SP

Surface-Potential-Based

Compact MOSFET Model

(**Model Summary v.32**)

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Updated 06/10/2004

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1 General Comments

This document contains a summary of the new surface-potential-based model **SP** [1]-[20]. To simplify the presentation we exclude some minor details of the model implementation.

The main features of SP are as follows.

- **SP** is surface-potential-based
- Surface potential is computed via extremely accurate non-iterative approximation valid in all regions of operation (including accumulation). There are no iteration loops anywhere in the program implementation.
- **SP** includes an engineering model of the bias dependence for the lateral field gradient, which traditionally is either neglected or is assumed to be bias-independent.
- Intrinsic charge model is based on the drain current model. Accumulation region [trans]capacitances are modeled physically.
- **SP** automatically satisfies benchmark tests including Gummel symmetry test. In order to accomplish this we use symmetric linearization of the bulk charge [7] [15].
- Gm/Id ratio is modeled correctly.
- **SP** includes all major short-channel effects.
- **SP**v.32 has 113 model parameters.

This summary describes the **core** model consisting of drain current and intrinsic charges. The extrinsic charge models, as well as noise and substrate current models are being developed right now and are not included.

In addition to the model summary this document includes a brief derivation of a simple model for the lateral gradient factor (Appendix A) and some simulation results (Section 13).

Terminology.

Local model parameters: appear in the model formulation below. Some of them must be scaled with the device geometry. They are sufficient for representing device characteristics of a single transistor. **SP** core model contains 28 local parameters which are listed in Appendix D and are denoted by **bold** script.

Global model parameters: these include those of the local parameters which do not scale with geometry and the scaling parameters which are used to introduce the geometry dependence of the remaining local parameters. **SP** core model global parameters are listed in Appendix E.

Note that some parameters are both local and global (e.g. **MU0**) and that only local parameters are used in the model formulation. This simplifies both the model description and the parameter extraction procedure.

The scaling equations are given in Appendix F.

2 Structure of the Core Model (Order of Computations)

- Compute fixed combinations of the model parameters
- Perform voltage conditioning
- Terminal flip (if $\mathrm{V_{ds}} < 0$)
- $\mathrm{V_{bs}}, \mathrm{V_{bd}}$ clamping to assure $V_{bs} < \phi_b, V_{bd} < \phi_b$
- Compute lateral gradient factor
- Compute surface potential ϕ_{ss} (at the source end of the channel) and related variables
- Compute effective drain-source voltage
- Compute $\phi, \phi_{sd} = \phi_{ss} + \phi$
- Compute mid-point surface potential ϕ_m and related variables
- Introduce QM and polysilicon depletion corrections
- Evaluate drain current
- Compute intrinsic charges

3 Bias-Independent Variables

Thermal voltage

$$V_t = k_B\mathbf{TABS}/q \tag{1}$$

Oxide capacitance

$$C_{\mathrm{OX}} = \varepsilon_{\mathrm{OX}}/\mathbf{TOX} \tag{2}$$

Effective doping

$$\mathbf{Nsub} = \mathbf{NSUB}\left(1 + \frac{\mathbf{LPKT}}{L_{\mu m}}\right) \tag{3}$$

Body factor

$$\gamma = \sqrt{2q\varepsilon_{si}\mathbf{Nsub}}/C_{OX} \tag{4}$$

Normalized body factor

$$G = \gamma/\sqrt{V_t} \tag{5}$$

Bulk potential

$$\phi_b = V_t \ln(\mathbf{Nsub}/n_i) \tag{6}$$

Constant for computing effective vertical field

$$E_{\mathrm{eff0}} = 10^{-8} \cdot C_{\mathrm{OX}}/\varepsilon_{si} \tag{7}$$

Variable used to introduce polysilicon depletion effect

$$k_P = 2C_{\mathrm{OX}}^2 V_t/q\varepsilon_{si}\mathbf{NP} \tag{8}$$

Variable used to introduce quantum-mechanical corrections

$$q_q = 16.1\mathbf{QMC}(\mathbf{TOX}^2 \cdot 10^{20} \cdot V_t \cdot \ \mathbf{TABS})^{-1/3} \tag{9}$$

4 Additional Notations

Surface Potentials

$\phi_s =$ surface potential

$\phi_{ss} =$ surface potential at the source end of the channel

$\phi_{sd} =$ surface potential at the drain end of the channel

$$\phi = \phi_{sd} - \phi_{ss} \tag{10}$$

Normalized surface potentials

$$x = \phi_s / V_t \tag{11}$$

$$x_s = \phi_{ss} / V_t \tag{12}$$

$$x_d = \phi_{sd} / V_t \tag{13}$$

$$\varphi = \phi / V_t \tag{14}$$

Normalized gate bias

$$x_g = (V_{gb} - V_{fb}) / V_t \tag{15}$$

Functions

$$\mathrm{MINA}(a, b, c) = \frac{1}{2}\left[a + b - \sqrt{(a-b)^2 + c}\,\right] \tag{16}$$

$$\mathrm{MAXA}(a, b, c) = \frac{1}{2}\left[a + b + \sqrt{(a-b)^2 + c}\,\right] \tag{17}$$

$$\sigma(a, c, \tau) = \frac{av}{\mu + \frac{v}{\mu} c (\frac{c^2}{3} - a)} \tag{18}$$

where

$$v = a + c \tag{19}$$

and

$$\mu = \frac{v^2}{\tau} + \frac{c^2}{2} - a \tag{20}$$

5 Lateral Gradient Factor [1]

Traditionally, lateral gradient factor

$$f = 1 - \frac{\varepsilon_{si}}{q\mathbf{NSUB}} \left(\frac{\partial^2 \phi_s}{\partial y^2} + \frac{\partial^2 \phi_s}{\partial z^2} \right) \tag{21}$$

is either set to be 1 (gradual-channel approximation) or assumed to be bias-independent. In **SP**, we include the reduction of the lateral field gradient (i.e. the increase of f) with the surface potential via semi-empirical equation

$$f = f_0(1 + \mathbf{B_f}\phi_f) \tag{22}$$

where

$$f_0 = \frac{\mathbf{F_0}}{1 + \mathbf{B_f}V_{\mathrm{sbx1}} + (\mathbf{C_f}V_{\mathrm{dsx}} + \mathbf{A_f}V_{\mathrm{sbx1}})(1 + \mathbf{DF} \cdot \mathbf{C_f}V_{\mathrm{dsx}} + \mathbf{EF} \cdot \mathbf{A_f}V_{\mathrm{sbx1}})} + 0.01 \tag{23}$$

$$V_{\mathrm{dsx}} = \sqrt{V_{\mathrm{ds}}^2 + 0.01} - 0.1 \tag{24}$$

$$V_{\mathrm{sbx1}} = \mathrm{MAXA}(V_{\mathrm{sbx}}, 0, 10^{-4}) \tag{25}$$

$$V_{\mathrm{sbx}} = V_{\mathrm{sb}} + \frac{1}{2}(V_{\mathrm{ds}} - V_{\mathrm{dsx}}) \tag{26}$$

The essential features of this expressions are (i) linear $f(\phi_f)$ dependence and (ii) decrease of f with V_{ds} and V_{bs}. A simple model leading to (22) is presented in Appendix A.

