GC}^*} \quad (15.247)$$

$$c''\{\psi_s\} = \frac{\partial^2 c\{\psi_s\}}{\partial \psi_s^2} = -\frac{2 \cdot c'\{\psi_s\}^2 - \frac{1}{k_p^2} \cdot \frac{\partial^2 hyp_1\{V_{GC}^*\{\psi_s\}, \epsilon_1\}}{\partial V_{GC}^{*2}}}{2 \cdot c\{\psi_s\} - 1} \quad (15.248)$$

$$V'_{ox}\{\psi_s\} = \frac{\partial V_{ox}\{\psi_s\}}{\partial \psi_s} = -\frac{1 + V_{ox}\{\psi_s\} \cdot c'\{\psi_s\}}{c\{\psi_s\}} \quad (15.249)$$

$$V''_{ox}\{\psi_s\} = \frac{\partial^2 V_{ox}\{\psi_s\}}{\partial \psi_s^2} = -\frac{2 \cdot c'\{\psi_s\} \cdot V'_{ox}\{\psi_s\} + V_{ox}\{\psi_s\} \cdot c''\{\psi_s\}}{c\{\psi_s\}} \quad (15.250)$$

$$\begin{aligned}
 d'\{\psi_s, \phi\} &= \frac{\partial d\{\psi_s, \phi\}}{\partial \psi_s} \\
 &= 1 - \exp\left(-\frac{\psi_s}{\phi_T}\right) + \frac{\phi_T}{m_{\phi_T}} \cdot \exp\left(-\frac{\phi}{m_{\phi_T}}\right) \cdot \left[\exp\left(\frac{\psi_s}{m_{\phi_T}}\right) - 1\right]
 \end{aligned} \tag{15.251}$$

$$d''\{\psi_s, \phi\} = \frac{\partial^2 d\{\psi_s, \phi\}}{\partial \psi_s^2} = \frac{\exp\left(-\frac{\psi_s}{\phi_T}\right)}{\phi_T} + \frac{\phi_T}{m_{\phi_T}} \cdot \frac{\exp\left(\frac{\psi_s - \phi}{m_{\phi_T}}\right)}{m_{\phi_T}} \tag{15.252}$$

The iterative loop is performed until  $|\psi_{i+1} - \psi_i| < 10^{-10} \cdot \phi_T$ , at which point  $\psi_s$  is taken to be equal to  $\psi_{i+1}$ . As a zero-order starting value  $\psi_0$ , the following approximation is used:

$$\left. \begin{array}{l}
 \text{if } V_{GB}^* \geq \phi_T \left\{ \begin{array}{l}
 \Psi_{sat} = \left( \frac{\sqrt{P_D \cdot (V_{GB}^* - \phi_T) + k_0^2/4 - k_0/2}}{P_D} \right)^2 + \phi_T \\
 \text{if } \Psi_{sat} \leq \phi \{ \Psi_0 = \Psi_{sat} \\
 \text{if } \Psi_{sat} > \phi \left\{ \begin{array}{l}
 V_{ox} = \frac{2 \cdot [V_{GB}^* - \phi]}{1 + \sqrt{1 + 4/k_p^2 \cdot [V_{GB}^* - \phi]}} \\
 x = k_0^2 \cdot \max(V_{ox}^2/k_0^2 - \phi + \phi_T, \phi_T) \\
 y = k_0^2 + \frac{2 \cdot V_{ox}}{\sqrt{1 + 4/k_p^2 \cdot [V_{GB}^* - \phi]}} \\
 z = 1 + 4/k_p^2 \cdot (V_{GB}^* - \phi) \\
 \Psi_0 = \phi + \frac{2 \cdot m_{\phi_T} \cdot x \cdot \ln\left(\frac{x}{\phi_T \cdot k_0^2}\right)}{x + m_{\phi_T} \cdot y + \sqrt{(x + m_{\phi_T} \cdot y)^2 - m_{\phi_T}^2 \cdot (x/z - y^2/2)} \cdot \ln\left(\frac{x}{\phi_T \cdot k_0^2}\right)}
 \end{array} \right. \\
 \text{if } V_{GB}^* < \phi_T \left\{ \begin{array}{l}
 \text{if } V_{GB}^* \geq 0 \{ \Psi_0 = 0 \\
 \text{if } V_{GB}^* < 0 \left\{ \begin{array}{l}
 x = V_{GB}^{*2} + \phi_T \cdot k_0^2 \\
 y = k_0^2 + 2 \cdot V_{GB}^* \\
 \Psi_0 = - \frac{2 \cdot \phi_T \cdot x \cdot \ln\left(\frac{x}{\phi_T \cdot k_0^2}\right)}{x - \phi_T \cdot y + \sqrt{(x - \phi_T \cdot y)^2 - \phi_T^2 \cdot (x - y^2/2)} \cdot \ln\left(\frac{x}{\phi_T \cdot k_0^2}\right)}
 \end{array} \right.
 \end{array} \right.
 \end{array} \right.
 \end{array} \right.
 \end{array}
 \quad (15.253)$$

When  $V_{GB}^* = 0$ , the starting value  $\psi_0$  is equal to zero. No iterative solution is necessary, and  $\psi_s$  is automatically taken to be equal to zero. Surface potentials at source and drain are now calculated from the following implicit relations:

$$F\{\psi_{s_0}, V_{SB_t}\} = 0 \quad (15.254)$$

$$F\{\psi_{s_L}, V_{DB_t}\} = 0 \quad (15.255)$$

**Auxiliary Variables:**

$$\Delta\psi = \psi_{s_L} - \psi_{s_0} \quad (15.256)$$

$$\bar{\psi} = \frac{\psi_{s_L} + \psi_{s_0}}{2} \quad (15.257)$$

Inversion-Layer Charge ( $Q_{inv} = -\epsilon_{ox}/t_{ox} \cdot V_{inv}$ ):

$$V_{inv}\{\psi_s, \phi\} = \begin{cases} 0 & \text{for: } V_{GB}^* - \psi_s \leq 0 \\ \frac{k_0 \cdot \phi_T \cdot \exp(-\phi/m_{\phi_T}) \cdot [\exp(\psi_s/m_{\phi_T}) - \psi_s/m_{\phi_T} - 1]}{\sqrt{d\{\phi, \psi_s\}} + \sqrt{\psi_s + \phi_T \cdot [\exp(-\psi_s/\phi_T) - 1]}} & \text{for: } V_{GB}^* - \psi_s > 0 \end{cases} \quad (15.258)$$

$$V_{inv_0} = V_{inv}\{\psi_{s_0}, V_{SB_t}\} \quad (15.259)$$

$$V_{inv_L} = V_{inv}\{\psi_{s_L}, V_{DB_t}\} \quad (15.260)$$

$$\bar{V}_{inv} = \frac{V_{inv_0} + V_{inv_L}}{2} \quad (15.261)$$

$$\bar{V}_{OX} = \frac{V_{ox}\{\psi_{s_0}\} + V_{ox}\{\psi_{s_L}\}}{2} \quad (15.262)$$

$$\bar{V}_{dep} = \bar{V}_{ox} - \bar{V}_{inv} \quad (15.263)$$

$$V_{eff} = \bar{V}_{inv} + \eta_{mob_T} \cdot (\bar{V}_{ox} - \bar{V}_{inv}) \quad (15.264)$$

$$\xi_{ox}(\Psi_s) = -\phi_T \cdot V'_{ox}\{\Psi_s\} \quad (15.265)$$

$$\bar{\xi}_{ox} = -\phi_T \cdot \frac{V'_{ox}\{\Psi_{s_0}\} + V'_{ox}\{\Psi_{s_L}\}}{2} \quad (15.266)$$

$$\xi\{\Psi_s\} = \begin{cases} \xi_{ox}\{\Psi_s\} + \phi_T \cdot \left[ \frac{1}{Acc} - 1 \right] & \text{for: } V_{GB}^* - \Psi_s \leq 0 \\ \xi_{ox}\{\Psi_s\} + \phi_T \cdot \frac{k_0 \cdot [1 - \exp(-\Psi_s/\phi_T)]}{2 \cdot \sqrt{\Psi_s + \phi_T} \cdot [\exp(-\Psi_s/\phi_T) - 1]} & \text{for: } V_{GB}^* - \Psi_s > 0 \end{cases} \quad (15.267)$$

$$\bar{\xi} = \frac{\xi\{\Psi_{s_0}\} + \xi\{\Psi_{s_L}\}}{2} \quad (15.268)$$

$$\bar{V}_{inv}^* = \bar{V}_{inv} + (1 + m_0) \cdot \bar{\xi} \quad (15.269)$$

### Second-Order Effects

The expressions related to the second-order effects (15.270) - (15.278) are only calculated for  $V_{GB}^* - \bar{\Psi} > 0$ :

**Mobility Degradation:**

$$G_{mob} = \frac{\mu_0}{\mu} = \begin{cases} 1 + \left[ (\theta_{ph_T} \cdot V_{eff})^{v_T/3} + (\theta_{sr_T} \cdot V_{eff})^{2 \cdot v_T} \right]^{1/v_T} + C_{s_T} \cdot \left( \frac{\bar{V}_{dep}}{\bar{V}_{dep} + \bar{V}_{inv} + \epsilon_4} \right)^2 & \text{for NMOS} \\ 1 + \left[ (\theta_{ph_T} \cdot V_{eff})^{v_T/3} + (\theta_{sr_T} \cdot V_{eff})^{v_T} \right]^{1/v_T} + C_{s_T} \cdot \left( \frac{\bar{V}_{dep}}{\bar{V}_{dep} + \bar{V}_{inv} + \epsilon_4} \right)^2 & \text{for PMOS} \end{cases} \quad (15.270)$$

**Channel Length Modulation:**

$$\frac{\Delta L}{L} = \alpha \cdot \ln \left[ \frac{V_{DS} - V_{DS_x} + \sqrt{(V_{DS} - V_{DS_x})^2 + V_p^2}}{V_p} \right] \quad (15.271)$$

$$G_{\Delta L} = \frac{1}{1 + (\Delta L/L) + (\Delta L/L)^2} \quad (15.272)$$

**Velocity Saturation:**

$$x_{sat} = \begin{cases} \frac{\theta_{sat_T} \cdot \Delta \psi}{G_{mob}} & \text{for NMOS} \\ \frac{\theta_{sat_T} \cdot \Delta \psi}{G_{mob} \cdot [1 + (\theta_{sat_T} \cdot \Delta \psi / G_{mob})^2]^{1/4}} & \text{for PMOS} \end{cases} \quad (15.273)$$

$$G_{vsat} = \frac{G_{mob}}{2} \cdot [1 + \sqrt{1 + 2 \cdot x_{sat}^2}] \quad (15.274)$$

**Series Resistance and Self-Heating:**

$$G_R = \theta_{R_T} \cdot \left( 1 + \frac{\theta_{R1}}{\theta_{R2} + \bar{V}_{inv}^*} \right) \cdot \bar{V}_{inv}^* \quad (15.275)$$

$$G_{Th} = \theta_{Th_T} \cdot V_{DS} \cdot \Delta\psi \cdot \bar{V}_{inv}^* \quad (15.276)$$

$$G_{tot}^* = G_{vsat} \cdot G_{\Delta L} + G_R \quad (15.277)$$

$$G_{tot} = G_{Th} + \frac{G_{tot}^*}{2} + \sqrt{\text{hyp}_1 \left\{ \frac{G_{tot}^{*2}}{4} - \frac{G_R}{G_{mob}} \cdot \frac{x_{sat}^2}{\sqrt{1 + 2 \cdot x_{sat}^2}}, \varepsilon_3 \right\}} \quad (15.278)$$

**Drain-Source Channel Current:**

Equations (15.279) - (15.280) are only calculated for  $V_{GB}^* - \bar{\psi} > 0$ :

$$I_{drift} = \beta_T \cdot \bar{V}_{inv} \cdot \Delta\psi \quad (15.279)$$

$$I_{diff} = \beta_T \cdot m_{\phi_T} \cdot (V_{inv0} - V_{invL}) \quad (15.280)$$

$$I_{DS} = \begin{cases} 0 & \text{for: } V_{GB}^* - \bar{\psi} \leq 0 \\ \frac{I_{drift} + I_{diff}}{G_{tot}} & \text{for: } V_{GB}^* - \bar{\psi} > 0 \end{cases} \quad (15.281)$$

**Weak-Avalanche:**

$$I_{avl} = \begin{cases} 0 & \text{for: } V_{DS} - a_3 \cdot V_{DSAT} \leq -a_2/A \\ a_{1T} \cdot I_{DS} \cdot \exp\left(-\frac{a_2}{V_{DS} - a_3 \cdot V_{DSAT}}\right) & \text{for: } V_{DS} - a_3 \cdot V_{DSAT} > -a_2/A \end{cases} \quad (15.282)$$

**Surface Potential in Gate Overlap Regions:**

The surface potential in the overlap region  $\psi_{ov}$  is given by the following implicit relation:

$$F_{ov}\{V_{GX}, \Psi_{ov}\} = -V_{ov}\{V_{GX}, \Psi_{ov}\}^2 + k_{ov}^2 \cdot d_{ov}\{\Psi_{ov}\} = 0 \quad (15.283)$$

where:

$$V_{GX}^*\{V_{GX}, \Psi_{ov}\} = V_{GX} - V_{FBov} - \Psi_{ov} \quad (15.284)$$

$$c_{ov}\{V_{GX}, \Psi_{ov}\} = \frac{1}{2} + \frac{1}{2} \cdot \sqrt{1 + 4/k_p^2 \cdot hyp_1\{V_{GX}^*\{V_{GX}, \Psi_{ov}\}, \epsilon_1\}} \quad (15.285)$$

$$V_{ov}\{V_{GX}, \Psi_{ov}\} = \frac{V_{GX}^*\{V_{GX}, \Psi_{ov}\}}{c\{V_{GX}, \Psi_{ov}\}} \quad (15.286)$$

$$d_{ov}\{\Psi_{ov}\} = -\Psi_{ov} + \phi_T \cdot \left[ \exp\left(\frac{\Psi_{ov}}{\phi_T}\right) - 1 \right] \quad (15.287)$$

The surface potential is iteratively calculated using a second-order Newton Raphson procedure, where the surface potential  $\psi_{i+1}$  in the  $i + 1^{\text{th}}$  iteration is given in terms of the surface potential  $\psi_i$  in the  $i^{\text{th}}$  iteration by:

$$\Psi_{i+1} = \Psi_i - \frac{F_{ov_i}}{F'_{ov_i} - \frac{1}{2} \cdot F_{ov_i} \cdot F''_{ov_i} / F'_{ov_i}} \quad (15.288)$$

where:

$$F_{ov_i} = F_{ov}\{V_{GX}, \Psi_i\} = -V_{ov}\{V_{GX}, \Psi_i\}^2 + k_{ov}^2 \cdot d_{ov}\{\Psi_i\} \quad (15.289)$$

$$F'_{ov_i} = \left. \frac{\partial F_{ov}\{V_{GX}, \Psi_{ov}\}}{\partial \Psi_{ov}} \right|_{\Psi_{ov} = \Psi_i} = -2 \cdot V_{ov}\{V_{GX}, \Psi_i\} \cdot V'_{ov}\{V_{GX}, \Psi_i\} + k_{ov}^2 \cdot d'_{ov}\{\Psi_i\} \quad (15.290)$$

$$F''_{ov_i} = \left. \frac{\partial^2 F_{ov}\{V_{GX}, \Psi_{ov}\}}{\partial \Psi_{ov}^2} \right|_{\Psi_{ov} = \Psi_i} \quad (15.291)$$

$$= -2 \cdot V'_{ov}\{V_{GX}, \Psi_i\}^2 - 2 \cdot V_{ov}\{V_{GX}, \Psi_i\} \cdot V''_{ov}\{V_{GX}, \Psi_i\} + k_{ov}^2 \cdot d''_{ov}\{\Psi_i\} \quad (15.292)$$