The functional form of V_{dsx} is motivated by the smoothing functions introduced in MOS9 and subsequently used in other compact models. Introduction of variables V_{dsx} and V_{sbx} assures

$$\left(\frac{\partial f}{\partial V_{ds}} \right)_{V_{ds}=0} = 0 \tag{27}$$

This condition is imposed in order to satisfy the Gummel symmetry test. For the same reason surface potential $\phi_f = x_f V_t$ corresponds to the imref splitting $\phi_n = V_{sbx}$ rather than to $\phi_n = V_{sb}$. A more subtle point is that ϕ_f is computed with less precision than surface potentials ϕ_{ss} and ϕ_{sd}. Indeed, evaluations of ϕ_{ss} and ϕ_{sd} requires that f be known (see Appendix B). In contrast, ϕ_f has to be evaluated before f is computed. It turns out that the following simple approximation for x_f is sufficient to account for the increase of f (i.e. the reduction of $\partial^2\phi_s/\partial y^2$) with the gate drive.

$$x_f = \eta_f + \sigma\left(\frac{a_f}{1-B_tG^2}, \frac{c_f}{1-B_tG^2}, \tau\right) \tag{28}$$

where

$$B_t = (f_0 - 0.01)\mathbf{B_f}V_t \tag{29}$$

$$\eta_f = \mathrm{MINA}(x_{subf}, \tilde{x}_0 + 3, 5) \tag{30}$$

$$x_{subf} = \frac{x_{gc}^2}{x_{gc} + \frac{1}{2}G^2 f_0 + G\left[B_t x_{gc}^2 + f_0 x_{gc} + \left(\frac{Gf_0}{2}\right)^2\right]^{1/2}} \tag{31}$$

$$x_{gc} = \mathrm{MAXA}(x_g, 0, 50) \tag{32}$$

$$\tilde{x}_0 = (2\phi_b + V_{sbx})/V_t \tag{33}$$

$$\tau = \tilde{x}_0 - \eta_f + \ln(a_f/G^2) \tag{34}$$

$$a_f = (x_{gc} - \eta_f)^2 - G^2(f_0 + B_t\eta_f) \tag{35}$$

$$c_f = 2(x_{gc} - \eta_f) + G^2(f_0 + 2B_t\eta_f) \tag{36}$$

6 Surface Potential ϕ_{ss} (at the Source End of the Channel) and Related Variables

In Appendix B, we present an approximate analytical solution for the surface potential in the form

$$x = \theta(V_{gb}, \phi_n) \tag{37}$$

where the normalized imref splitting

$$\phi_n = (F_p - F_n)/q \tag{38}$$

In particular

$$x_s = \theta(V_{gb}, V_{sb}) \tag{39}$$

In the process of computing surface potential, the following variables are computed as well:

$$E_s = \exp(-x_s) \tag{40}$$

$$\Delta_s = \Delta_{ns}/(E_s) \tag{41}$$

$$D_s = (E_s^{-1} - E_s - 2x_s)\Delta_{ns} \tag{42}$$

where

$$\Delta_{ns} = \frac{1}{f}\exp(-x_{ns}) \tag{43}$$

and

$$x_{ns} = (2\phi_b + V_{sb})/V_t \tag{44}$$

In the code, the evaluation of E_s, Δ_s and Δ_{ns} is carefully ordered to avoid over/underflow problems.

After evaluating surface potential x_s , one computes normalized inversion charge at the source

$$V_1 = \frac{G_f^2 V_t D_s}{x_{gs} + G_f S_s} \tag{45}$$

where

$$S_s = \sqrt{P_s} \tag{46}$$

$$P_s = x_s - 1 + E_s \tag{47}$$

$$x_{gs} = G_f \sqrt{D_s + P_s} \tag{48}$$

and

$$G_f = G\sqrt{f} \tag{49}$$

Note that while $x_{gs} = x_g - x_s$, using (45) reduces the numerical noise for V_{gs} close to V_{fb}.

Series resistance

$$R_t = \frac{R_{t1}(1 + \mathbf{RB} \cdot V_{sbx})}{1 + R_g V_1} \tag{50}$$

Series resistance factor

$$\rho = \mathbf{MU0}(C_{OX}/L) R_t V_1 \tag{51}$$

Effective vertical field

$$E_{\text{eff}} = E_{\text{eff0}}(q_b + \eta_\mu V_1) \tag{52}$$

$$q_b = V_t G_f S_s \tag{53}$$

where $\eta_\mu = 1/2$ for n-channel and $1/3$ for p channel MOSFET's.

Effective mobility at the source end of the channel [11]

$$\mu_s = \frac{\mathbf{MU0} \cdot \mu_x}{1 + (\mu_E \cdot E_{\text{eff}})^{\theta_{\mathbf{MU}}} + \mathbf{CS}\frac{q_b^2}{(V_1 + q_b)^2} + \rho} \tag{54}$$

The variable

$$\mu_x = (1 + \mathbf{X_{cor}} \cdot V_{sbx})/(1 + 0.2\mathbf{X_{cor}} \cdot V_{sbx}) \tag{55}$$

where the term $(1+\mathbf{X_{cor}} \cdot V_{sbx})$ introduces non-universality essential for devices with significant Coulomb scattering. The denominator assures that μ_x does not exceed 5 for extreme (and unphysical) V_{sbx} that may occur during SPICE convergence process.

Note: V_1 and μ_s are "temporary variables". Eventually these will be changed to assure the symmetry of the model. Also, $\rho = 0$ if external model of series resistance is used.

7 Effective Drain-Source Voltage

"Saturation voltage"

$$V_{dsat} = \phi_{sat} - V_t \ln \left[1 + \frac{\phi_{sat}(\phi_{sat} - 2a_{sat}V_t)}{G_f^2 \Delta_s V_t^2} \right] \tag{56}$$

where

$$a_{sat} = x_{gs} + \frac{1}{2} G_f^2 \tag{57}$$

In particular

$$\phi_{sat} = \frac{2\phi_0\phi_2}{\phi_0 + \phi_2 + \sqrt{(\phi_0 + \phi_2)^2 - 3.96\phi_0\phi_2}} \tag{58}$$

$$\phi_2 = \frac{V_t G_f^2 \Delta_s \mathbf{S0}}{a_{sat} + \sqrt{a_{sat}^2 - G_f^2 \Delta_s \mathbf{S0}}} \tag{59}$$

$$\phi_0 = \psi_0 \frac{V_c + \frac{V_2}{4} + \psi_0(\frac{1}{8} + \frac{\delta_0^2}{2})}{V_c + V_2\delta_0(1 - \delta_0) + \psi_0\delta_0^2} \tag{60}$$

$$\delta_0 = \frac{\psi_0}{\psi_0 + \mathbf{G_{hf}} V_c} \tag{61}$$

$$\psi_0 = \frac{2V_2}{1 + \frac{V_2}{4V_c} + \sqrt{1 + \frac{V_2}{V_c} + \left(\frac{V_2}{4V_c}\right)^2}} \tag{62}$$

$$V_2 = (V_1/\alpha_s) + V_t \tag{63}$$

$$V_c = \frac{u_{sat} L}{\mu_s} \tag{64}$$

$$u_{sat} = \frac{\mathbf{VSAT}}{1 + \mathbf{K_{sm}} \cdot w_{sat}} \tag{65}$$

$$w_{sat} = \frac{100V_1(1 + \mathbf{STX} \cdot V_{sbx})}{100 + V_1(1 + \mathbf{STX} \cdot V_{sbx})} \tag{66}$$

and

$$\alpha_s = 1 + \frac{G_f(1 - E_s)}{2S_s} \tag{67}$$

Effective drain-source voltage

$$V_{dse} = \frac{V_{ds}}{[1 + (V_{ds}/V_{dsat})^{\mathbf{a_x}}]^{1/\mathbf{a_x}}} \tag{68}$$

8 Surface Potential ϕ_{sd} (at the Drain End of the Channel) and Related Variables

Surface potential at the drain end of the channel $\phi_{sd} = x_d V_t$ where [compare to Eq. (39) above]

$$x_d = \theta(V_{gb}, V_{sb} + V_{dse}) \tag{69}$$

However, as a matter of convenience we use the above equation only when

$$x_g > x_{g23} = G\sqrt{f_{23}(x_{23} - 1)} \tag{70}$$

where

$$f_{23} = f_0 + B_t x_{23} \tag{71}$$

and

$$x_{23} = \begin{cases} (\phi_b + V_{sb})/V_t, & \text{for} V_{sb} \geq 0 \\ (\phi_b + 0.5V_{sb})/V_t, & \text{for} V_{sb} < 0 \end{cases} \tag{72}$$

For $x_g < x_{g23}$, it is more efficient to compute x_s then determine normalized drain-source surface potential difference $\varphi = \phi/V_t$ and finally compute $x_d = x_s + \varphi$. An approximate analytical solution for φ in the region $x_g < x_{g23}$ is given in Appendix C.

In the process of computing surface potential x_d , the following variables are computed as well:

$$E_d = \exp(-x_d) \tag{73}$$

$$D_d = (E_d^{-1} - E_d - 2x_d)\Delta_{nd} \tag{74}$$

where

$$\Delta_{nd} = \frac{1}{f}\exp(-x_{nd}) \tag{75}$$

$$x_{nd} = (2\phi_b + V_{sb} + V_{dse})/V_t \tag{76}$$

9 Mid-Point Surface Potential $\phi_\mathbf{m}$ and Related Variables

Midpoint (subscript "m") is defined as corresponding to a surface potential

$$\phi_m = \frac{1}{2}(\phi_{ss} + \phi_{sd}) \tag{77}$$

The following variables are used

$$x_m = \frac{1}{2}(x_s + x_d) \tag{78}$$

$$E_m = \sqrt{E_s E_d} \tag{79}$$

$$D_m = \frac{1}{2}(D_s + D_d) + \frac{1}{8}\varphi^2 \left(E_m - \frac{2}{G_f^2} \right) \tag{80}$$

$$P_m = x_m - 1 + E_m \tag{81}$$

$$x_{gm} = G_f \sqrt{D_m + P_m} \tag{82}$$

and

$$S_m = \sqrt{P_m} \tag{83}$$

Normalized inversion charge

$$V_m = \frac{G_f^2 V_t D_m}{x_{gm} + G_f S_m} \tag{84}$$

Linearization coefficient

$$\alpha = 1 + \frac{G_f(1 - E_m)}{2S_m} \tag{85}$$

Series resistance

$$R_t = \frac{R_{t1}(1 + \mathbf{RB} \cdot V_{sbx})}{1 + \mathbf{R_g} V_m} \tag{86}$$

Series resistance factor

$$\rho = \mathbf{MU0}(C_{OX}/L) R_t V_m \tag{87}$$

Effective vertical field

$$E_{\text{eff}} = E_{\text{eff0}}(q_b + \eta_\mu V_m) \tag{88}$$

$$q_b = V_t G_f S_m \tag{89}$$

where $\eta_\mu = 1/2$ for n-channel and 1/3 for p channel MOSFETs.

Effective mobility

$$\mu_m = \frac{\mathbf{MU0} \cdot \mu_x}{1 + (\mu_{\mathbf{E}} \cdot E_{\text{eff}})^{\theta_{\mathbf{MU}}} + \mathbf{CS}\frac{q_b^2}{(V_m + q_b)^2} + \rho} \tag{90}$$

10 Quantum-Mechanical Corrections [4]

In SP quantum-mechanical (QM) correction are introduced based on the method described in [4]. The difference is that in [4] we have only considered the most common case $\phi_s \geq 3V_t$ which is of interest for the charge-sheet models. The equations given below are conditioned for a wide voltage range. Furthermore, we develop QM corrections directly for $x_m = \phi_m/V_t$ and $\varphi = (\phi_{sd} - \phi_{ss})/V_t$. This is preferable to correcting ϕ_{ss} and ϕ_{sd}, especially in the case when φ is a small difference of two larger variables. In what follows superscript "(0)" refers to variables uncorrected for QM effects.