The first-order and second-order derivatives are given by:

$$\begin{aligned} c'_{ov}\{V_{GX}, \Psi_{ov}\} &= \frac{\partial c_{ov}\{V_{GX}, \Psi_{ov}\}}{\partial \Psi_{ov}} \\ &= -\frac{1}{4} \cdot \frac{4/k_p^2}{2 \cdot c_{ov}\{V_{GX}, \Psi_{ov}\} - 1} \cdot \frac{\partial hyp_1\{V_{GX}^*\{V_{GX}, \Psi_{ov}\}, \varepsilon_1\}}{\partial V_{GX}^*} \end{aligned} \quad (15.293)$$

$$\begin{aligned} c''_{ov}\{V_{GX}, \Psi_{ov}\} &= \frac{\partial^2 c_{ov}\{V_{GX}, \Psi_{ov}\}}{\partial \Psi_{ov}^2} \\ &= -\frac{2 \cdot c'_{ov}\{V_{GX}, \Psi_{ov}\}^2 - \frac{1}{k_p^2} \cdot \frac{\partial^2 hyp_1\{V_{GX}^*\{V_{GX}, \Psi_{ov}\}, \varepsilon_1\}}{\partial V_{GX}^*}}{2 \cdot c_{ov}\{V_{GX}, \Psi_{ov}\} - 1} \end{aligned} \quad (15.294)$$

$$V'_{ov}\{V_{GX},\Psi_{ov}\} = \frac{\partial V_{ov}\{V_{GX},\Psi_{ov}\}}{\partial \Psi_{ov}} = -\frac{1 + V_{ov}\{V_{GX},\Psi_{ov}\} \cdot c'_{ov}\{V_{GX},\Psi_{ov}\}}{c_{ov}\{V_{GX},\Psi_{ov}\}} \quad (15.295)$$

$$\begin{aligned} V''_{ov}\{V_{GX},\Psi_{ov}\} &= \frac{\partial^2 V_{ov}\{V_{GX},\Psi_{ov}\}}{\partial \Psi_{ov}^2} \\ &= -\frac{2 \cdot c'_{ov}\{V_{GX},\Psi_{ov}\} \cdot V'_{ov}\{V_{GX},\Psi_{ov}\} + V_{ov}\{V_{GX},\Psi_{ov}\} \cdot c''_{ov}\{V_{GX},\Psi_{ov}\}}{c_{ov}\{V_{GX},\Psi_{ov}\}} \end{aligned} \quad (15.296)$$

$$d'_{ov}\{\Psi_{ov}\} = \frac{\partial d_{ov}\{\Psi_{ov}\}}{\partial \Psi_{ov}} = -1 + \exp\left(\frac{\Psi_{ov}}{\phi_T}\right) \quad (15.297)$$

$$d''_{ov}\{\Psi_{ov}\} = \frac{\partial^2 d_{ov}\{\Psi_{ov}\}}{\partial \Psi_{ov}^2} = \frac{\exp\left(\frac{\Psi_{ov}}{\phi_T}\right)}{\phi_T} \quad (15.298)$$

The iterative loop is performed until  $|\psi_{i+1} - \psi_i| < 10^{-8} \cdot \phi_T$ , at which point  $\psi_{ov}$  is taken to be equal to  $\psi_{i+1}$ . As a zero-order starting value  $\psi_0$ , the following approximation is used:

$$\left. \begin{array}{l}
 \text{if } V_{GX} \leq V_{FBov} \\
 \text{if } V_{GX} > V_{FBov}
 \end{array} \right\} \begin{array}{l}
 \left. \begin{array}{l}
 x = Acc_{ov} \cdot (V_{GX} - V_{FBov}) / \phi_T \\
 \Delta_{acc} = \begin{cases} -\phi_T & \text{for: } x \leq -2 \\ \phi_T \cdot [\exp(x) - 1] & \text{for: } x > -2 \end{cases} \\
 \psi_0 = \left( -\sqrt{-(V_{GX} - V_{FBov}) + \Delta_{acc} + \frac{k_{ov}^2}{4} - \frac{k_{ov}}{2}} \right)^2 + \Delta_{acc}
 \end{array} \\
 \\
 \left. \begin{array}{l}
 V_{ov} = \frac{2 \cdot (V_{GX} - V_{FBov})}{1 + \sqrt{1 + 4/k_p^2 \cdot [V_{GX} - V_{FBov}]}} \\
 x = V_{ov}^2 + \phi_T \cdot k_{ov}^2 \\
 y = -k_{ov}^2 + \frac{2 \cdot V_{ov}}{\sqrt{1 + 4/k_p^2 \cdot [V_{GX} - V_{FBov}]}} \\
 z = 1 + 4/k_p^2 \cdot (V_{GX} - V_{FBov}) \\
 \psi_0 = \frac{2 \cdot \phi_T \cdot x \cdot \ln\left(\frac{x}{\phi_T \cdot k_{ov}^2}\right)}{x + \phi_T \cdot y + \sqrt{(x + \phi_T \cdot y)^2 - \phi_T^2 \cdot (x/z - y^2/2)} \cdot \ln\left(\frac{x}{\phi_T \cdot k_{ov}^2}\right)}
 \end{array} \right.
 \end{array} \quad (15.299)$$

When  $V_{GX} - V_{FBov} = 0$ , the starting value  $\psi_0$  is equal to zero. No iterative solution is necessary, and  $\psi_{ov}$  is automatically taken to be equal to zero. Surface potentials in the gate/source overlap  $\psi_{ov_0}$  and in the gate/drain overlap  $\psi_{ov_L}$  are calculated from the following implicit relations:

$$F_{ov}\{V_{GS}, \psi_{ov_0}\} = 0 \quad (15.300)$$

$$F_{ov}\{V_{GD} - V_{DS}, \psi_{ov_L}\} = 0 \quad (15.301)$$

The oxide voltages in the gate/source overlap  $\psi_{ov_0}$  and the gate/drain overlap  $\psi_{ov_L}$  are given by:

$$V_{ov_0} = V_{ov}\{V_{GS}, \Psi_{ov_0}\} \quad (15.302)$$

$$V_{ov_L} = V_{ov}\{V_{GD} - V_{DS}, \Psi_{ov_L}\} \quad (15.303)$$

### Gate Current Equations:

The tunnelling probability is given by:

$$P_{tun}\{V_{ox}, \chi_B, B\} = \begin{cases} \exp\left(-\frac{B}{\chi_B} \cdot \frac{\left[\left(\frac{V_{ox}}{\chi_B}\right)^2 - 3 \cdot \frac{V_{ox}}{\chi_B} + 3\right]}{1 + \left(1 - \frac{V_{ox}}{\chi_B}\right)^{\frac{3}{2}}}\right) & V_{ox} < \chi_B \\ \exp(-B/V_{ox}) & V_{ox} \geq \chi_B \end{cases} \quad (15.304)$$

### Source/Drain Gate Overlap Current:

The gate tunnelling in both gate/source and gate/drain overlap are given by:

$$P_{ov}\{V_{ov}\} = P_{tun}\{V_{ov}, \chi_{B_{inv}}, B_{inv}\} \quad (15.305)$$

$$I_{Gov}\{V_{GX}, V_{ov}\} = I_{GOV} \cdot V_{GX} \cdot V_{ov} \cdot [P_{ov}\{V_{ov}\} - P_{ov}\{-V_{ov}\}] \quad (15.306)$$

$$I_{Gov_0} = I_{Gov}\{V_{GS}, V_{ov_0}\} \quad (15.307)$$

$$I_{Gov_L} = I_{Gov}\{V_{GS} - V_{DS}, V_{ov_L}\} \quad (15.308)$$

**Intrinsic Gate-to-Bulk Current:**

The gate tunnelling current in accumulation:

$$P_{acc} = P_{tun}\{-\bar{V}_{ov}, \chi_{B_{acc}}, B_{acc}\} \quad (15.309)$$

$$V_{acc} = \bar{V}_{ox} - h\gamma p_1\{\bar{V}_{ox}, \epsilon_3\} \quad (15.310)$$

$$I_{GB} = -I_{GACC} \cdot (V_{GS} + V_{SB}) \cdot V_{acc} \cdot P_{acc} \quad (15.311)$$

**Intrinsic Gate-to-Channel Current:**

The tunnelling current in inversion, including quantum-mechanical barrier lowering  $\Delta\chi_B$ .

Equations are only calculated for  $V_{GB}^* - \bar{\psi} > 0$ :

$$\Delta\chi_B = QM_{\psi} \cdot (\bar{V}_{inv}/3 + \bar{V}_{ox} - \bar{V}_{inv})^{2/3} \quad (15.312)$$

$$\chi_{B_{eff}} = 0.7 \cdot \chi_{B_{inv}} + h\gamma p_1\{0.3 \cdot \chi_{B_{inv}} - \Delta\chi_B, \epsilon_3\} \quad (15.313)$$

$$B_{eff} = B_{inv} \cdot (\chi_{B_{eff}}/\chi_{B_{inv}})^{3/2} \quad (15.314)$$

$$P_{inv} = P_{tun}\{\bar{V}_{ox}, \chi_{B_{eff}}, B_{eff}\} \quad (15.315)$$

$$r_B = \frac{3}{8} \cdot \frac{B_{eff}}{\chi_{B_{eff}}} \cdot \frac{\bar{\xi}_{ox}}{\phi_T} \quad (15.316)$$

$$r^* = \frac{\bar{\xi}}{\phi_T \cdot \bar{V}_{inv}^*} \quad (15.317)$$

$$r_{ox} = \frac{\bar{\xi}_{ox}}{\phi_T \cdot \bar{V}_{ox}} \quad (15.318)$$

$$P_{GC} = 1 + \frac{r_B^2 + 4 \cdot r_B \cdot r^* + 2 \cdot r_B \cdot r_{ox} + 2 \cdot r^{*2} + 4 \cdot r_{ox} \cdot r^*}{24} \cdot \Delta\psi^2 \quad (15.319)$$

$$\bar{I}_{GC} = I_{GINV} \cdot G_{\Delta L} \cdot \left( V_{GS} - \frac{1}{2} V_{DS_x} \right) \cdot P_{inv} \quad (15.320)$$

The total intrinsic gate current  $I_{GC}$ :

$$I_{GC} = \bar{I}_{GC} \cdot \bar{V}_{inv} \cdot P_{GC} \quad (15.321)$$

$$P_{GS} = [r_B + r_{ox}] \cdot \frac{\Delta\psi}{12} \quad (15.322)$$

$$I_{GS} = \begin{cases} I_{Gov_0} & \text{for: } V_{GB}^* - \bar{\psi} \leq 0 \\ \frac{1}{2} \cdot I_{GC} + \left( P_{GS} \cdot \bar{V}_{inv} + \frac{V_{inv_0} - V_{inv_L}}{12} \right) \cdot \bar{I}_{GC} + I_{Gov_0} & \text{for: } V_{GB}^* - \bar{\psi} > 0 \end{cases} \quad (15.323)$$

$$I_{GD} = \begin{cases} I_{Gov_L} & \text{for: } V_{GB}^* - \bar{\psi} \leq 0 \\ I_{GC} - I_{GS} + I_{Gov_0} + I_{Gov_L} & \text{for: } V_{GB}^* - \bar{\psi} > 0 \end{cases} \quad (15.324)$$

**Gate-Induced Drain/Source Leakage Current:**

$$V_{tov}\{V_{ov}, V\} = \sqrt{(V_{ov} - hyp_1\{V_{ov}, \epsilon_3\})^2 + C_{GIDL}^2 \cdot V^2} \quad (15.325)$$

$$I_{gixl}\{V_{ov},V\} = \begin{cases} A_{GIDL} \cdot V \cdot V_{tov}\{V_{ov},V\}^2 \cdot \exp\left(-\frac{B_{GIDL_T}}{V_{tov}\{V_{ov},V\}}\right) & \text{for: } V_{tov}\{V_{ov},V\} > -\frac{B_{GIDL_T}}{A} \\ 0 & \text{for: } V_{tov}\{V_{ov},V\} \leq -\frac{B_{GIDL_T}}{A} \end{cases} \quad (15.326)$$

$$I_{gisl} = I_{gixl}\{V_{ov_0}, V_{SB}\} \quad (15.327)$$

$$I_{gidl} = I_{gixl}\{V_{ov_L}, V_{DS} + V_{SB}\} \quad (15.328)$$

### Extended Charge Equations

#### Bias-Dependent Overlap Capacitance:

$$Q_{ov_0} = C_{GSO} \cdot V_{ov_0} \quad (15.329)$$

$$Q_{ov_L} = C_{GDO} \cdot V_{ov_L} \quad (15.330)$$

#### Intrinsic Charges:

$$C_{OX_{eff}} = \frac{C_{OX}}{1 + QM_{tox} \cdot \left[ \left( \frac{V_{eff}}{\eta_{mob_T}} \right)^2 + (5 \cdot V_{limit})^2 \right]^{-1/6}} \quad (15.331)$$

$$\Delta V_{inv} = (V_{inv_0} - V_{inv_L}) \cdot \left( 1 - \frac{G_R}{G_{tot}} \right) \quad (15.332)$$

$$F_j = \frac{1}{2} \cdot \frac{\Delta V_{inv}}{\bar{V}_{inv}^*} \quad (15.333)$$

$$Q_S = -\frac{C_{OX_{eff}} \cdot G_{\Delta L}}{2} \cdot \left[ \bar{V}_{inv} + \frac{\Delta V_{inv}}{6} \cdot \left( F_j - \frac{F_j^2}{5} + 1 \right) \right] \quad (15.334)$$

$$Q_D = -\frac{C_{OX_{eff}} \cdot G_{\Delta L}}{2} \cdot \left[ \bar{V}_{inv} + \frac{\Delta V_{inv}}{6} \cdot \left( F_j + \frac{F_j^2}{5} - 1 \right) \right] \quad (15.335)$$

$$Q_G = C_{OX_{eff}} \cdot \left[ \bar{V}_{ox} + \frac{\Delta V_{inv}}{6} \cdot F_j \cdot \frac{\bar{\xi}_{ox}}{\bar{\xi}} \right] \quad (15.336)$$

$$Q_B = -[Q_S + Q_D + Q_G] \quad (15.337)$$

### Extended Noise Equations

The noise equations (15.338) to (15.356) are only calculated for  $V_{GB}^* - \bar{\psi} > 0$ . In these equations  $f$  represents the operation frequency of the transistor.

$$G_{eff} = 1 - \frac{G_R}{G_{tot}} \quad (15.338)$$

$$x_{sat}^2 = \begin{cases} \theta_{sat_T}^2 \cdot \Delta \psi^2 \cdot G_{eff}^2 & \text{for NMOS} \\ \frac{\theta_{sat_T}^2 \cdot \Delta \psi^2 \cdot G_{eff}^2}{\sqrt{1 + \theta_{sat_T}^2 \cdot \Delta \psi^2 \cdot G_{eff}^2}} & \text{for PMOS} \end{cases} \quad (15.339)$$

$$G_{vsatR} = \frac{G_{mob} + \sqrt{G_{mob}^2 + 2 + x_{sat}^2}}{2} \quad (15.340)$$

$$t_1 = \frac{\bar{V}_{inv}}{\bar{V}_{inv}^*} \quad (15.341)$$

$$t_2 = \frac{F_j^2}{36} \quad (15.342)$$

$$t_{sat} = \frac{x_{sat}^2}{G_{vsatR}^2} \quad (15.343)$$

$$g_{ideal} = \frac{\beta_T \cdot \bar{V}_{inv}^*}{G_{vsatR} \cdot G_{\Delta L}} \quad (15.344)$$

$$S_{th} = N_{T_T} \cdot G_{eff}^2 \cdot g_{ideal} \cdot \max \cdot \{t_1 + 12 \cdot t_2 \cdot (1 - 2 \cdot t_{sat} - 2 \cdot t_{sat}^2), 0\} \quad (15.345)$$

$$C_{G_{eff}} = C_{OX_{eff}} \cdot \frac{\bar{\xi}_{ox}}{\phi_T} \cdot \frac{G_{vsatR} \cdot G_{\Delta L}}{G_{mob}} \quad (15.346)$$

$$m_{ig} = \frac{1}{g_{ideal}} \cdot \left[ \frac{t_1}{12} - t_1 \cdot t_2 - \frac{t_2}{5} + 12 \cdot t_2^2 \right. \\ \left. + t_{sat} \cdot \left( \frac{t_1}{12} + 3 \cdot t_1 \cdot t_2 - \frac{9 \cdot t_2}{5} - 36 \cdot t_2^2 \right) \right. \\ \left. + t_{sat}^2 \cdot \left( \frac{t_1}{12} + 4 \cdot t_1 \cdot t_2 - \frac{17 \cdot t_2}{5} - 24 \cdot t_2^2 \right) \right] \quad (15.347)$$

$$m_{igth} = G_{eff} \cdot \sqrt{t_2} \cdot [1 - 12 \cdot t_2 + t_{sat} \cdot \left(\frac{1}{2} - t_1 + 30 \cdot t_2\right) + t_{sat}^2 \cdot \left(\frac{3}{8} - \frac{3 \cdot t_1}{2} + \frac{51 \cdot t_2}{2}\right)] \quad (15.348)$$

$$f_{cross} = \frac{1}{2 \cdot \pi \cdot C_{G_{eff}} \cdot m_{ig}} \quad (15.349)$$

$$S_{ig} = \frac{N_T}{m_{ig}} \cdot \frac{(f_{op}/f_{cross})^2}{1 + (f_{op}/f_{cross})^2} \quad (15.350)$$

$$S_{igid} = j \cdot \frac{N_T}{m_{ig}} \cdot m_{igid} \cdot \frac{f_{op}/f_{cross}}{\sqrt{1 + (f_{op}/f_{cross})^2}} \quad (15.351)$$

$$\text{for } GATENOISE = 1 : \begin{cases} g_{ideal} = \frac{\beta_T \cdot \bar{V}_{inv}}{G_{mob} \cdot G_{\Delta L}} \\ S_{th} = N_{T_T} \cdot G_{eff}^2 \cdot g_{ideal} / \sqrt{1 + t_{sat} + t_{sat}^2} \\ S_{ig} = 0 \\ S_{igth} = 0 \end{cases} \quad (15.352)$$

$$N_0 = \frac{\epsilon_{ox}}{q \cdot t_{ox}} \cdot \left( \bar{V}_{inv} + \frac{\Delta V_{inv}}{2} \right) \quad (15.353)$$

$$N_L = \frac{\epsilon_{ox}}{q \cdot t_{ox}} \cdot \left( \bar{V}_{inv} - \frac{\Delta V_{inv}}{2} \right) \quad (15.354)$$

$$N^* = \frac{\epsilon_{ox}}{q \cdot t_{ox}} \cdot \bar{\xi} \quad (15.355)$$

$$\begin{aligned} S_{fl} = & \frac{q \cdot \phi_T^2 \cdot t_{ox} \cdot \beta_T \cdot I_{DS}}{f \cdot \epsilon_{ox} \cdot G_{vsat} \cdot N^*} \cdot [(N_{FA} - N^* \cdot N_{FB} + N^{*2} \cdot N_{FC}) \cdot \ln\left(\frac{N_0 + N^*}{N_L + N^*}\right) \\ & + (N_{FB} - N^* \cdot N_{FC}) \cdot (N_0 - N_L) + \frac{N_{FC}}{2} \cdot (N_0^2 - N_L^2)] \\ & + \frac{\phi_T \cdot I_{DS}^2}{f} \cdot (1 - G_{\Delta L}) \cdot \left[ \frac{N_{FA} + N_{FB} \cdot N_L + N_{FC} \cdot N_L^2}{(N_L + N^*)^2} \right] \end{aligned} \quad (15.356)$$

## 15.5.2 Parasitic Resistance

MOS Model 11 contains one parasitic element, the gate resistance. The gate resistance is scaled with the geometry, facilitating the implementation of multi-finger devices.

$$W_f = \frac{W}{NF} \quad (15.357)$$

$$W_{E,f} = W_f + \Delta W_{OD} \quad (15.358)$$

$$L_f = L + \Delta L_{PS} \quad (15.359)$$

$$L_{sil,f} = L_f + DLSIL \quad (15.360)$$

$$X_{GWE} = XGW - 0.5 \cdot \Delta W_{OD} \quad (15.361)$$

$$RG = \frac{RGO}{N_{MULT}} + \frac{1}{NF \cdot N_{MULT}} \cdot \left( \frac{RSHG \cdot \left( \frac{W_{E,f}}{3 \cdot NGCON} + X_{GWE} \right)}{NGCON \cdot L_{sil,f}} + \frac{RINT + RVPOLY}{W_{E,f} \cdot L_f} \right) \quad (15.362)$$

Note that if the values  $L_f$ ,  $W_f$ ,  $L_{sil,f}$  or  $X_{GWE}$  are smaller than 1e-9, they will be clipped to 1e-9.

$NGCON$  is rounded of to an integer number (1 or 2).

### 15.5.3 Numerical Adaptation

The implemented electrical equations of MOS Model 11 are essentially based on the physical description given in Section 15.2. The following numerical adaptations have been made in order to obtain smooth transitions and prevent numerical problems, leading to the equations given in the section titled *Extended Equations on page 129* 15.5.115.5.115.5.1:

- The piece-wise eqs. (15.20) for  $V_{GB_{eff}}$ , (15.23) for  $D_{sf}$ , (15.28) for  $V_{DSAT_{long}}$ , (15.33) for  $V_{DSAT}$  and (15.77) for  $I_{GB}$  have been replaced by smooth  $C_\infty$ -continuous functions based on hyp-functions.
- Expression (15.22) describing the drain-induced barrier lowering effect has no numerical solution for  $V_{SB} + \phi_{B_T} < 0$ . In order to solve this problem the expression  $V_{SB} + \phi_B$  is clipped at a minimum value of  $0.1 \cdot \phi_{B_T}$  using Eq. (15.223). In order to maintain symmetry (with respect to source and drain) the same method must be applied to the drain side, this is done in Eq. (15.237).

- In the accumulation region (i.e.,  $V_{GB}^* \leq 0$ ), the inversion-layer charge density is equal to zero (i.e.,  $V_{inv_0} = V_{inv_L} = 0$ ), as a result the drain-source channel current  $I_{DS}$ , the weak-avalanche current  $I_{avl}$ , the gate-to-channel current  $I_{GC}$ , the total drain charge  $Q_D$  and source charge  $Q_S$ , and the noise spectral densities  $S_{th}$ ,  $S_{fl}$  and  $S_{ig}$  are all equal to zero. In this case, the model equations can be simplified and only certain equations need to be calculated. The equations that only need to be calculated in the inversion region (i.e.,  $V_{GB}^* > 0$ ) are indicated.
- For a very small positive value of  $\psi_s$  (i.e.,  $\psi_s < 10^{-9}$  just above  $V_{GB}^* = 0$ ), the expression (15.40) for  $V_{inv}$  may become numerically inaccurate. In this case  $V_{inv}$  is very small and can be taken to be equal to zero, see (15.258).
- The Coulomb-scattering part of the mobility model, Eq. (15.53) is protected against zero-division by adding a small  $\epsilon_4 = 1 \cdot 10^{-14}$  to its denominator, see Eq. (15.270).
- The theoretical channel length modulation expression (15.54) can become negative for high values of  $\alpha$  and  $V_{DS}$ . This corresponds to a negative effective channel length, which is not physical. In order to prevent  $G_{\Delta L}$  from becoming negative, a second-order Taylor polynomial in  $\Delta L/L$  is used in the actual implementation, see eqs. (15.271) and (15.272).
- The term in the square root of Eq. (15.59) can become negative for very high values of parameter  $\theta_R$ , which would result in numerical errors. This has been prevented in the actual implementation (15.278) by using a hyp-smoothing function.
- The derivative of the weak-avalanche expression (15.63) with respect to  $V_{DS}$  may become numerically unstable for  $V_{DS}$  values just above  $a_3 \cdot V_{DSAT}$ . This problem has been circumvented by using (15.308), where  $A$  is a numerical constant defined in Section 15.3.1.
- The exponent in the tunnelling probability  $P_{tun}$ , given by Eq. (15.71), results in zero divided by zero for  $V_{ox} = 0$ . By simply rewriting the exponent, this problem can be circumvented as has been done in Eq. (15.315).
- For very high gate bias values, which could occur during the iteration process of the circuit simulator, the expression of effective oxide barrier  $\chi_{B_{eff}}$ , given by Eq. (15.79), can become zero or negative resulting in numerical errors. In order to prevent this problem  $\chi_{B_{eff}}$

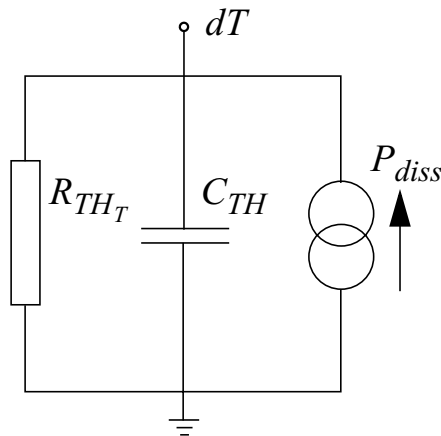
is clipped at a minimum (arbitrary) value of  $0.7 \cdot \chi_{B_{inv}}$  using a hyp-smoothing function, see Eq. (15.333).

- Gate-induced drain (or source) leakage only occurs when the oxide voltage in the drain overlap region is negative, in other words when the overlapped  $n^+$ -drain region is depleted. For positive oxide voltage, no GIDL occurs, because, as the overlapped region is in accumulation, the band bending is minimal and as a result band-to-band tunnelling cannot occur. This is, however, not automatically accomplished using (15.112). In order to take this effect into account empirically, we replace  $V_{ov}$  in (15.111) by a smoothing function which is equal to  $V_{ov}$  for negative values of  $V_{ov}$  and equal to 0 for positive values, see (15.341).
- Similar to the weak-avalanche expression (15.63), the derivatives of the gate-induced drain leakage expression (15.112) may become numerically unstable for  $V_{tov}$  very close to 0. This problem has been circumvented in the same way as has been done for (15.308), see Eq. (15.342).
- The expression of effective oxide capacitance (15.97) due to quantum-mechanical effects gives erroneous results for  $V_{eff} = 0$  (i.e.,  $V_{GB} = V_{FB}$ ). This can be prevented by replacing  $V_{eff}/\eta_{mob}$  by  $\sqrt{(V_{eff}/\eta_{mob})^2 + (20 \cdot \phi_T)^2}$ , where the value of  $20 \cdot \phi_T$  is rather arbitrary but it nevertheless ensures a smooth transition from accumulation to depletion/inversion.
- The thermal noise spectral density  $S_{th}$  given by Eq. (15.112) can become negative for very high values of parameter  $\theta_{sat}$ , which is not physical. In order to prevent this,  $S_{th}$  is clipped to zero in these cases, see Eq. (15.346).
- The spectral density of induced gate noise is given by Eq. (15.115), keeps rising infinitely for high frequencies. This is not realistic and unwanted in circuit simulations. Therefore the induced gate noise as well as the cross-spectral density  $S_{igth}$  are limited above a cross-over frequency  $f_{cross}$ , see Eqs. (15.349), (15.350) and (15.351).

## 15.6 Self-heating

### 15.6.1 Equivalent circuit

Self-heating is part of the model. It is defined in the usual way by adding a self-heating network (see Figure 71) containing a current source describing the dissipated power and both a thermal resistance  $R_{TH}$  and a thermal capacitance  $C_{TH}$ .



| Material         | $A_{th}$ |
|------------------|----------|
| Si               | 1.3      |
| Ge               | 1.25     |
| GaAs             | 1.25     |
| AlAs             | 1.37     |
| InAs             | 1.1      |
| InP              | 1.4      |
| GaP              | 1.4      |
| SiO <sub>2</sub> | 0.7      |

Figure 71: On the left, the self-heating network, where the node voltage  $V_{dT}$  is used in the temperature scaling relations. Note that for increased flexibility the node  $dT$  is available to the user. On the right are parameter values that can be used for  $A_{th}$ .

The resistance and capacitance are both connected between ground and the temperature node  $d_T$ . The value of the voltage  $V_{dT}$  at the temperature node gives the increase in local temperature, which is included in the calculation of the temperature scaling relation (15.3) and (15.206), see sections 15.2.2 and 15.4.

For the value of  $A_{th}$  we recommend using values from literature that describes the temperature scaling of the thermal conductivity. For the most important materials, the values are given in Figure 71, which is largely based on Ref. [23], see also [24].

For example, if the value of  $V_{dT}$  is 0.5V, the increase in temperature is 0.5 degrees Celsius.

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

$$\begin{aligned}
 P_{diss} &= I_D^e \cdot V_D^e + I_G^e \cdot V_G^e + I_S^e \cdot V_S^e + I_B^e \cdot V_B^e \\
 &= I_{DS}'' \cdot V_{DS}'' + I_{DB}'' \cdot (V_{DS}'' - V_{SB}'') + I_{SB}'' \cdot V_{SB}'' + I_{GS}'' \cdot V_{GS}'' \\
 &\quad + I_{GD}'' \cdot (V_{GS}'' - V_{DS}'') + I_{GB}'' \cdot (V_{GS}'' - V_{SB}'')
 \end{aligned}$$

where all variables are given in figure 72 on the previous pages. Note that only the steady-state currents contribute to the dissipated power.

The total dissipation applies for the electrical model (mnet<sup>1</sup>, mpet<sup>1</sup>, mos1102et<sup>2</sup>), geometrical binning model (mnt<sup>1</sup>, mpt<sup>1</sup>, mos11021t<sup>2</sup>), and geometrical physical model (mnt<sup>1</sup>, mpt<sup>1</sup>, mos11020t<sup>2</sup>).

Below a *Pstar* example is given to illustrate how self-heating works.

### q Example

Title: example self-heating 1102;

```

circuit;
mnet_1(Vd, Vg, Vs, 0, dt) level=1102, Rth=1e4,Cth=1e-9;
R_1 ( Vdd, Vd) 100;
R_2 ( Vgg, Vg) 1k;
R_3 ( Vs, 0) 100;
e_SRC_2 (Vgg ,net101) 5;
e_SRC_1 ( Vdd, 0) 1;
e_SRC_3 ( net101, 0) 0;
end;

dc;
print: vn(dt), op(pdiss.mnet_1);
end; run;

result:
DC Analysis.
VN(dt)          =9.533E+00
Pdiss.MNT_1     =953.327E-6

```

1.*Pstar* model name.

2.*Spectre/ADS* model name.

The voltage on node *dt* is 9.533E+00 V, which means that the local temperature is increased by 9.533E+00 °C.

## 15.7 DC Operating point output

### 15.7.1 DC operating point output

The DC operating point output facility gives information on the state of a device at its operation point. Besides terminal currents and voltages, the magnitudes of linearized internal elements are given. In some cases, meaningful quantities can be derived which are then also given (e.g.  $f_T$ ). The objective of the DC operating-facility is twofold:

- Calculate small-signal equivalent circuit element values.
- Open a window on the internal bias conditions of the device and its basic capabilities.