For $x_g \geq 0$ (i.e. for $V_{gb} \geq V_{fb}$)

$$x_m = x_m^{(0)} + u_{QM} \tag{91}$$

and

$$\varphi = \varphi^{(0)} \frac{k_m(\bar{D} + d_0)}{d + k_m \overline{D} a_{QM}} \tag{92}$$

where

$$u_{QM} = \frac{q_{QM}}{p_{QM} - q_{QM}/p_{QM}} \tag{93}$$

$$q_{QM} = G_f^2 D_m^{(0)} \Delta e_g^{'} \tag{94}$$

$$\Delta e_g^{'} = g_{QMP} \Delta e_g \tag{95}$$

$$\Delta e_g = q_q x_{gm}^{2/3} \tag{96}$$

$$g_{QMP} = \frac{D_m^{(0)}}{D_m^{(0)} + P_m^{(0)}} \tag{97}$$

$$p_{QM} = 2x_{gm} + G_f^2 \left[1 - E_m^{(0)} + D_m^{(0)} a_{QM}\right] \tag{98}$$

$$a_{QM} = 1 + \frac{2\Delta e_g^{'}}{3x_{gm}} \tag{99}$$

$$k_m = \exp\left(a_{QM} u_{QM} - \Delta e_g^{'}\right) \tag{100}$$

$$\bar{D} = \frac{D_s + D_d}{2} \tag{101}$$

$$d_0 = 1 - E_m^{(0)} + 2x_{gm}/G_f^2 \tag{102}$$

$$d = d_0 + \left(E_m^{(0)} - 2/G_f^2\right) u_{QM} \tag{103}$$

For $x_g < 0$

$$x_m = x_m^{(0)} - \frac{\Delta e_g^{'} \phi_m^2}{\phi_m^2 + \frac{0.04}{1+3|\phi_m|}} \tag{104}$$

There is no correction for φ. This form is introduced to eliminate the singularity or unphysical behavior near $V_{gb} = V_{fb}$. Coefficients 0.04 and 3 are not affected by model parameters and are fixed. In addition to correcting ϕ_m and x_m, QM effects are introduced into

$$D_m = k_m D_m^{(0)} \tag{105}$$

and variables P_m, x_{gm} , which are given by expressions (81) and (82) above but with x_m corrected for QM effects.

11 Polysilicon Depletion [2]

In SP polysilicon depletion is described essentially using the technique of [2]. The equations are conditioned to provide smooth device characrteristics for a wide voltage range but at present the poly effects are only included for $v_{gb} > V_{fb}$. The normalized poly surface potential at midpoint

$$x_{pm} = k_p \left[\frac{x_{gm}^{(0)}}{1 + \eta_p^{-1}} \right]^2 \tag{106}$$

where k_p is given by eq. (8) in section 3 and

$$\eta_p = \left[1 + k_p x_{gm}^{(0)} \right]^{-1/2} \tag{107}$$

In this section superscript "(0)" indicates that the variable is not corrected for poly depletion effect. As in section 10, poly corrections are introduced into $x_m = \phi_m / V_t$ and $\varphi = (\phi_{sd} - \phi_{ss})/V_t$ rather than into ϕ_{ss} and ϕ_{sd} directly. The corrected midpoint surface potential is

$$x_m = x_m^{(0)} + u_p \tag{108}$$

where

$$u_p = \frac{q}{p - q/p} \tag{109}$$

$$p = 2 \left[x_{gm}^{(0)} - x_{pm} \right] + G_f^2 \left[1 - E_m^{(0)} + D_m^{(0)} \right] \tag{110}$$

and

$$q = x_{pm} \left[x_{pm} - 2 x_{gm}^{(0)} \right] \tag{111}$$

The correction to normalized surface potential difference φ is as follows

$$\varphi = \varphi^{(0)} \frac{k_m (d_0 + \bar{D})}{d + k_m \bar{D}} \tag{112}$$

where d_0 is given by (102) with a different meaning of "(0)" as explained above,

$$d = 1 - E_m^{(0)} - 2 \eta_p x_{gm} / G_f^2 \tag{113}$$

$$k_m = \exp(u_p) \tag{114}$$

and $\bar{D}$ is given by (101).

In addition to changing the surface potentials, poly correction affects the linearization of inversion charge and intrinsic charges. The expressions in sections 12 and 13 include these corrections. The case of no poly effect can be recovered by setting $\eta_p = 1$. While physically this corresponds to **NP** $\rightarrow \infty$, in SP eliminating poly effects is formally prescribed by setting **NP**=0 in the parameter file.

12 Drain Current Computation

Velocity saturation factor L_{sat}

$$V_c = Lu_{\rm sat}/\mu_m \tag{115}$$

$$u_{sat} = \frac{\mathbf{VSAT}}{1 + \mathbf{K_{sm}} w_{sat}} \tag{116}$$

$$w_{sat} = \frac{100 V_m (1 + \mathbf{STX} \cdot V_{sbx})}{100 + V_m (1 + \mathbf{STX} \cdot V_{sbx})} \tag{117}$$

This form assures that $w_{sat} < 100$ and $u_{sat} > 0.3\mathbf{VSAT}$ during SPICE convergence process when V_m can be unphysically high.

$$\delta = \frac{\phi}{\phi + \mathbf{G_{hf}} V_c} \tag{118}$$

$$L_{sat} = \frac{\delta \phi \mu_m}{u_{sat}} \tag{119}$$

Channel length modulation factor L_{CLM}

$$L_{CLM} = \delta L_{q2d} \ln[1 + \mathbf{CLM3} \cdot (V_{ds} - \phi)] \tag{120}$$