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

| No. | Symbol    | Program Name | Units | Description  |
|-----|-----------|--------------|-------|--|
| 0   | $I_{DS}$  | IDS          | A     | Drain current, excl. avalanche and tunnel currents.  |
| 1   | $I_{avl}$ | IAVL         | A     | Substrate current due to weak-avalanche  |
| 2   | $I_{GS}$  | IGS          | A     | Gate-to-source current due to direct tunnelling  |
| 3   | $I_{GD}$  | IGD          | A     | Gate-to-drain current due to direct tunnelling   |
| 4   | $I_{GB}$  | IGB          | A     | Gate-to-bulk current due to direct tunnelling  |
| 5   | $V_{DS}$  | VDS          | V     | Drain-Source voltage   |
| 6   | $V_{GS}$  | VGS          | V     | Gate-Source voltage  |
| 7   | $V_{SB}$  | VSB          | V     | Source-Bulk voltage  |
| 8   | $V_{TO}$  | VTO          | V     | Zero-bias threshold voltage:<br>$V_{TO} = V_{FB} + P_D \cdot (\phi_B + 2 \cdot \phi_T) + k_0 \cdot \sqrt{\phi_B + 2 \cdot \phi_T}$   |
| 9   | $V_{TS}$  | VTS          | V     | Threshold voltage including back-bias effects:<br>$V_{TS} = V_{FB} + P_D \cdot (V_{SB_i} + 2 \cdot \phi_T) - (V_{SB_i} - \phi_B) + k_0 \cdot \sqrt{V_{SB_i} + 2 \cdot \phi_T}$ |

| No. | Symbol         | Program Name | Units | Description  |
|-----|----------------|--------------|-------|--|
| 10  | $V_{TH}$       | VTH          | V     | Threshold voltage including back-bias and drain-bias effects:<br>$V_{TH} = V_{FB} + P_D \cdot (V_{SB_t} + 2 \cdot \phi_T) - (V_{SB_t} - \phi_B) + k_0 \cdot \sqrt{V_{SB_t} + 2 \cdot \phi_T} - \Delta V_G$ |
| 11  | $V_{GT}$       | VGT          | V     | Effective gate drive including back-bias and drain voltage effects: $V_{GT} = V_{inv_0}$   |
| 12  | $V_{DSAT}$     | VDSS         | V     | Drain saturation voltage at actual bias  |
| 13  | $V_{DS_{eff}}$ | VSAT         | V     | Saturation limit: $V_{DS_{eff}} = V_{DS} - V_{DSAT}$   |
| 14  | $g_m$          | GM           | A/V   | Transconductance (assumed $V_{DS} > 0$ ):<br>$g_m = \partial I_{DS} / \partial V_{GS}$   |
| 15  | $g_{mb}$       | GMB          | A/V   | Substrate-transconductance (assumed $V_{DS} > 0$ ):<br>$g_{mb} = \partial I_{DS} / \partial V_{BS}$  |
| 16  | $g_{ds}$       | GDS          | A/V   | Output conductance:<br>$g_{ds} = \partial I_{DS} / \partial V_{DS}$  |
| 17  | $C_{D(D)}$     | CDD          | F     | $C_{D(D)} = \partial Q_D / \partial V_{DS}$  |
| 18  | $C_{D(G)}$     | CDG          | F     | $C_{D(G)} = -\partial Q_D / \partial V_{GS}$   |
| 19  | $C_{D(S)}$     | CDS          | F     | $C_{D(S)} = C_{D(D)} - C_{D(G)} - C_{D(B)}$  |
| 20  | $C_{D(B)}$     | CDB          | F     | $C_{D(B)} = \partial Q_D / \partial V_{SB}$  |
| 21  | $C_{G(D)}$     | CGD          | F     | $C_{G(D)} = -\partial Q_G / \partial V_{DS}$   |
| 22  | $C_{G(G)}$     | CGG          | F     | $C_{G(G)} = \partial Q_G / \partial V_{GS}$  |
| 23  | $C_{G(S)}$     | CGS          | F     | $C_{G(S)} = C_{G(G)} - C_{G(D)} - C_{G(B)}$  |
| 24  | $C_{G(B)}$     | CGB          | F     | $C_{G(B)} = \partial Q_G / \partial V_{SB}$  |
| 25  | $C_{S(D)}$     | CSD          | F     | $C_{S(D)} = -\partial Q_S / \partial V_{DS}$   |
| 26  | $C_{S(G)}$     | CSG          | F     | $C_{S(G)} = -\partial Q_S / \partial V_{GS}$   |

| No. | Symbol               | Program Name | Units           | Description   |
|-----|----------------------|--------------|-----------------|---|
| 27  | $C_{S(S)}$           | CSS          | F               | $C_{S(S)} = C_{S(G)} + C_{S(D)} + C_{S(B)}$   |
| 28  | $C_{S(B)}$           | CSB          | F               | $C_{S(B)} = \partial Q_S / \partial V_{SB}$   |
| 29  | $C_{B(D)}$           | CBD          | F               | $C_{B(D)} = -\partial Q_B / \partial V_{DS}$  |
| 30  | $C_{B(G)}$           | CBG          | F               | $C_{B(G)} = -\partial Q_B / \partial V_{GS}$  |
| 31  | $C_{B(S)}$           | CBS          | F               | $C_{B(S)} = C_{B(B)} - C_{B(D)} - C_{B(G)}$   |
| 32  | $C_{B(B)}$           | CBB          | F               | $C_{B(B)} = -\partial Q_B / \partial V_{SB}$  |
| 33  | $C_{GD_{ov}}$        | CGDOL        | F               | Gate-drain overlap capacitance of the actual transistor: $C_{GD_{ov}} = \partial Q_{OV_L} / \partial V_{DS}$  |
| 34  | $C_{GS_{ov}}$        | CGSOL        | F               | Gate-source overlap capacitance of the actual transistor: $C_{GS_{ov}} = \partial Q_{OV_0} / \partial V_{GS}$ |
| 35  | $W_E$                | WE           | m               | Effective channel width for geometrical models  |
| 36  | $L_E$                | LE           | m               | Effective channel length for geometrical models   |
| 37  | $u$                  | U            | -               | Transistor gain: $u = g_m / g_{ds}$   |
| 38  | $R_{out}$            | ROUT         | $\Omega$        | Small-signal output resistance: $R_{out} = 1 / g_{ds}$  |
| 39  | $V_{Early}$          | VEARLY       | V               | Equivalent Early voltage: $V_{Early} =  I_{DS}  / g_{ds}$   |
| 40  | $k_{eff}$            | KEFF         | $\sqrt{V}$      | Body effect parameter: $k_{eff} = k_0$  |
| 41  | $\beta_{eff}$        | BEFF         | $A / V^2$       | Gain factor: $2 \cdot  I_{DS}  / V_{inv_0}^2$   |
| 42  | $f_T$                | FUG          | Hz              | Unity gain frequency at actual bias:<br>$f_T = \frac{g_m}{2\pi(C_{G(G)} + C_{GS_{ov}} + C_{GD_{ov}})}$        |
| 43  | $\sqrt{S_{V_{Gth}}}$ | SQRTSFW      | $V / \sqrt{Hz}$ | Input-referred RMS white noise voltage density:<br>$\sqrt{S_{V_{Gth}}} = \sqrt{S_{th}} / g_m$                 |

| No. | Symbol               | Program Name | Units         | Description   |
|-----|----------------------|--------------|---------------|---|
| 44  | $\sqrt{S_{V_{Gfl}}}$ | SQRTSFF      | $V/\sqrt{Hz}$ | Input-referred RMS white noise voltage density at 1 kHz: $\sqrt{S_{V_{Gfl}}} = \sqrt{S_{fl}(1kHz)}/g_m$ |
| 45  | $f_{knee}$           | FKNEE        | Hz            | Cross-over frequency above which white noise is dominant: $f_{knee} = 1Hz \cdot S_{fl}(1Hz)/S_{th}$     |
| 46  | $R_g$                | RG           | $\Omega$      | Gate resistance   |

When the parameter PRINTSCALED is set to 1, the device parameter set after geometrical and temperature scaling is added to the OP output:

| Quantity      | Description   |
|---------------|---|
| <i>VFB</i>    | Flat-band voltage for the actual transistor                             |
| <i>KO</i>     | Body-effect factor  |
| <i>KPINV</i>  | Inverse of body-effect factor of the poly-silicon gate                  |
| <i>PHIB</i>   | Surface potential at the onset of strong inversion                      |
| <i>BET</i>    | Gain factor   |
| <i>THESR</i>  | Mobility degradation parameter due to surface roughness scattering      |
| <i>THEPH</i>  | Mobility degradation parameter due to phonon scattering                 |
| <i>ETAMOB</i> | Effective field parameter for dependence on depletion charge            |
| <i>NU</i>     | Exponent of field dependence of mobility model                          |
| <i>CS</i>     | Coefficient of Coulomb scattering                                       |
| <i>THER</i>   | Coefficient of series resistance  |
| <i>THER1</i>  | Numerator of gate voltage dependent part of series resistance           |
| <i>THER2</i>  | Denominator of gate voltage dependent part of series resistance         |
| <i>THESAT</i> | Velocity saturation parameter due to optical/acoustic phonon scattering |
| <i>THETH</i>  | Coefficient of self-heating   |
| <i>SDIBL</i>  | Drain-induced barrier lowering parameter                                |
| <i>MO</i>     | Parameter for (short-channel) subthreshold slope                        |
| <i>SSF</i>    | Static-feedback parameter   |
| <i>ALP</i>    | Factor of channel length modulation                                     |
| <i>VP</i>     | Characteristic voltage of channel-length modulation                     |

| <b>Quantity</b>  | <b>Description</b>   |
|------------------|--|
| <i>MEXP</i>      | Smoothing factor   |
| <i>A1</i>        | Factor of the weak-avalanche current   |
| <i>A2</i>        | Exponent of the weak-avalanche current   |
| <i>A3</i>        | Factor of the drain-source voltage above which weak-avalanche occurs               |
| <i>IGINV</i>     | Gain factor for intrinsic gate tunnelling current in inversion                     |
| <i>BINV</i>      | Probability factor for intrinsic gate tunnelling current in inversion              |
| <i>IGACC</i>     | Gain factor for intrinsic gate tunnelling current in accumulation                  |
| <i>BACC</i>      | Probability factor for intrinsic gate tunnelling current in accumulation           |
| <i>VFBOV</i>     | Flat-band voltage for the Source/Drain overlap extensions                          |
| <i>KOV</i>       | Body-effect factor for the Source/Drain overlap extensions                         |
| <i>IGOV</i>      | Gain factor for Source/Drain overlap tunnelling current                            |
| <i>AGIDL</i>     | Gain factor for gate-induced leakage current                                       |
| <i>BGIDL</i>     | Probability factor for gate-induced drain leakage current at reference temperature |
| <i>CGIDL</i>     | Factor for the lateral field dependence of the gate-induced leakage current        |
| <i>COX</i>       | Oxide capacitance for the intrinsic channel  |
| <i>CGDO</i>      | Oxide capacitance for the gate-drain overlap                                       |
| <i>CGSO</i>      | Oxide capacitance for the gate-source overlap                                      |
| <i>GATENOISE</i> | Flag for in/exclusion of induced gate thermal noise                                |
| <i>NT</i>        | Thermal noise coefficient  |
| <i>NFA</i>       | First coefficient of the flicker noise   |
| <i>NFB</i>       | Second coefficient of the flicker noise  |
| <i>NFC</i>       | Third coefficient of the flicker noise   |
| <i>TOX</i>       | Thickness of gate oxide layer  |

## 15.8 Embedding

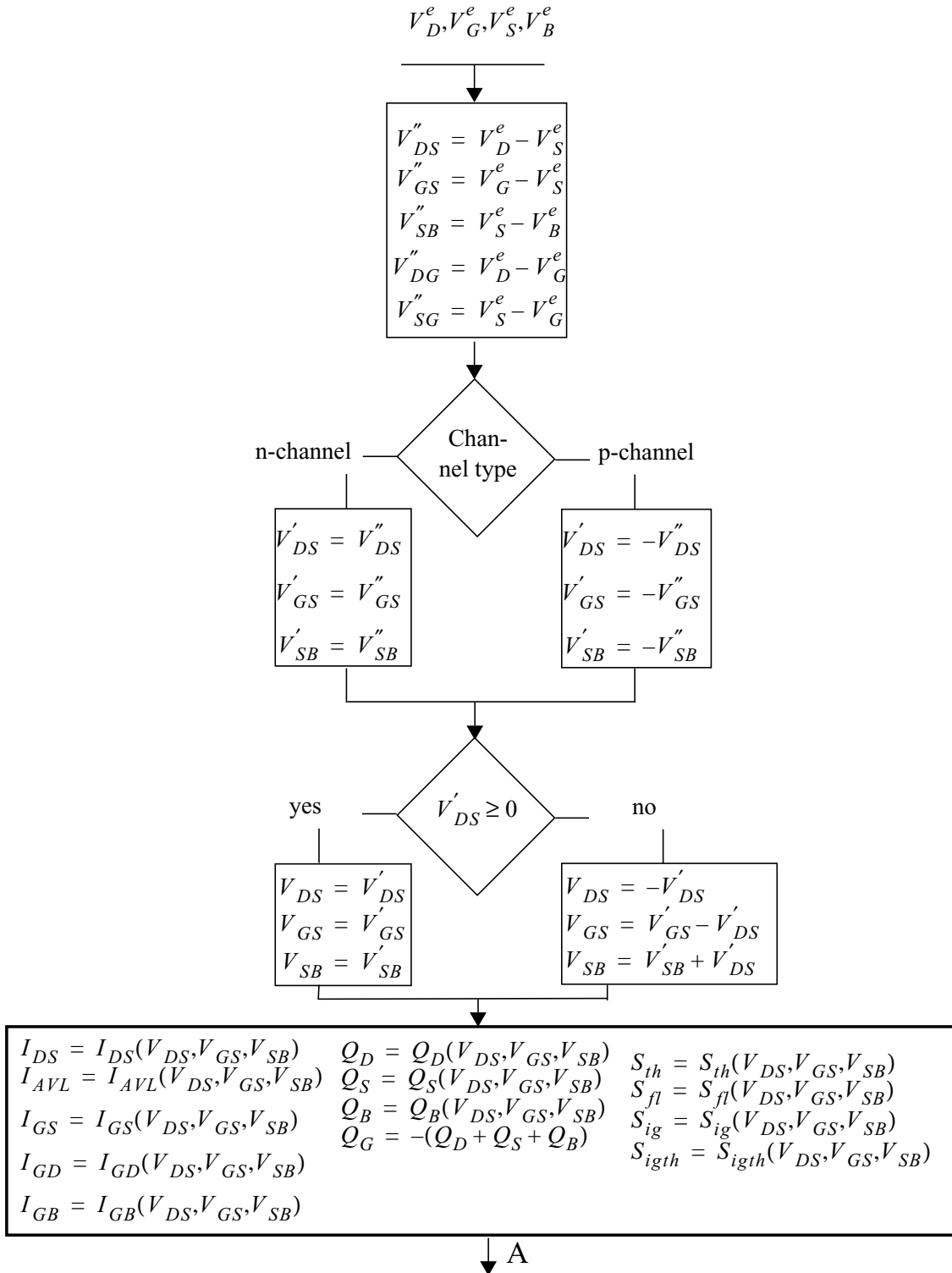
### 15.8.1 Model embedding in a circuit simulator

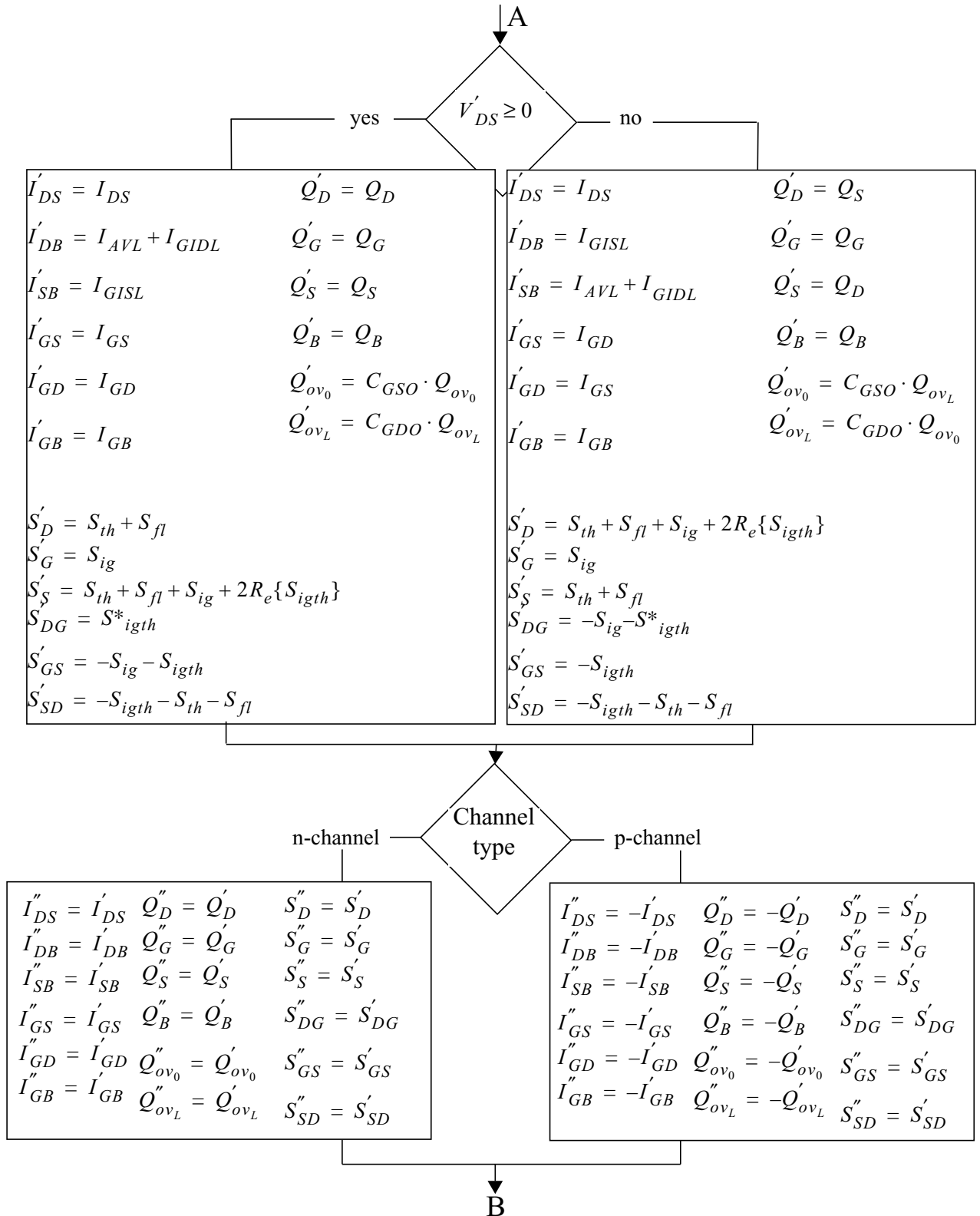
In CMOS technologies both n- and p-channel MOS transistors are supported. It is convenient to use one model for both type of transistors instead of two separate models. This is accomplished by mapping a p-channel device with its bias conditions and parameter set onto an equivalent n-channel device with appropriately changed bias conditions (i.e. currents, voltages and charges) and parameters. In this way both type of transistors can be treated as an n-channel transistor. Nevertheless, the electrical behaviour of electrons and holes is not exactly the same (e.g. the mobility and tunnelling behaviour), and consequently slightly different equations have to be used in case of n- or p-type transistors, see **section 15.2.3 on page 21**.

As said earlier, any circuit simulator internally identifies the terminals of a MOS transistor by a number. However, designers are used to the standard terminology of source, drain, gate and bulk. Therefore, in the context of a circuit simulator it is traditionally possible to address, say, the drain of 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 a so called  $V_{DS}$ ,  $V_{GS}$  and  $V_{SB}$  based on an a priori assignment of source, drain and bulk that is independent of the actual bias conditions. Since MOS Model 1102 assumes 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 MOS Model 1102 care has been taken to preserve symmetry with respect to drain and source at  $V_{DS} = 0$ . In other words no non-singularities will occur in the higher-order derivatives at  $V_{DS} = 0$ .

In detail, in order to embed MOS Model 1102 correctly into a circuit simulator, the following procedure, illustrated in figure 72 should be followed. We have assumed that indeed the simulator provides the nodal potentials  $V_D^e$ ,  $V_G^e$ ,  $V_S^e$  and  $V_B^e$  based on an a priori assignment of drain, gate, source and bulk.

- Step 1** Calculate the voltages  $V''_{DS}$ ,  $V''_{GS}$  and  $V''_{SB}$ , and the additional voltages  $V''_{DG}$  and  $V''_{SG}$ . The latter are used for calculating the charges associated with overlap capacitances.
- Step 2** Based on n- or p-channel devices, calculate the modified voltages  $V'_{DS}$ ,  $V'_{GS}$  and  $V'_{SB}$ . From here onwards only n-channel behaviour needs to be considered.
- Step 3** Based on a positive or negative  $V'_{DS}$ , calculate the internal nodal voltages. At this level, the voltages - and the parameters, see below - comply to all the requirements for input quantities of MOS Model 1102.
- Step 4** Evaluate all the internal output quantities - channel current, weak-avalanche current, gate current, nodal charges, and noise-power spectral densities - using the standard MOS Model 1102 equations and the internal voltages.
- Step 5** Correct the internal output quantities for a possible source-drain interchange. In fact, this directly establishes the external noise power spectral densities.
- Step 6** Correct for a possible p-channel transformation.
- Step 7** Change from branch current to nodal currents, establishing the external current output quantities. Calculate the overlap charges that are related to the physical regions and add them to the nodal charges, thus forming the external charge output quantities.





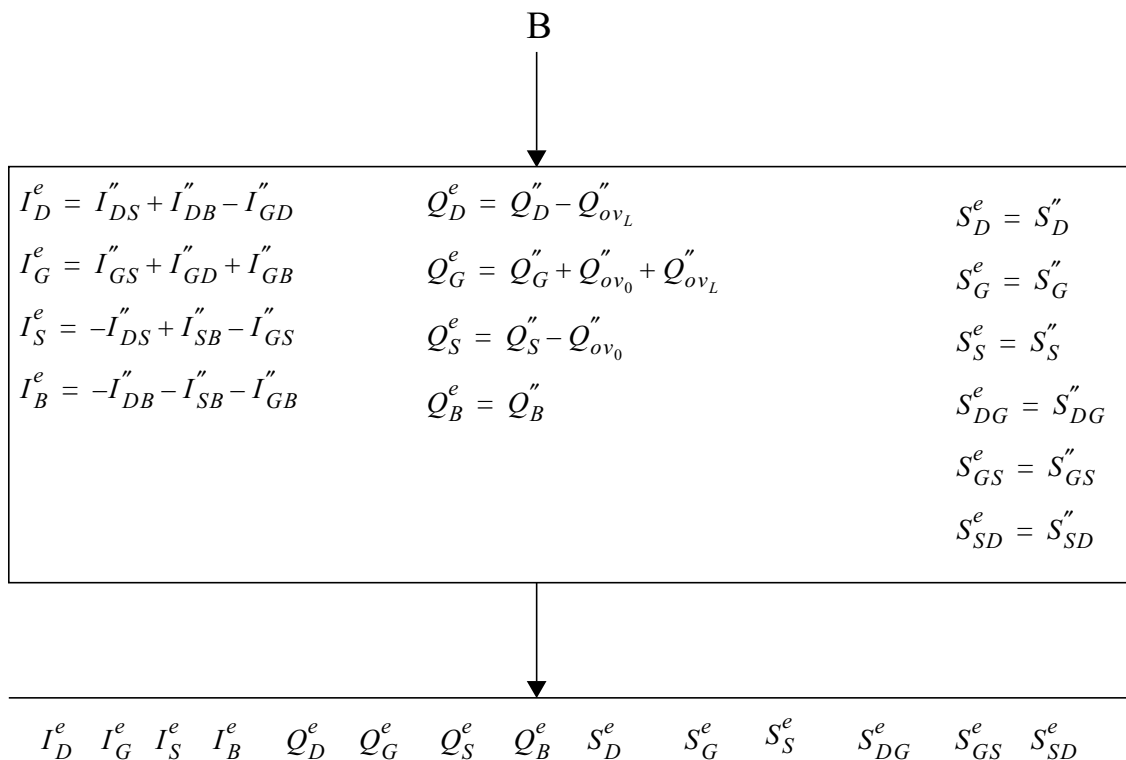


Figure 72: Transformation scheme

It is customary to have separate user models in the circuit simulators for n- and p-channel transistors. In that manner it is easy to use a different set of reference and scaling parameters for the two channel types. As a consequence, the changes in the parameter values necessary for a p-channel type transistor are normally already included in the parameter sets on file. The changes should not be included in the simulator.

## 15.9 Simulator specific items

### 15.9.1 Pstar syntax

|  |  |
|--|--|
| n channel electrical model:                        | mne_n (d,g,s,b) level=1102,<parameters>      |
| p channel electrical model:                        | mpe_n (d,g,s,b) level=1102, <parameters>     |
| n channel electrical self-heating model:           | mnet_n (d,g,s,b,dt) level=1102,<parameters>  |
| p channel electrical self-heating model:           | mpet_n (d,g,s,b,dt) level=1102, <parameters> |
| n channel physical geometrical model:              | mn_n (d,g,s,b) level=11020 <parameters>      |
| p channel physical geometrical model:              | mp_n (d,g,s,b) level=11020 <parameters>      |
| p channel physical geometrical self-heating model: | mpt_n (d,g,s,b,dt) level=11020 <parameters>  |
| n channel physical geometrical self-heating model: | mnt_n (d,g,s,b,dt) level=11020 <parameters>  |
| n channel binning geometrical model:               | mn_n (d,g,s,b) level=11021 <parameters>      |
| p channel binning geometrical model:               | mp_n (d,g,s,b) level=11021 <parameters>      |
| n channel binning geometrical self-heating model:  | mnt_n (d,g,s,b,dt) level=11021 <parameters>  |
| p channel binning geometrical self-heating model:  | mpt_n (d,g,s,b,dt) level=11021 <parameters>  |

n : occurrence indicator

<parameters> : list of model parameters

d,g,s and b are drain, gate, source, bulk and self-heating terminals respectively.

## 15.9.2 Spectre syntax

|  |   |
|--|---|
| n channel electrical model:                        | model modelname mos1102e type=n <modpar><br>componentname d g s b modelname <inpar>     |
| p channel electrical model:                        | model modelname mos1102e type=p <modpar><br>componentname d g s b modelname <inpar>     |
| n channel electrical self-heating model:           | model modelname mos1102et type=n <modpar><br>componentname d g s b dt modelname <inpar> |
| p channel electrical self-heating model:           | model modelname mos1102et type=p <modpar><br>componentname d g s b dt modelname <inpar> |
| n channel physical geometrical model:              | model modelname mos11020 type=n <modpar><br>componentname d g s b modelname <inpar>     |
| p channel physical geometrical model:              | model modelname mos11020 type=p <modpar><br>componentname d g s b modelname <inpar>     |
| n channel physical geometrical self-heating model: | model modelname mos11020t type=n <modpar><br>componentname d g s b dt modelname <inpar> |
| p channel physical geometrical self-heating model: | model modelname mos11020t type=p <modpar><br>componentname d g s b dt modelname <inpar> |
| n channel binning geometrical model:               | model modelname mos11021 type=n <modpar><br>componentname d g s b modelname <inpar>     |
| p channel binning geometrical model:               | model modelname mos11021 type=p <modpar><br>componentname d g s b modelname <inpar>     |
| n channel binning geometrical self-heating model:  | model modelname mos11021t type=n <modpar><br>componentname d g s b dt modelname <inpar> |
| p channel binning geometrical self-heating model:  | model modelname mos11021t type=p <modpar><br>componentname d g s b dt modelname <inpar> |

|               |   |                             |
|---------------|---|-----------------------------|
| modelname     | : | name of model, user defined |
| componentname | : | occurrence indicator        |
| <modpar>      | : | list of model parameters    |
| <inpar>       | : | list of instance parameters |

d,g,s and b are drain, gate, source, bulk and self-heating terminals respectively.

### 3 Note

Warning! In Spectre, use only the parameter statements `type=n` or `type=p`. Using any other string and/or numbers will result in unpredictable and possibly erroneous results.

#### 15.9.3 ADS syntax

n channel electrical model:      `model modelname mos1102e gender=1 <modpar>`  
    `modelname:componentname d g s b <instpar>`

p channel electrical model:      `model modelname mos1102e gender=0 <modpar>`  
    `modelname:componentname d g s b <instpar>`

n channel electrical self-heating model:  
    `model modelname mos1102et gender=1 <modpar>`  
    `modelname:componentname d g s b dt <instpar>`

p channel electrical self-heating model:  
    `model modelname mos1102et gender=0 <modpar>`  
    `modelname:componentname d g s b dt <instpar>`

n channel physical geometrical model:  
    `model modelname mos11020 gender=1 <modpar>`  
    `modelname:componentname d g s b <instpar>`

p channel physical geometrical model:  
    `model modelname mos11020 gender=0 <modpar>`  
    `modelname:componentname d g s b <instpar>`

n channel physical geometrical self-heating model:  
    `model modelname mos11020t gender=1 <modpar>`  
    `modelname:componentname d g s b dt <instpar>`

p channel physical geometrical self-heating model:  
    `model modelname mos11020t gender=0 <modpar>`  
    `modelname:componentname d g s b dt <instpar>`

n channel binning geometrical model:  
    `model modelname mos11021 gender=1 <modpar>`  
    `modelname:componentname d g s b <instpar>`

p channel binning geometrical model:  
    `model modelname mos11021 gender=0 <modpar>`  
    `modelname:componentname d g s b <instpar>`

n channel binning geometrical self-heating model:  
    `model modelname mos11021t gender=1 <modpar>`  
    `modelname:componentname d g s b dt <instpar>`

p channel binning geometrical self-heating model:

```
model modelname mos11021t gender=0 <modpar>
modelname:componentname d g s b dt <instpar>
```

modelname : name of model, user defined

componentname : occurrence indicator

<modpar> : list of model parameters

<instpar> : list of instance parameters

d,g,s and b are drain, gate, source, bulk and self-heating terminals respectively.

### 15.9.4 The ON/OFF condition for Pstar

The solution for a circuit involves a process of successive calculations. The calculations are started from a set of 'initial guesses' for the electrical quantities of the nonlinear elements. A simplified DCAPPROX mechanism for devices using ON/OFF keywords is mentioned in [9]. By default the devices start in the default state.

| n-channel |         |      |     |
|-----------|---------|------|-----|
|           | Default | ON   | OFF |
| $V_{DS}$  | 1.25    | 1.25 | 2.5 |
| $V_{GS}$  | 1.25    | 1.25 | 0.0 |
| $V_{SB}$  | 0.0     | 0.0  | 0.0 |

| p-channel |         |       |      |
|-----------|---------|-------|------|
|           | Default | ON    | OFF  |
| $V_{DS}$  | -1.25   | -1.25 | -2.5 |
| $V_{GS}$  | -1.25   | -1.25 | 0.0  |
| $V_{SB}$  | 0.0     | 0.0   | 0.0  |

### 15.9.5 The ON/OFF condition for Spectre

| n-channel |     |        |            |              |         |         |           |
|-----------|-----|--------|------------|--------------|---------|---------|-----------|
|           | OFF | Triode | Saturation | Subthreshold | Reverse | Forward | Breakdown |
| $V_{DS}$  | 0.0 | 0.75   | 1.25       | 2.0          | 0       | 0       | 0         |
| $V_{GS}$  | 0.0 | 2.0    | 1.25       | 0.25         | 0       | 0       | 0         |
| $V_{SB}$  | 0.0 | 0.0    | 0.0        | 0.0          | 0       | 0       | 0         |

| p-channel |     |        |            |              |         |         |           |
|-----------|-----|--------|------------|--------------|---------|---------|-----------|
|           | OFF | Triode | Saturation | Subthreshold | Reverse | Forward | Breakdown |
| $V_{DS}$  | 0.0 | -0.75  | -1.25      | -2.0         | 0       | 0       | 0         |
| $V_{GS}$  | 0.0 | -2.0   | -1.25      | -0.25        | 0       | 0       | 0         |
| $V_{SB}$  | 0.0 | 0.0    | 0.0        | 0.0          | 0       | 0       | 0         |

### 15.9.6 The ON/OFF condition for ADS

| n-channel |         |
|-----------|---------|
|           | Default |
| $V_{DS}$  | 0       |
| $V_{GS}$  | 0       |
| $V_{SB}$  | 0       |

| p-channel |         |
|-----------|---------|
|           | Default |
| $V_{DS}$  | 0       |
| $V_{GS}$  | 0       |
| $V_{SB}$  | 0       |

## 15.10 Parameter Extraction

The parameter extraction strategy for MOS Model 11 using an **optimization method** consists of four main steps:

1. measurements
2. extraction of miniset parameters at room temperature
3. extraction of temperature scaling parameters
4. extraction of geometry scaling parameters.

The above steps will be briefly described in the following sections.