Drain current

$$I_d = \frac{\mu_m W C_{OX} (V_m + \alpha V_t) \phi}{L_{red} + L_{sat}} \tag{121}$$

where the inversion charge linearization (including polysilicon depletion effect)

$$\alpha = \eta_p + \frac{G_f (1 - E_m)}{2 S_m} \tag{122}$$

and the “reduced channel length”

$$L_{red} = \frac{L}{1 + L_{CLM}/L} \tag{123}$$

13 Intrinsic Charges [2, 10, 17]

All charges are normalized to C_{oxt} (see Appendix F)
Gate charge

$$Q_G = x_{gm} V_t + \frac{\eta_p \phi}{2} \left(\frac{\phi \, r_L}{6H} - 1 + r_L \right) \tag{124}$$

where

$$H = \frac{V_m/\alpha + V_t}{1 + L_{sat}/L_{red}} \tag{125}$$

and

$$r_L = L_{red}/L \tag{126}$$

Inversion layer charge

$$|Q_I| = r_L (V_m + \alpha \phi^2/12H) + Q_{CLM} \tag{127}$$

$$Q_{CLM} = (1 - r_L)(V_m - 0.5\alpha\phi) \tag{128}$$

Drain charge (computed using Ward-Dutton partition)

$$|Q_D| = \frac{1}{2} r_L^2 \left\{ V_m - \frac{\alpha\phi}{6} \left[1 - \frac{\phi}{2H} - \frac{1}{5} \left(\frac{\phi}{2H} \right)^2 \right] \right\} + \frac{1}{2} Q_{CLM} (1 + r_L) \tag{129}$$

Source charge

$$|Q_s| = |Q_I| - |Q_D| \tag{130}$$

Bulk charge

$$|Q_B| = Q_G - |Q_I| \tag{131}$$

Part II

Extrinsic Model

14 General Comments

This document summarizes the extrinsic SP model, which at present includes overlap charges, gate current, substrate current, and noise sources models. The main features of the SP extrinsic model are as follows:

- The surface potential in the overlap regions is evaluated using a newly developed streamlined analytical approximation.
- The physical modelling of the overlap charge is enabled by the availability of the surface potential in the overlap regions.
- Gate current model is physically based.
- A new formulation of the substrate current is developed to achieve the asymptotically correct behavior in the subthreshold region without using smoothing functions.
- The description of parameters, variables, and other notations in the summary of the intrinsic model is not repeated in this document.

15 Bias-Independent Variables

Overlap capacitance

$$C_{oxov} = \varepsilon_{ox} / \mathbf{TOXOV} \tag{132}$$

Overlap body factor

$$\gamma_{ov} = \sqrt{2q\varepsilon_{Si}\mathbf{NOV}} / C_{oxov} \tag{133}$$

Normalized overlap body factor

$$G_{ov} = \gamma_{ov} / \sqrt{V_t} \tag{134}$$

Tunnelling current density constant (in A/m^2)

$$J_0 = \frac{q m_0 k_B^2 \mathbf{TABS}^2}{2\pi^2 \hbar^3} = 1.082 \times 10^{11} \times \left(\frac{\mathbf{TABS}}{300} \right)^2 \tag{135}$$

Channel tunnelling current density exponential constant (dimensionless)

$$B = 2\mathbf{TOX} \left(2q m_0 \chi_B \right)^{1/2} / \hbar = 6.831 \times 10^9 \mathbf{TOX} \sqrt{\chi_B} \tag{136}$$

Overlap tunnelling current density exponential constant (dimensionless)

$$B_{ov} = 2\mathbf{TOXOV} \left(2q m_0 \chi_B \right)^{1/2} / \hbar = 6.831 \times 10^9 \mathbf{TOXOV} \sqrt{\chi_B} \tag{137}$$

Auxiliary variable of gate current model

$$\alpha_b = E_g / \left(2q \right) + \phi_b \tag{138}$$

In (136) and (137), the Si/SiO_2 conduction band offset, $\chi_B = 3.13V$.

16 Additional Notations

ϕ_{sov} surface potential in the source overlap region
ϕ_{dov} surface potential in the drain overlap region
$V_{oxm} = V_{gb} - V_{fb} - \phi_m$ oxide voltage in the potential mid-point
$V_{oxovs} = V_{gs} - \phi_{sov}$ oxide voltage in the source overlap region
$V_{oxovd} = V_{gd} - \phi_{dov}$ oxide voltage in the drain overlap region

17 Streamlined Surface Potential Approximation [19]

The availability of the surface potential in the overlap regions is essential to the physical modelling of the charge and gate current components. In this section, a streamlined analytical approximation of the surface potential is presented. It excludes the effects of minority carriers and consequently is even simpler and more efficient than the one employed in the channel region.

In what follows,

$$\xi = 1 + G_{ov}/\sqrt{2} \tag{139}$$

and

$$x_{margin} = 10^{-7}\xi \tag{140}$$

For $|x_g| \leq x_{margin}$

$$x = x_g/\xi \tag{141}$$

For $x_g < -x_{margin}$, proceed in the following steps,

$$y_g = -x_g \tag{142}$$

$$z = 1.25 y_g/\xi \tag{143}$$

$$\eta = (1/2)\left\{z + 10 - \left[(z-6)^2 + 64\right]^{1/2}\right\} \tag{144}$$

$$a = (y_g - \eta)^2 + G_{ov}^2\,(\eta + 1) \tag{145}$$

$$c = 2\,(y_g - \eta) - G_{ov}^2 \tag{146}$$

$$\tau = -\eta + \log\left(a/G_{ov}^2\right) \tag{147}$$

$$y_0 = \eta + \sigma\,(a, c, \tau) \tag{148}$$

$$\Delta_0 = \exp(y_0) \tag{149}$$

$$p = 2\left(y_g - y_0\right) + G_{ov}^2\left(\Delta_0 - 1\right) \tag{150}$$

$$q = \left(y_g - y_0\right)^2 + G_{ov}^2\left(y_0 - \Delta_0 + 1\right) \tag{151}$$

$$x = -y_0 - \frac{2q}{p + \sqrt{p^2 - 2q\left(2 - G_{ov}^2\Delta_0\right)}} \tag{152}$$

For $x_g > x_{margin}$, compute

$$x_1 = 1.25 \tag{153}$$

$$x_{g1} = x_1 + G_{ov}\sqrt{\exp\left(-x_1\right) + x_1 - 1} \tag{154}$$

$$\overline{x} = \left(x_g/\xi\right)\left[1 + x_g\left(\xi x_1 - x_{g1}\right)/x_{g1}^2\right] \tag{155}$$

$$\overline{E} = \exp\left(-\overline{x}\right) \tag{156}$$

$$\omega = 1 - \overline{E} \tag{157}$$

$$x_0 = x_g + G_{ov}^2/2 - G_{ov}\left(x_g + G_{ov}^2/4 - \omega\right)^{1/2} \tag{158}$$

$$\Delta_1 = \exp(-x_0) \tag{159}$$

$$p = 2\left(x_g - x_0\right) + G_{ov}^2\left(1 - \Delta_1\right) \tag{160}$$

$$q = \left(x_g - x_0\right)^2 - G_{ov}^2\left(x_0 + \Delta_1 - 1\right) \tag{161}$$

$$x = x_0 + \frac{2q}{p + \sqrt{p^2 - 2q\left(2 - G_{ov}^2\Delta_1\right)}} \tag{162}$$

In the code, the evaluation of Δ_0 and Δ_1 is carefully ordered to avoid over/underflow problems.