### 15.10.1 Measurements

The parameter extraction routine consists of four different dc-measurements and two (optional) capacitance measurements<sup>1</sup>:

- **Measurement I:**  $I_D/g_m/I_G-V_{GS}$  - characteristics in linear region:

n-channel :  $V_{GS} = 0 \dots V_{sup}$  (with steps of maximum 50 mV).  
 $V_{DS} = 50 \text{ mV}$   
 $V_{BS} = 0 \dots -V_{sup}$

p-channel :  $V_{GS} = 0 \dots -V_{sup}$  (with steps of maximum 50 mV).  
 $V_{DS} = -50 \text{ mV}$   
 $V_{BS} = 0 \dots V_{sup}$

- **Measurement II:** Subthreshold  $I_D-V_{GS}$  - characteristics:

n-channel :  $V_{GS} = V_T - 0.6 \text{ V} \dots V_T + 0.3 \text{ V}$   
 $V_{DS} = 3 \text{ values starting from } 100 \text{ mV to } V_{sup}$   
 $V_{BS} = 0 \dots -V_{sup}$

p-channel :  $V_{GS} = V_T + 0.6 \text{ V} \dots V_T - 0.3 \text{ V}$   
 $V_{DS} = 3 \text{ values starting from } -100 \text{ mV to } -V_{sup}$   
 $V_{BS} = 0 \dots V_{sup}$

<sup>1</sup>The bias conditions to be used for the measurements are dependent on the supply voltage of the process. Of course it is advisable to restrict the range of voltages to this supply voltage  $V_{sup}$ . Otherwise physical effects, atypical for normal transistor operation and therefore less well described by MOS Model 11, may dominate the characteristics.

- **Measurement III:**  $I_D/g_{DS}/I_G-V_{DS}$  - characteristics:
  - n-channel :  $V_{DS} = 0 \dots V_{sup}$  (with steps of maximum 50 mV).  
 $V_{GS} = 4$  values starting from  $V_T + 0.1$  V , not above  $V_{sup}$   
 $V_{BS} = 3$  values starting from 0 V to  $-V_{sup}$
  - p-channel :  $V_{DS} = 0 \dots -V_{sup}$  (with steps of maximum 50 mV).  
 $V_{GS} = 4$  values starting from  $V_T + 0.1$  V , not below  $-V_{sup}$   
 $V_{BS} = 3$  values starting from 0 V to  $V_{sup}$
  
- **Measurement IV:**  $I_D/I_S/I_G/I_B-V_{GS}$  - characteristics in all operation regions:
  - n-channel :  $V_{GS} = -V_{sup} \dots V_{sup}$  (with steps of maximum 50 mV).  
 $V_{DS} = 4$  values starting from 0 V to  $V_{sup}$   
 $V_{BS} = 0$  V
  - p-channel :  $V_{GS} = -V_{sup} \dots -V_{sup}$  (with steps of maximum 50 mV).  
 $V_{DS} = 4$  values starting from 0 V to  $-V_{sup}$   
 $V_{BS} = 0$  V
  
- **Measurement V:**  $C_{gg}-V_{GS}$  - characteristics (optional):
  - n/p-channel :  $V_{GS} = -V_{sup} \dots V_{sup}$  (with steps of maximum 50 mV).  
 $V_{DS} = 0$  V  
 $V_{BS} = 0$  V
  
- **Measurement VI:**  $C_{cg}-V_{GS}$  - characteristics:
  - n/p-channel :  $V_{GS} = -V_{sup} \dots V_{sup}$   
 $V_{DS} = 0$  V  
 $V_{BS} = 0$  V

The values of transconductance  $g_m$  and output conductance  $g_{DS}$  are extracted from the I - V-curves by calculating in a numerical way the derivative of  $I_D$  to  $V_{GS}$  and  $V_{DS}$ , respectively. In the subthreshold measurements, Measurement II, use is made of threshold voltage  $V_T$ , which has to be determined for all the bulk-source bias values  $V_{BS}$ . The determination of  $V_T$  is rather arbitrary, and it can be either determined using the lineas extrapolation method or the constant current criterion. The channel-to-gate capacitance  $C_{cg}$  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.

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

### 15.10.2 Extraction of Miniset Parameters at Room Temperature

The extraction of miniset parameters is performed for every device. In order to ensure that the temperature scaling relations do not affect the behaviour at room temperature, the reference temperature  $T_R$  is chosen equal to room temperature. In general the simultaneous determination of all miniset parameters is not advisable, because the value of some parameters can be wrong due to correlation and suboptimization. Therefore it is more practical to split the parameters into several groups, where each parameter group can be determined using specific measurements.

Although the poly-depletion effect affects the dc-behaviour of a MOSFET, the poly-depletion parameter KPINV can only be determined accurately from  $C$ - $V$ -measurements. If the (physical) oxide thickness  $t_{ox}$  and the polysilicon impurity concentration  $N_p$  are known, the parameter KPINV ( $= 1/(k_p)$ ) can be calculated from<sup>1</sup>:

$$k_p = \frac{t_{ox} \cdot \sqrt{2 \cdot q \cdot \epsilon_{si} \cdot N_p}}{\epsilon_{ox}} \quad (15.363)$$

If the polysilicon impurity concentration  $N_p$  is not known, as a good first-order estimate one can use  $N_p = 1 \cdot 10^{26} \text{ m}^{-3}$  for  $n^+$ -polysilicon gates and  $N_p = 5 \cdot 10^{25} \text{ m}^{-3}$  for  $p^+$ -polysilicon gates. In the latter case a measured  $C_{GG}$ - $V_{GS}$ -characteristic for a long-channel transistor is essential for an accurate determination of KPINV.

1. For metal gates the poly-depletion effect does not occur and in this case KPINV = 0.

Table 19: Starting miniset parameter values for parameter extraction at room temperature  $T_R$  of a typical MOSFET with channel length  $L$  (m), channel width  $W$ (m), oxide thickness  $t_{ox}$  (m), polysilicon impurity concentration  $N_P$  ( $m^{-3}$ ) and minimum technology feature size  $L_{min}$ . If the polysilicon concentration  $N_P$  is not known, one can use  $N_p = 1 \cdot 10^{26} m^{-3}$  or  $5 \cdot 10^{25} m^{-3}$  for  $n^+$ - resp.  $p^+$ -polysilicon gates. Parameters  $C_{ox}$ ,  $C_{GSO}$  and  $C_{GDO}$  are only important for the charge model, and do not affect the dc-model; they have to be extracted from C-V-characteristics. In order to determine the parameter geometry-scaling, the last column indicates for which conditions the parameters have to be extracted: L=long-channel device (fixed for short-channel devices), S=short-channel devices, A=all devices and F=fixed parameter.

| Parameter      | Program Name | Parameter Value                              |  | Extracted for |
|----------------|--------------|--|--|---------------|
|                |              | NMOS   | PMOS   |               |
| $V_{FB}$       | VFB          | -1.1   | -0.95  | L             |
| $k_0$          | KO           | 0.25   | 0.25   | A             |
| $1/k_p$        | KPINV        | $6.0 \cdot 10^3 / (t_{OX} \cdot \sqrt{N_p})$ | $6.0 \cdot 10^3 / (t_{OX} \cdot \sqrt{N_p})$ | L             |
| $\phi_B$       | PHIB         | 0.95   | 0.95   | A             |
| $\beta$        | BET          | $1.7 \cdot 10^{-12} / t_{OX} \cdot W/L$      | $4.5 \cdot 10^{-13} / t_{OX} \cdot W/L$      | A             |
| $\theta_{sr}$  | THESR        | $1.5 \cdot 10^{-9} / t_{OX}$                 | $2.3 \cdot 10^{-9} / t_{OX}$                 | L             |
| $\theta_{ph}$  | THEPH        | $1.3 \cdot 10^{-10} / t_{OX}$                | $2.2 \cdot 10^{-10} / t_{OX}$                | L             |
| $\eta_{mob}$   | ETAMOB       | 1.3  | 3.0  | L             |
| $\nu$          | NU           | 2.0  | 2.0  | A             |
| $C_s$          | CS           | 0.1  | 0.1  | A             |
| $\theta_R$     | THER         | $1.3 \cdot 10^{-7} / L$                      | $8.0 \cdot 10^{-8} / L$                      | S             |
| $\theta_{R1}$  | THER1        | 0  | 0  | -             |
| $\theta_{R2}$  | THER2        | 1  | 1  | -             |
| $\theta_{sat}$ | THESAT       | $4.5 \cdot 10^{-7} / L$                      | $2.0 \cdot 10^{-7} / L$                      | A             |
| $\theta_{Th}$  | THETH        | $1.0 \cdot 10^{-6}$                          | $1.0 \cdot 10^{-6}$                          | A             |

Table 19: Starting miniset parameter values for parameter extraction at room temperature  $T_R$  of a typical MOSFET with channel length  $L$  (m), channel width  $W$ (m), oxide thickness  $t_{ox}$  (m), polysilicon impurity concentration  $N_P$  ( $m^{-3}$ ) and minimum technology feature size  $L_{min}$ . If the polysilicon concentration  $N_P$  is not known, one can use  $N_p = 1 \cdot 10^{26} m^{-3}$  or  $5 \cdot 10^{25} m^{-3}$  for  $n^+$ - resp.  $p^+$ -polysilicon gates. Parameters  $C_{ox}$ ,  $C_{GSO}$  and  $C_{GDO}$  are only important for the charge model, and do not affect the dc-model; they have to be extracted from C-V-characteristics. In order to determine the parameter geometry-scaling, the last column indicates for which conditions the parameters have to be extracted: L=long-channel device (fixed for short-channel devices), S=short-channel devices, A=all devices and F=fixed parameter.

| Parameter       | Program Name | Parameter Value                              |  | Extracted for |
|-----------------|--------------|--|--|---------------|
|                 |              | NMOS   | PMOS   |               |
| $\sigma_{dibl}$ | SDIBL        | $5.0 \cdot 10^{-2} \cdot (L_{min}/L)^2$      | $5.0 \cdot 10^{-2} \cdot (L_{min}/L)^2$      | S             |
| $m_0$           | MO           | $1.0 \cdot 10^{-3}$                          | $1.0 \cdot 10^{-3}$                          | A             |
| $\sigma_{sf}$   | SSF          | $6.0 \cdot 10^{-2} \cdot L_{min}/L$          | $6.0 \cdot 10^{-2} \cdot L_{min}/L$          | A             |
| $\alpha$        | ALP          | $6.0 \cdot 10^{-2} \cdot L_{min}/L$          | $6.0 \cdot 10^{-2} \cdot L_{min}/L$          | A             |
| $V_p$           | VP           | $5.0 \cdot 10^{-2}$                          | $1.0 \cdot 10^{-1}$                          | F             |
| $m$             | MEXP         | use Eq. (12.132)                             | use Eq. (12.132)                             | -             |
| $a_1$           | A1           | 25   | 100  | A             |
| $a_2$           | A2           | 25   | 37   | A             |
| $a_3$           | A3           | 1  | 1  | A             |
| $I_{GINV}$      | IGINV        | $3.0 \cdot 10^{-5} \cdot W \cdot L/t_{ox}^2$ | $4.0 \cdot 10^{-5} \cdot W \cdot L/t_{ox}^2$ | A             |
| $B_{INV}$       | BINV         | $2.9 \cdot 10^{+10} \cdot t_{ox}$            | $4.3 \cdot 10^{+10} \cdot t_{ox}$            | L             |
| $I_{GACC}$      | IGACC        | $3.0 \cdot 10^{-5} \cdot W \cdot L/t_{ox}^2$ | $2.0 \cdot 10^{-5} \cdot W \cdot L/t_{ox}^2$ | A             |
| $B_{ACC}$       | BACC         | $B_{INV}$                                    | $2.9 \cdot 10^{+10} \cdot t_{ox}$            | L             |
| $V_{FBov}$      | VFBOV        | 0.1  | 0.1  | L             |
| $k_{ov}$        | KOV          | $9.3 \cdot 10^{+8} \cdot t_{ox}$             | $3.8 \cdot 10^{+8} \cdot t_{ox}$             | L             |
| $I_{GOV}$       | IGOV         | $5.0 \cdot 10^{-13} \cdot W/t_{ox}^2$        | $5.0 \cdot 10^{-12} \cdot W/t_{ox}^2$        | A             |

Table 19: Starting miniset parameter values for parameter extraction at room temperature  $T_R$  of a typical MOSFET with channel length  $L$  (m), channel width  $W$ (m), oxide thickness  $t_{ox}$  (m), polysilicon impurity concentration  $N_P$  ( $m^{-3}$ ) and minimum technology feature size  $L_{min}$ . If the polysilicon concentration  $N_P$  is not known, one can use  $N_p = 1 \cdot 10^{26} m^{-3}$  or  $5 \cdot 10^{25} m^{-3}$  for  $n^+$ - resp.  $p^+$ -polysilicon gates. Parameters  $C_{ox}$ ,  $C_{GSO}$  and  $C_{GDO}$  are only important for the charge model, and do not affect the dc-model; they have to be extracted from C-V-characteristics. In order to determine the parameter geometry-scaling, the last column indicates for which conditions the parameters have to be extracted: L=long-channel device (fixed for short-channel devices), S=short-channel devices, A=all devices and F=fixed parameter.

| Parameter  | Program Name | Parameter Value                       |                                       | Extracted for |
|------------|--------------|---------------------------------------|---------------------------------------|---------------|
|            |              | NMOS                                  | PMOS                                  |               |
| $A_{GIDL}$ | AGIDL        | $1.6 \cdot 10^{-13} \cdot W/t_{ox}^2$ | $1.2 \cdot 10^{-17} \cdot W/t_{ox}^2$ | A             |
| $B_{GIDL}$ | BGIDL        | $1.6 \cdot 10^{+8} \cdot t_{ox}$      | $1.0 \cdot 10^{+10} \cdot t_{ox}$     | L             |
| $C_{GIDL}$ | CGIDL        | 0                                     | 0                                     | L             |

Before the optimization is started a parameter set has to be determined which contains a first estimation of the parameters to be extracted and the parameters which remain constant. The value of smoothing factor  $m$  is calculated from the device length  $L$  and from the minimum feature size of the technology  $L_{min}$  using Eq. (15.136). The parameter set used as a first-order estimation of the parameters to be extracted is given in Table 20. With this parameter set a first optimization following the scheme below, is performed. After this the new parameter set serves as an estimation for the second optimization, which is performed following the same scheme. This method yields a proper set of parameters after the second optimization. Experi-

ments with transistors of different processes show that the parameter set does not change very much after a third optimization.

Table 20: DC-parameter extraction procedure for a long-channel n-MOSFET, where Steps 2 and 12 are optional. For p-type transistors all voltages and currents have to be multiplied by -1. The optimization is either performed on the absolute or relative deviation between model and measurements. Parameter  $I_{tst}$  is 2.5  $\mu A$  for NMOS and 0.8  $\mu A$  for PMOS. For n-MOSFETs  $B_{acc} = B_{inv}$ , and as a result  $B_{acc}$  does not have to be extracted. For p-MOSFETs this is not the case, see Table. 10.

| Step | Optimised Parameters                            | Measurement | Fitted On | Absolute/Relative | Specific Conditions                    |
|------|---|-------------|-----------|-------------------|--|
| 1    | $\phi_B, k_0, \beta, \theta_{sr}, C_s$          | I           | $I_D$     | Absolute          | -                                      |
| 2    | $V_{FB}, k_0, k_p, C_{ox}$                      | V           | $C_{gg}$  | Relative          | -                                      |
| 3    | $\phi_B, k_0, m_0$                              | II          | $I_D$     | Relative          | -                                      |
| 4    | $\beta, \theta_{sr}, \theta_{ph}, C_s$          | I           | $I_D/g_m$ | Relative          | $V_{SB} = 0V$<br>$V_{GS} > V_T + 0.3V$ |
| 5    | $\eta_{mob}$                                    | I           | $I_D$     | Absolute          | $I_D > W/L \cdot I_{tst}$              |
| 6    | $\theta_{sat}$                                  | III         | $I_D$     | Absolute          | -                                      |
| 7    | $\sigma_{sf}, \alpha, \theta_{Th}$              | III         | $g_{DS}$  | Relative          | -                                      |
| 8    | $\theta_{sat}$                                  | III         | $I_D$     | Absolute          | -                                      |
| 9    | $I_{GINV}, B_{INV}$                             | I           | $I_G$     | Absolute          | -                                      |
| 19   | $I_{GOV}, (B_{ACC}), I_{GACC}, k_{ov}$          | IV          | $I_G$     | Relative          | $V_{GS} < 0V$                          |
| 11   | $a_1, a_2, a_3$                                 | IV          | $I_B$     | Absolute          | $V_{GS} \geq 0V$                       |
| 12   | $A_{GIDL}, B_{GIDL}, C_{GIDL}$                  | IV          | $I_B$     | Absolute          | $V_{GS} < 0V$                          |
| 13   | $V_{FB}, k_p, C_{ox}$                           | V           | $C_{gg}$  | Relative          | -                                      |
| 14   | Repeat steps 3, 4, 5, 6, 7, 8, 9, 10, 11 and 12 |             |           |                   |  |

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 the poly-depletion parameter  $1/k_p$ , the flat-band voltage VFB, the carrier mobility (i.e.  $\theta_{sr}$ ,  $\theta_{ph}$ ,  $\eta_{mob}$ , and  $C_s$ ) and the gate tunnel-

ling probability factors ( $B_{inv}$  and  $B_{acc}$ ) can be determined, and they can subsequently be fixed for the short and narrow-channel devices, see Tab. 20. In Table 21 the extraction procedure for long-channel transistors is given. Since the value of body-factor  $k_0$  may change much over geometry and over technology, the first-order estimate in Tab. 7.1 is very crude and a more accurate, preliminary value is obtained using Step 1. In Step 2 (optional) more accurate values of the poly-depletion parameter  $1/k_P$  and the flat-band voltage  $V_{FB}$  (which determines the onset of accumulation) are extracted. Next the subthreshold parameters  $\phi_B$ ,  $k_0$  and  $m_0$  are optimized in Step 3, neglecting short-channel effects such as drain-induced barrier-lowering (DIBL). After that the mobility parameters are optimized using Steps 4 and 5, neglecting the influence of series-resistance. In Step 6 a preliminary value of the velocity saturation parameter is obtained, and subsequently the conductance parameters  $\sigma_{sf}$ ,  $\alpha$  and  $\theta_{Th}$  are determined in Step 7. A more accurate value of  $\theta_{sat}$  can now be obtained using Step 8 (which is Step 6 repeated). The gate current parameters are determined in Steps 9 and 10, followed by the weak-avalanche parameters in Step 11, and finally, the gate-induced leakage current parameters are optimized in step 12.

Table 21: DC-parameter extraction procedure for a short-channel n-MOSFET. For p-type transistors all voltages and currents have to be multiplied by -1. Parameters  $1/k_P$ ,  $V_{FB}$ ,  $\theta_{sr}$ ,  $\theta_{ph}$ ,  $\eta_{mob}$ ,  $B_{inv}$ ,  $B_{acc}$ ,  $k_{ov}$ ,  $B_{GIDL}$  and  $C_{GIDL}$  are taken from the long-channel case. The optimization is either performed on the absolute or relative deviation between model and measurements.

| Step | Optimised Parameters                              | Measurement | Fitted On | Absolute/Relative | Specific Conditions                    |
|------|---|-------------|-----------|-------------------|--|
| 1    | $\phi_B, k_0, \beta, \theta_R, C_s$               | I           | $I_D$     | Absolute          | -                                      |
| 2    | $\phi_B, k_0, m_0, \sigma_{dibl}$                 | II          | $I_D$     | Relative          | -                                      |
| 3    | $\beta, \theta_R, C_s$                            | I           | $I_D/g_m$ | Relative          | $V_{SB} = 0V$<br>$V_{GS} > V_T + 0.3V$ |
| 4    | $\theta_{sat}$                                    | III         | $I_D$     | Absolute          | -                                      |
| 5    | $\sigma_{sf}, \alpha, \theta_{Th}, \sigma_{dibl}$ | III         | $g_{DS}$  | Relative          | -                                      |
| 6    | $\theta_{sat}$                                    | III         | $I_D$     | Absolute          | -                                      |
| 7    | $I_{GINV}, I_{GOV}, I_{GACC}$                     | IV          | $I_D$     | Relative          | -                                      |
| 8    | $a_1, a_2, a_3$                                   | IV          | $I_B$     | Absolute          | $V_{GS} \geq 0V$                       |

Table 21: DC-parameter extraction procedure for a short-channel n-MOSFET. For p-type transistors all voltages and currents have to be multiplied by - 1. Parameters  $1/k_p$ ,  $V_{FB}$ ,  $\theta_{sr}$ ,  $\theta_{ph}$ ,  $\eta_{mob}$ ,  $B_{inv}$ ,  $B_{acc}$ ,  $k_{ov}$ ,  $B_{GIDL}$  and  $C_{GIDL}$  are taken from the long-channel case. The optimization is either performed on the absolute or relative deviation between model and measurements.

| Step | Optimised Parameters                 | Measurement | Fitted On | Absolute/Relative | Specific Conditions |
|------|--------------------------------------|-------------|-----------|-------------------|---------------------|
| 9    | $A_{GIDL}$                           | IV          | $I_B$     | Absolute          | $V_{GS} < 0V$       |
| 10   | Repeat steps 2, 3, 4, 5, 7, 8 and 9. |             |           |                   |                     |

For short-channel devices the values of the poly-depletion parameter  $1/k_p$ , flat-band voltage  $V_{FB}$ , the carrier mobility parameters ( $\theta_{sr}$ ,  $\theta_{ph}$  and  $\eta_{mob}$ ) and the gate tunnelling probability factors ( $B_{inv}$  and  $B_{acc}$ ) of the long-channel device are copied, and next the extraction procedure as given in Table 23 is executed. In contrast to the long-channel case, the extraction procedure for short-channel devices also optimizes the parameters for series-resistance<sup>1</sup> and DIBL.

Table 22: Starting miniset parameter values for AC-parameter extraction of a typical MOSFET with channel length  $L$  (m), channel width  $W$  (m) and oxide thickness  $t_{ox}$  (m).

| Parameter | Program Name | Parameter Value                        |  |
|-----------|--------------|--|--|
|           |              | NMOS                                   | PMOS                                   |
| $C_{ox}$  | COX          | $\epsilon_{ox}/t_{ox} \cdot W \cdot L$ | $\epsilon_{ox}/t_{ox} \cdot W \cdot L$ |
| $C_{GDO}$ | CGDO         | $3.0 \cdot 10^{-10} \cdot W$           | $3.0 \cdot 10^{-10} \cdot W$           |
| $C_{GSO}$ | CGSO         | $3.0 \cdot 10^{-10} \cdot W$           | $3.0 \cdot 10^{-10} \cdot W$           |

**AC-parameters:** In Table 22, a first-order estimation of the AC-parameters is given. The AC-parameters  $C_{ox}$ ,  $C_{GSO}$ ,  $C_{GDO}$ ,  $k_{ov}$  and  $V_{FBov}$  cannot be (accurately) de-termined from DC-characteristics, and as a consequence they have to be determined from C–V– characteristics<sup>2</sup>. Since normal MOS transistors are symmetrical devices, one can assume that the oxide

1. Note that in Table 10 parameters  $\theta_{R1}$  and  $\theta_{R2}$  are not included, which implies that the series-resistance is assumed to be voltage-independent. This holds true for modern CMOS technologies, where no use is made of LDD-structures.

2. Although parameter  $k_{ov}$  can be determined from overlap gate current, see Table 9, it is nonetheless more accurately determined from the  $C_{cg}$ - $V_{GS}$  characteristics.

capacitance of the source and drain extension are identical, which implies that  $C_{GSO}=C_{GDO}$ . The oxide capacitance of the intrinsic MOSFET  $C_{ox}$  can be extracted from Measurement VI. In Table 23 the extraction procedure for the AC-parameters is given.

*Table 23: AC-parameter extraction procedure for a MOSFET. Here it is assumed that  $C_{GSO} = C_{GDO}$ . In the first instance flat-band voltage  $V_{FBov}$  is not optimised, although it may be optimised during Step 1 in order to obtain more accurate results. The optimization is either performed on the absolute or relative deviation between model and measurements.*

| Step | Optimised Parameters | Measurement | Fitted On | Absolute/Relative | Specific Conditions |
|------|----------------------|-------------|-----------|-------------------|---------------------|
| 1    | $k_{ov}, C_{GSO}$    | VI          | $C_{cg}$  | Relative          | $V_{GS} < 0V$       |
| 2    | $C_{ox}$             | V           | $C_{gg}$  | Relative          | -                   |
| 3    | Repeat steps 1 and 2 |             |           |                   |                     |

### 15.10.3 Extraction of Temperature Scaling Parameters

For a specific device the temperature scaling parameters can be extracted after the miniset at room temperature has been extracted. In order to do so, measurements I, III and IV need to be performed at various temperature values (at least two values different from room temperature, typically - 40° C and 125° C).

Since the reference temperature  $T_R$  has been chosen equal to room temperature, the modelled behaviour at room temperature is not affected by different values of the temperature scaling parameters. As a first-order estimation of the temperature scaling parameter values, the

default values as given in Section 15.3.2 are used. Again the parameter extraction scheme is slightly different for the long-channel and for the short-channel case.

*Table 24: Temperature scaling parameter extraction procedure for a long-channel n-MOSFET, where measurements have been performed at various temperature values. For p-type transistors all voltages and currents have to be multiplied by -1. The optimization is either performed on the absolute or relative deviation between model and measurements. Parameter  $I_{tst}$  is  $2.5 \mu A$  for NMOS and  $0.8 \mu A$  for PMOS.*

| Step | Optimised Parameters  | Measurement | Fitted On | Absolute/Relative | Specific Conditions       |
|------|---|-------------|-----------|-------------------|---------------------------|
| 1    | $S_{T;\phi_B}$  | I           | $I_D$     | Relative          | $I_D < W/L \cdot I_{tst}$ |
| 2    | $\eta_{\beta}, \eta_{sr}, \eta_{ph}, v_{exp}, S_{T;\eta_{mob}}, \eta_{C_s}$ | I           | $I_D$     | Relative          | $I_D > W/L \cdot I_{tst}$ |
| 3    | $\eta_{sat}$  | III         | $I_D$     | Absolute          | -                         |
| 4    | $S_{T;a_1}$   | IV          | $I_B$     | Absolute          | $V_{GS} \geq 0V$          |
| 5    | $S_{T;B_{GIDL}}$  | IV          | $I_B$     | Absolute          | $V_{GS} < 0V$             |

For an accurate extraction, the temperature scaling parameters for a long-channel device have to be determined first. In the long-channel case the carrier mobility parameters (i.e.  $\eta_{sr}, \eta_{ph}, v_{exp}$  and  $S_{T;\eta_{mob}}$ ) can be determined, and they can subsequently be fixed for the short-channel devices. In Table 24 the extraction procedure for long-channel transistors 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 Step 4 the temperature dependence of impact ionization is determined, and finally, in step 5 the temperature dependence of the gate-induced drain leakage is optimized.

For short-channel devices the values of the mobility reduction temperature scaling parameters (i.e.  $\eta_{sr}, \eta_{ph}, v_{exp}$  and  $S_{T;\eta_{mob}}$ ) of the long-channel device are copied, and next the extraction procedure as given in Table 25 is executed. In contrast to the long-channel case,

the extraction procedure for short-channel devices optimizes the parameter for series-resistance.

Table 25: Temperature scaling parameter extraction procedure for a short-channel  $n$ -MOSFET, where measurements have been performed at various temperature values. For  $p$ -type transistors all voltages and currents have to be multiplied by  $-1$ . The optimization is either performed on the absolute or relative deviation between model and measurements. Parameter  $I_{tst}$  is  $2.5 \mu A$  for NMOS and  $0.8 \mu A$  for PMOS.

| Step | Optimised Parameters             | Measurement | Fitted On | Absolute/Relative | Specific Conditions       |
|------|----------------------------------|-------------|-----------|-------------------|---------------------------|
| 1    | $S_{T;\phi_B}$                   | I           | $I_D$     | Relative          | $I_D < W/L \cdot I_{tst}$ |
| 2    | $\eta_\beta, \eta_R, \eta_{C_s}$ | I           | $I_D$     | Relative          | $I_D > W/L \cdot I_{tst}$ |
| 3    | $\eta_{sat}$                     | III         | $I_D$     | Absolute          | -                         |
| 4    | $S_{T;a_1}$                      | IV          | $I_B$     | Absolute          | $V_{GS} \geq 0V$          |
| 5    | $S_{T;B_{GIDL}}$                 | IV          | $I_B$     | Absolute          | $V_{GS} < 0V$             |

## 15.10.4 Extraction of Geometry Scaling Parameters

In general the most important part of the geometry scaling scheme is the determination of  $\Delta L$  and  $\Delta W$ , see eqs. (15.114) and (15.117), since it affects the DC-, the AC- as well as the noise model. Traditionally  $\Delta W$  can be determined from the extrapolated zero-crossing in the gain factor  $\beta$  versus mask width  $W$ . In a similar way  $\Delta L$  can be determined from the inverse gain factor  $1/\beta$  versus mask length  $L$ . For modern MOS devices with pocket implants, however, it has been found that the above  $\Delta L$  extraction method is no longer valid [16], [18]. Another, more accurate method is to measure the gate-to-bulk capacitance  $C_{GB}$  in accumulation for different channel lengths [17], [18]. In this case the extrapolated zero-crossing in the  $C_{GB}$  versus mask length  $L$  curve will give  $\Delta L$ . Unfortunately for CMOS technologies in which gate current is non-negligible, capacitance measurements may be hampered by gate current [19]. In this case either gate current parameter  $I_{GINV}$  or  $I_{GACC}$  plotted as a function of channel length  $L$  may be used to extract  $\Delta L$  [19].

In MM11, Level 1102, one can use either physical or binning geometry scaling rules. When using the binning rules of Section 15.3.3, the scaling parameters for one bin can be directly calculated from the minisets of the four corner devices of the bin. The binning scheme ensures that the minisets are exactly reproduced in the bin corners, and that no humps occur

in parameter values across bin borders. The exact way to calculate binning parameters from minisets is described in Appendix B.

When using the physical scaling relations of Section 15.3.2 it is possible to calculate a parameter set for a process, given the parameter set of typical transistors of this process. To accomplish this, transistors of different lengths, widths and at different temperatures have to be measured. Using these measurements the sensitivities of the parameters on length, width and temperature can be found. For the determination of a geometry-scaled parameter set a three-step procedure is recommended:

1. Determine minisets ( $\phi_B, k_0, \beta, \dots$ ) for all measured devices, as explained in Sections 15.10.2 and 15.10.3.
2. The width and length sensitivity coefficients are optimized by fitting the appropriate geometry scaling rules to these miniset parameters.
3. Finally the width and length sensitivity coefficients are optimized by fitting the result of the scaling rules and current equations to the measured currents of all devices simultaneously.

Parameter sets have been determined for several processes using this parameter extraction strategy and taking care of not exceeding the supply voltage. For all processes good results have been obtained.