18 Extrinsic Charge Model

The source and drain overlap regions are modelled as MOS capacitors. [12]

The charge of the source overlap region

$$Q_{\text{sov}} = W \cdot \mathbf{LOV} \cdot C_{\text{oxov}} \left(V_{\text{gs}} - \phi_{\text{sov}}\right) \tag{163}$$

The charge of the drain overlap region

$$Q_{\text{dov}} = W \cdot \mathbf{LOV} \cdot C_{\text{oxov}} \left(V_{\text{gd}} - \phi_{\text{dov}}\right) \tag{164}$$

The charge of the bulk overlap region

$$Q_{\text{bov}} = L \cdot \mathbf{CGBO} \cdot V_{\text{gb}} \tag{165}$$

Inner fringe charge correction [16]

$$\Delta Q_G = -\Delta Q_S - \Delta Q_D \tag{166}$$

$$\Delta Q_S = \mathbf{IFKJ} \cdot W(1 + \mathbf{IFCJ} V_{\text{sb}})(\mathbf{IFVBI} + V_{\text{sb}} - \phi_{\text{ss}})^{1/2} \tag{167}$$

$$\Delta Q_D = \mathbf{IFKJ} \cdot W(1 + \mathbf{IFCJ} V_{\text{db}})(\mathbf{IFVBI} + V_{\text{db}} - \phi_{\text{sd}})^{1/2} \tag{168}$$

Outer fringe charge

$$Q_{\text{ofs}} = W \cdot \mathbf{CF} \cdot V_{\text{gs}} \tag{169}$$

$$Q_{\text{ofd}} = W \cdot \mathbf{CF} \cdot V_{\text{gd}} \tag{170}$$

The terminal charges are given by

$$Q_G = Q_G^{(i)} + Q_{\text{sov}} + Q_{\text{dov}} + \Delta Q_G + Q_{\text{ofs}} + Q_{\text{ofd}} + Q_{\text{bov}} \tag{171}$$

$$Q_S = Q_S^{(i)} - Q_{\text{sov}} + \Delta Q_S - Q_{\text{ofs}} \tag{172}$$

$$Q_D = Q_D^{(i)} - Q_{\text{dov}} + \Delta Q_D - Q_{\text{ofd}} \tag{173}$$

$$Q_B = Q_B^{(i)} - Q_{\text{bov}} \tag{174}$$

where superscript (i) indicates the value given by the intrinsic ("core") SP model.

19 Gate Current Model [18]

The tunnelling gate current of MOSFET is physically modeled. The total gate current (I_g) is given by,

$$I_g = I_{gc} + I_{gsov} + I_{gdov} \tag{175}$$

Channel contribution

$$I_{gc} = I_{gc0} i_{gc} \tag{176}$$

$$I_{gc0} = WLJ_{gc} \tag{177}$$

$$J_{gc} = J_0 F_s \exp\left\{B\left[-\mathbf{GC1} + \frac{U_{oxm}}{\chi_B}\left(\mathbf{GC2} + \frac{\mathbf{GC3} \cdot U_{oxm}}{\chi_B}\right)\right]\right\} \tag{178}$$

$$U_{oxm} = \sqrt{V_{oxm}^2 + 10^{-6}} \tag{179}$$

Here, F_s is the supply function describing the difference of the population of carriers across the oxide in the mid-potential point, given by

$$F_s = \ln\left[\frac{1 + \Delta_{Si}}{1 + \Delta_{Si}\exp\left(-V_{gs}/V_t\right)}\right] \tag{180}$$

$$\Delta_{Si} = \exp\left[\left(\phi_{ss} - \alpha_b - V_x + \psi_t\right)/V_t\right] \tag{181}$$

$$\psi_t = \mathrm{MINA}\left(0, V_{ox} + D, 0.05\right) \tag{182}$$

$$D = \mathbf{GC0} \cdot V_t \tag{183}$$

$$i_{gc} = (1 - b)\,\frac{\sinh(x)}{x} + b\cosh(x) \tag{184}$$

$$x = \phi/\left(2u_0\right) \tag{185}$$

$$b = u_0/H \tag{186}$$

$$u_0 = \chi_B/\left[\mathbf{GC2} + 2\mathbf{GC3} \cdot \left(U_{oxm}/\chi_B\right)\right] \tag{187}$$

Source-drain partition

The partition of the gate current in the channel area into the source and drain is essential for the MOSFET compact modelling, which is accomplished in SP using the symmetrical linearization method.
The drain portion is given by

$$I_{gcd} = I_{gc0} i_{gcd} \tag{188}$$

$$i_{gcd} = \frac{i_{gc}}{2} - B_g \sinh(x) - A_g \frac{\sinh(x)}{x} \left[\coth(x) - \frac{1}{x}\right] \tag{189}$$

$$A_g = \left(1 - 3b + 3b^2\right)/2 \tag{190}$$

$$B_g = b\,(1 - b)\,/2 \tag{191}$$

and the source portion is given by

$$I_{gcs} = I_{gc} - I_{gcd} \tag{192}$$

The Eqs. (184) and (189) are written in a form that shows that there are no singularity at $x = 0$. Their implementation in the code is simpler and more efficient.

Source overlap region contribution

$$I_{gsov} = W \cdot \mathbf{LOV} \cdot J_{gsov} \tag{193}$$

$$J_{gsov} = J_0 F_{sovs} \exp\left\{B_{ov}\left[-\mathbf{GC1} + \frac{U_{oxovs}}{\chi_B}\left(\mathbf{GC2} + \frac{\mathbf{GC3} \cdot U_{oxovs}}{\chi_B}\right)\right]\right\} \tag{194}$$

$$U_{oxovs} = \sqrt{V_{oxovs}^2 + 10^{-6}} \tag{195}$$

The supply function, F_{sovs}, describing the difference of the population of carriers across the oxide in the source overlap region, given by

$$F_{sovs} = \ln\left[\frac{1 + \Delta_{Siovs}}{1 + \Delta_{Siovs} \exp\left(-V_{gs}/V_t\right)}\right] \tag{196}$$

$$\Delta_{Siovs} = \exp\left[\left(3.0 + \phi_{sov} + \psi_{tovs}\right)/V_t\right] \tag{197}$$

$$\psi_{tovs} = \mathrm{MINA}\left(0, V_{oxovs} + \mathbf{GC0} \cdot V_t, 0.05\right) \tag{198}$$

Drain overlap region contribution

$$I_{gdov} = W \cdot \mathbf{LOV} \cdot J_{gdov} \tag{199}$$

$$J_{gdov} = J_0 F_{sovd} \exp\left\{B_{ov}\left[-\mathbf{GC1} + \frac{U_{oxovd}}{\chi_B}\left(\mathbf{GC2} + \frac{\mathbf{GC3} \cdot U_{oxovd}}{\chi_B}\right)\right]\right\} \tag{200}$$

$$U_{oxovd} = \sqrt{V_{oxovd}^2 + 10^{-6}} \tag{201}$$

The supply function, F_{sovd}, describing the difference of the population of carriers across the oxide in the drain overlap region, given by

$$F_{sovd} = \ln\left[\frac{1 + \Delta_{Siovd}}{1 + \Delta_{Siovd} \exp\left(-V_{gd}/V_t\right)}\right] \tag{202}$$

$$\Delta_{Siovd} = \exp\left[\left(3.0 + \phi_{dov} + \psi_{tovd}\right)/V_t\right] \tag{203}$$

$$\psi_{tovd} = \mathrm{MINA}\left(0, V_{oxovd} + \mathbf{GC0} \cdot V_t, 0.05\right) \tag{204}$$

By setting **SW_IGATE** $\neq 1$, gate current model is turned off.

20 Substrate Current Model [13]

The substrate current of MOSFET due to impact ionization is given by

$$I_b = a_1 \cdot \exp\left[-a_2/\left(V_{ds} - a_3\phi\right)\right] \cdot I_d \tag{205}$$

$$a_1 = \mathbf{IIA1} + \mathbf{IIA1L} \cdot A_\mathrm{L} \tag{206}$$

$$a_2 = \mathbf{IIA2}\left[1 + a_4\left(\sqrt{V_x + 2\phi_b} - \sqrt{2\phi_b}\right)\right] \tag{207}$$

$$a_3 = \mathbf{IIA3} + \mathbf{IIA3L} \cdot A_\mathrm{L} \tag{208}$$

$$a_4 = \mathbf{IIA4} + \mathbf{IIA4L} \cdot A_\mathrm{L} \tag{209}$$

21 Total Terminal Currents

The effects of I_b and I_g on the gate, source, drain and body components are as follows

$$I_G = I_{gc} + I_{gsov} + I_{gdov} \tag{210}$$

$$I_S = I_S^{(i)} - \left(1 - \mathbf{IIPARTITION}\right) I_b - I_{gcs} S_g(x_g) - I_{gsov} \tag{211}$$

$$I_D = I_d^{(i)} + I_b - I_{gcd} S_g(x_g) - I_{gdov} \tag{212}$$

$$I_B = I_B^{(i)} - \mathbf{IIPARTITION} \cdot I_b - I_{gc}\left[1 - S_g(x_g)\right] \tag{213}$$

where $I_S^{(i)}$, $I_D^{(i)}$ and $I_B^{(i)}$ are terminal currents produced by the intrinsic ("core") SP model and

$$S_g(x_g) = \frac{1}{2}\left(1 + \frac{x_g}{\sqrt{x_g^2 + \varepsilon}}\right) \tag{214}$$

The computation of the impact ionization current can be turned off by setting parameter **SW_IMPACT**=0 (default) and turned on by setting **SW_IMPACT**=1.

22 Noise [15, 16]

Channel thermal noise

$$S_{I_d^2} = \frac{4k_B \cdot \mathbf{TABS}}{L_{red}^2} \left(\mu_m Q_{inv} + \mathbf{NDELTA} \frac{I_d \phi}{E_{crit}^2} \right) \tag{215}$$

$$Q_{inv} = WLC_{ox} \left(Q_I - Q_{CLM} \right) \tag{216}$$

$$E_{crit} = \mathbf{VSAT} / \mu_m \tag{217}$$

Flicker noise
If **SW_FLICKER**=0 (default)

$$S_{I_d^2}(f) = S_{I_d^2}(\text{drift}) + S_{I_d^2}(\text{diff}) \tag{218}$$

$$\begin{aligned} S_{I_d^2}(\text{drift}) = \frac{C_{ox} \phi_t I_d \mu_m}{\alpha_m \gamma_{FN} L_{red}^2 f^{\mathbf{NEF}}} & \\ \left\{ \left[\mathbf{NOIC} \cdot (V_m - 2 \cdot V_*) + B^* - u_n V_* \right] \alpha_m \phi \right. & \\ \left. + \left(A^* - 2B^* \cdot V_* + 3 \cdot \mathbf{NOIC} \cdot V_*^2 \right) \ln \left(q_+ / q_- \right) \right\} & \end{aligned} \tag{219}$$

$$\begin{aligned} S_{I_d^2}(\text{diff}) = \frac{C_{ox} \phi_t^2 I_d \mu_m}{\gamma_{FN} L_{red}^2 f^{\mathbf{NEF}}} & \\ \left[\left(\mathbf{NOIC} + u_n \right) \alpha_m \phi + \left(B^* - 2 \cdot \mathbf{NOIC} \cdot V_* \right) \ln \left(q_+ / q_- \right) \right] & \end{aligned} \tag{220}$$