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Available on request. Write to: [Ronald.van.Langevelde@philips.com](mailto:Ronald.van.Langevelde@philips.com)
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# **A Hyp functions**

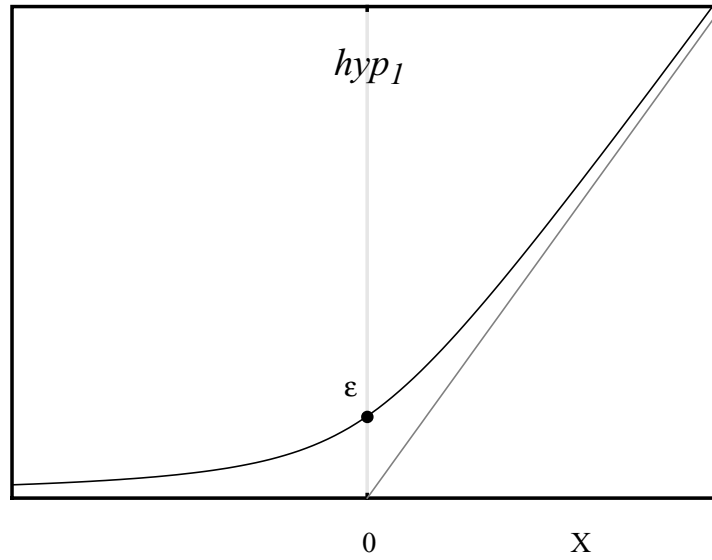


Figure 73:  $hyp_1(x;\epsilon) = \frac{1}{2} \cdot (x + \sqrt{x^2 + 4 \cdot \epsilon^2})$

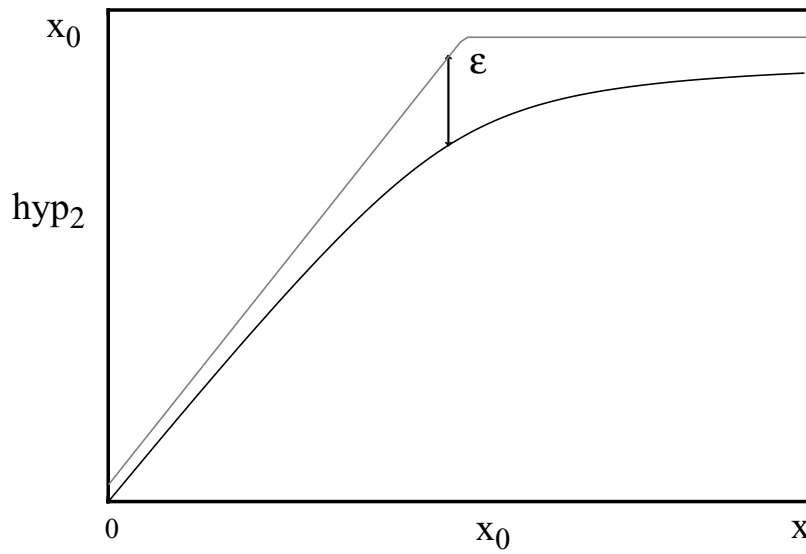


Figure 74:  $hyp_2(x;x_0;\epsilon) = x - hyp_1(x - x_0;\epsilon)$

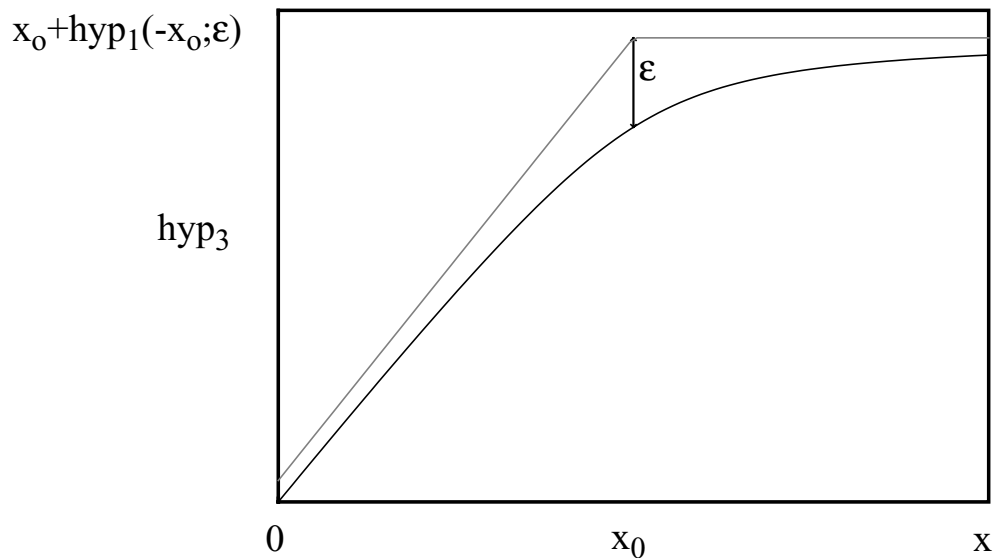


Figure 75:  $hyp_3(x; x_0; \epsilon) = hyp_2(x; x_0; \epsilon) - hyp_2(0; x_0; \epsilon)$  for  $\epsilon = \epsilon(x_0)$

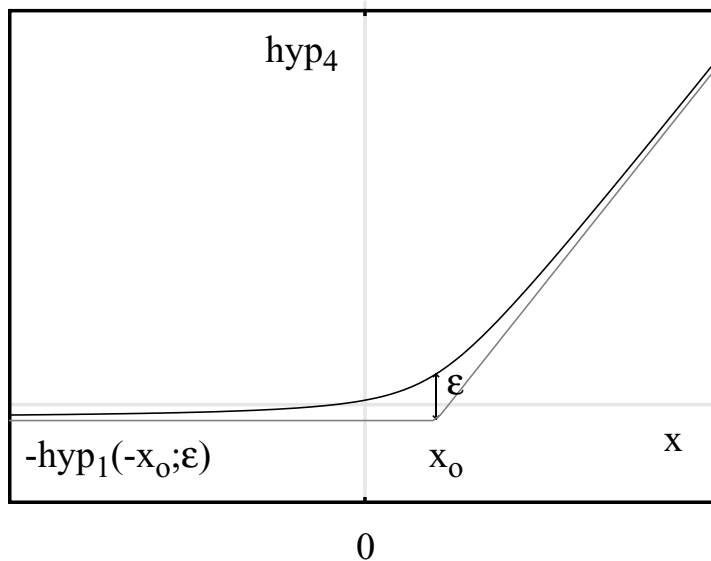


Figure 76:  $hyp_4(x; x_0; \epsilon) = hyp_1(x - x_0; \epsilon) - hyp_1(-x_0; \epsilon)$

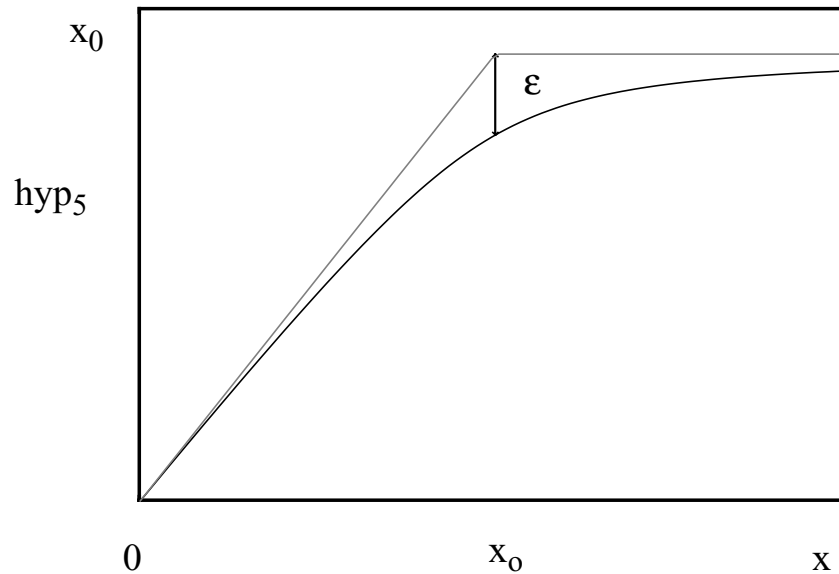


Figure 77:  $\text{hyp}_5(x; x_0; \varepsilon) = x_0 - \text{hyp}_1\left(x_0 - x - \frac{\varepsilon^2}{x_0}, \varepsilon\right)$  for  $\varepsilon = \varepsilon(x_0)$

**The hypm-function:**

$$\text{hypm}[x, y; m] = \frac{x \cdot y}{(x^{2 \cdot m} + y^{2 \cdot m})^{1/(2 \cdot m)}} \quad (15.364)$$

# **B** Spectre Specific Information

## Imax, Imelt, Jmelt parameters

### Introduction

Imax, Imelt and Jmelt are Spectre-specific parameters used to help convergence and to prevent numerical problems. We refer in this text only to the use of Imax model parameter in Spectre with SiMKit devices since the other two parameters, Imelt and Jmelt, are not part of the SiMKit code. For information on Imelt and Jmelt refer to Cadence documentation.

### Imax model parameter

Imax is a model parameter present in the following SiMKit models:

- juncap and juncap2
- psp and pspnqs (since they contain juncap models)

In Mextram 504 (bjt504) and Modella (bjt500) SiMKit models, Imax is an internal parameter and its value is set through the adapter via the Spectre-specific parameter Imax.

The default value of the Imax model parameter is 1000A. Imax should be set to a value which is large enough so it does not affect the extraction procedure.

In models that contain junctions, the junction current can be expressed as:

$$I = I_s \exp\left(\frac{V}{N \cdot \phi_{TD}} - 1\right) \quad (15.365)$$

The exponential formula is used until the junction current reaches a maximum (explosion) current Imax.

$$I_{max} = I_s \exp\left(\frac{V_{expl}}{N \cdot \phi_{TD}} - 1\right) \quad (15.366)$$

The corresponding voltage for which this happens is called Vexpl (explosion voltage). The voltage explosion expression can be derived from (1):

$$V_{expl} = N \cdot \phi_{TD} \log\left(\frac{I_{max}}{I_s}\right) + 1 \quad (15.367)$$

For  $V > V_{expl}$  the following linear expression is used for the junction current:

$$I = I_{max} + (V - V_{expl}) \frac{I_s}{N \cdot \phi_{TD}} \exp\left(\frac{V_{expl}}{N \cdot \phi_{TD}}\right) \quad (15.368)$$

## Region parameter

Region is an Spectre-specific model parameter used as a convergence aid and gives an estimated DC operating region. The possible values of region depend on the model:

- For Bipolar models:
  - subth: Cut-off or sub-threshold mode
  - fwd: Forward
  - rev: Reverse
  - sat: Saturation.
  - off<sup>1</sup>
  -
- For MOS models:
  - subth: Cut-off or sub-threshold mode;
  - triode: Triode or linear region;
  - sat: Saturation
  - off<sup>1</sup>

For PSP and PSPNQS all regions are allowed, as the PSP(NQS) models both have a MOS part and a juncap (diode). Not all regions are valid for each part, but when e.g. region=fwd is set, the initial guesses for the MOS will be set to zero. The same holds for setting a region that is not valid for the JUNCAP.

- For diode models:
  - fwd: Forward
  - rev: Reverse
  - brk: Breakdown
  - off<sup>1</sup>

## Model parameters for device reference temperature in Spectre

This text describes the use of the tnom, tref and tr model parameters in Spectre with SiMKit devices to set the device reference temperature.

---

<sup>1</sup>.Off is not an electrical region, it just states that the user does not know in what state the device is operating

A Simkit device in Spectre has three model parameter aliases for the model reference temperature, `tnom`, `tref` and `tr`. These three parameters can only be used in a model definition, not as instance parameters.

There is no difference in setting `tnom`, `tref` or `tr`. All three parameters have exactly the same effect. The following three lines are therefore completely equivalent:

```
model nmos11020 mos11020 type=n tnom=30
model nmos11020 mos11020 type=n tref=30
model nmos11020 mos11020 type=n tr=30
```

All three lines set the reference temperature for the `mos11020` device to 30 C.

Specifying combinations of `tnom`, `tref` and `tr` in the model definition has no use, only the value of the last parameter in the model definition will be used. E.g.:

```
model nmos11020 mos11020 type=n tnom=30 tref=34
```

will result in the reference temperature for the `mos11020` device being set to 34 C, `tnom=30` will be overridden by `tref=34` which comes after it.

When there is no reference temperature set in the model definition (so no `tnom`, `tref` or `tr` is set), the reference temperature of the model will be set to the value of `tnom` in the options statement in the Spectre input file. So setting:

```
options1 options tnom=23 gmin=1e-15 reltol=1e-12 \
  vabstol=1e-12 iabstol=1e-16
model nmos11020 mos11020 type=n
```

will set the reference temperature of the `mos11020` device to 23 C.

When no `tnom` is specified in the options statement and no reference temperature is set in the model definition, the default reference temperature is set to 27 C.

So the lines:

```
options1 options gmin=1e-15 reltol=1e-12 vabstol=1e-12 \
  iabstol=1e-16
model nmos11020 mos11020 type=n
```

will set the reference temperature of the `mos11020` device to 27 C.

The default reference temperature set in the SiMKit device itself is in the Spectre simulator never used. It will always be overwritten by either the default "options tnom", an explicitly set option tnom or by a tnom, tref or tr parameter in the model definition.



# C OvervoltageSpecification

## Overvoltage warnings in SiMKit

### Introduction

Overvoltage flagging is signalling that a (terminal) voltage is outside a specified safe range. A warning will be given when the conditions for giving a warning are fulfilled.

Simple checks for overvoltage have been added to the following models: mos903, mos1100, mos1101, mos1102, mos2002, mos2003, mos3100, mos4000, psp102, psp103.

The checks are done on terminal voltages of the models.

There are many ways to define overvoltage. For a general overvoltage flagging solution Verilog-A should be used.

### Extra parameters for overvoltage flagging

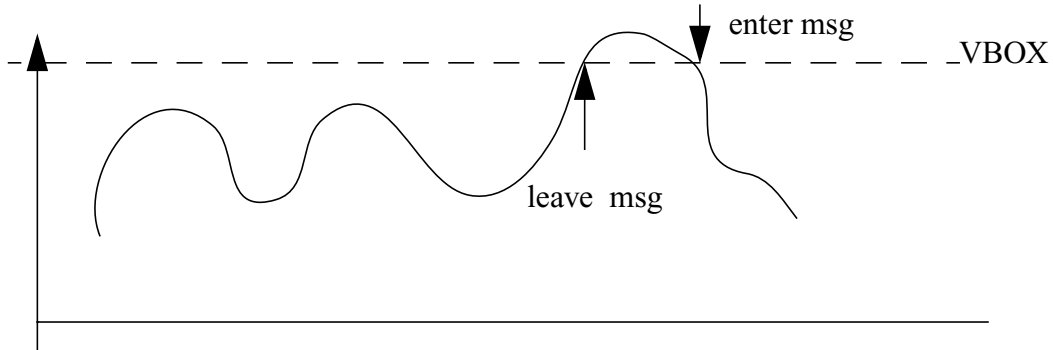
A set of extra parameters has been added to the mos models mos903, mos1100, mos1101, mos1102, mos2002, mos2003, mos3100, mos4000, psp102, psp103.

Table 26:

| Name | Unit | Default | Description   |
|------|------|---------|---|
| VBOX | V    | 0.0     | Oxide breakdown voltage.<br>Checking will be done if $VBOX > 0$       |
| VBDS | V    | 0.0     | Drain-source breakdown voltage<br>Checking will be done if $VBDS > 0$ |
| TMIN | s    | 0.0     | Ovcheck tmin value  |

For mos models the safe region is:

$$|V_{gs}| < VBOX \text{ and } |V_{gd}| < VBOX \text{ and } |V_{ds}| < VBDS$$



### Ovcheck: two terminal dummy model

A (dummy) two-terminal model ovcheck has been implemented that can be used to check if the voltage between the two terminals is within or without a so called safe region.

The model parameters are:

| Name  | Unit | Default | Description   |
|-------|------|---------|---|
| VLOW  | V    | 0.0     | Lower bound of safe region  |
| VHIGH | V    | 0.0     | Upper bound of safe region<br>Checking will be done when $VHIGH > VLOW$ |
| TMIN  | s    | 0.0     | Ovcheck tmin value  |

For the ovcheck model the safe region is:

$$VLOW \leq V_{t1} - V_{t2} \leq VHIGH, \text{ where } t1 \text{ is the first and } t2 \text{ is the second terminal.}$$

### Functionality

#### In Spectre and Pstar

At the end of a DC analysis or in a transient analysis after each time step a check will be done if the device is inside or outside the safe region.

A warning is given whenever the device enters or leaves the safe region.

**In Spectre only**

To prevent too many warnings in a Spectre transient analysis the model parameter TMIN has been introduced. If the time between leaving and entering the safe region is less than the TMIN value no warning is given.

Because of the TMIN parameter a warning cannot be issued when leaving the safe region. A warning is given when the device enters the safe region again. This warning includes the time and the voltage when the safe region was exited. At the end of the transient warnings are given for devices that are still out of the safe range.

In Pstar TMIN may be specified as a model parameter, but it will be ignored.

# D Parameter PARAMCHK

## Parameter PARAMCHK

### Introduction

All models have the parameter PARAMCHK. It is not related to the model behavior, but has been introduced control the clip warning messages. Various situations may call for various levels of warnings. This is made possible by setting this parameter.

### PARAMCHK model parameter

This model parameter has been added to control the amount of clip warnings.

|          |   |   |   |
|----------|---|---|---|
| PARAMCHK | < | 0 | No clip warnings  |
| PARAMCHK | ≥ | 0 | Clip warnings for instance parameters (default)   |
| PARAMCHK | ≥ | 1 | Clip warnings for model parameters  |
| PARAMCHK | ≥ | 2 | Clip warnings for electrical parameters at initialisation   |
| PARAMCHK | ≥ | 3 | Clip warnings for electrical parameters during evaluation.<br>This highest level is of interest only for selfheating jobs,<br>where electrical parameters may change dependent on<br>temperature. |

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