$${}^1\gamma_{FN} = 10^{10} \quad \left[\text{m}^{-1} \right] \tag{221}$$

$$V_* = \phi_t \left(1 + \frac{G}{2\sqrt{x_m + 10^{-6}}} \right) \tag{222}$$

$$A^* = \mathbf{NOIA} \cdot q^2 / C_{ox}^2 \tag{223}$$

$$B^* = \mathbf{NOIB} \cdot q / C_{ox} \tag{224}$$

[1] In BSIM3 model, $\gamma_{FN} = 10^8\ \text{m}^{-1}$, whereas in BSIM4, $\gamma_{FN} = 10^{10}\ \text{m}^{-1}$.
$\mathbf{NOIA}_{\text{SP}} = \mathbf{NOIA}_{\text{BSIM4}} = 10^2 \mathbf{NOIA}_{\text{BSIM3}}$
$\mathbf{NOIB}_{\text{SP}} = \mathbf{NOIB}_{\text{BSIM4}} = 10^2 \mathbf{NOIB}_{\text{BSIM3}}$
$\mathbf{NOIC}_{\text{SP}} = \mathbf{NOIC}_{\text{BSIM4}} = 10^2 \mathbf{NOIC}_{\text{BSIM3}}$

$$u_n = \left(A^* - B^* V_* + \mathbf{NOIC} \cdot V_*^2\right) / (q_+ q_-) \tag{225}$$

$$q_+ = V_* + V_m + \alpha_m \phi \tag{226}$$

$$q_- = V_* + V_m - \alpha_m \phi \tag{227}$$

If **SW_FLICKER** is set to 1 then

$$S_{I_d^2} = \frac{\mathbf{KF} \cdot g_m^2}{C_{ox} W L f^{\mathbf{NEF}}} \tag{228}$$

Series resistances thermal noise

$$S_{R_D} = 4kT/r_{\text{drain}} \tag{229}$$

$$S_{R_S} = 4kT/r_{\text{source}} \tag{230}$$

$$S_{R_G} = 4kT/r_{\text{gate}} \tag{231}$$

where

$$r_{\text{drain}} = \mathbf{RSH} \cdot \mathbf{NRD} \tag{232}$$

$$r_{\text{source}} = \mathbf{RSH} \cdot \mathbf{NRS} \tag{233}$$

$$r_{\text{gate}} = \mathbf{RGSH} \frac{W_{\text{DR}}}{L_{\text{DR}} \cdot \mathbf{NF}} \tag{234}$$

Channel induced gate noise

$$S_{I_g^2} = \mathbf{DVDZ} \cdot \frac{\mathbf{TABS} \cdot 16 k_B \pi^2 f^2 W C_{\text{ox}} L_{\text{red}}^3}{\mu_m \alpha_m H^3} \left[\frac{\phi^4}{1728 H^2} - \phi^2 \left(\frac{1}{720} + \frac{H'}{144H}\right) + \frac{HH'}{12}\right] \tag{235}$$

where

$$H' = \frac{V_m/\alpha - V_t L_{\text{sat}}/L_{\text{red}}}{1 + L_{\text{sat}}/L_{\text{red}}} \tag{236}$$

Crosscorrelation coefficient

$$S_{I_g I_d} = j \frac{\mathbf{TABS} \cdot 8 k_B \pi f W C_{\text{ox}} L_{\text{red}}}{H^2} \left(\frac{H\phi}{12} - \frac{\phi^3}{144H}\right) \tag{237}$$

$$c = \frac{S_{I_g I_d}}{\sqrt{S_{I_g^2} \cdot S_{I_d^2}}} \tag{238}$$

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Appendix A Simple Model of the Lateral Gradient Factor

We present a motivation behind (22) in Section 5.
Assuming position independent

$$f = 1 - \frac{\varepsilon_{si}}{q\mathbf{NSUB}} \frac{\partial^2 \phi_s}{\partial y^2} \tag{A1}$$

is equivalent to a parabolic *f(y)* dependence

$$\phi_s = a(y - y_0)^2 + \phi_f \tag{A2}$$

where a, y_0 and ϕ_f are functions of the terminal voltages and

$$f = 1 - \frac{2\varepsilon_{si} a}{q\mathbf{NSUB}} \tag{A3}$$

With reference to boundary conditions

$$\phi_s(0) = V_{sb} + V_{bi} \tag{A4}$$

$$\phi_s(L) = \phi_s(0) + V_{ds} \tag{A5}$$

one finds

$$a = \frac{\xi}{L^2} \left(2 + \frac{V_{ds}}{\xi} + 2\sqrt{1 + \frac{V_{ds}}{\xi}} \right) \tag{A6}$$

where

$$\xi = V_{sb} + V_{bi} - \phi_f \tag{A7}$$

In view of the approximate nature of this analysis it is appropriate to linearize $a(V_{ds})$ dependence by neglecting V_{ds} under the square root in (A6). This preserves correct form for both $V_{ds} = 0$ and for $V_{ds} >> \xi$. Then from (A3)

$$f = 1 - \frac{8\varepsilon_{si}}{q\mathbf{N_{sub}} L^2} (V_{sb} + V_{bi} - \phi_f + \frac{V_{ds}}{4}) \tag{A8}$$

This is equivalent to (22) with

$$f_0 = 1 - \frac{8\varepsilon_{si}}{q\mathbf{N_{sub}} L^2} (V_{sb} + V_{bi} + \frac{V_{ds}}{4}) \tag{A9}$$

and

$$\mathbf{F_0 B_f} = \frac{8\varepsilon_{si} V_t}{q\mathbf{N_{sub}} L^2} \tag{A10}$$

A simple derivation presented here ignores the *f(W)* dependence [$\frac{\partial^2 \phi_s}{\partial z^2}$ term is dropped in (A1)] and predicts a rather simple *f(L)* dependence. This necessitates the introduction of empirical factors in section 5. In addition, variables x_f, V_{sbx} and V_{dsx} were introduced to satisfy the Gummel symmetry test. However, the main feature of (A8) which is a linear $f(\phi_f)$ dependence is quite physical and is implemented in **SP**. The decrease of f with V_{ds} and V_{sb} predicted by (A9) is linear and may result in negative f for large V_{ds} and V_{sb}. Hence the function form of f_0 is changed to (23) in order to assure $f_0 > 0$ for arbitrary large terminal voltages.

Appendix B Analytical Approximation for the Surface Potential [2, 19]

The results presented here extend our earlier work to arbitrary V_{gs}.
In what follows

$$\xi = 1 + \frac{G_f}{\sqrt{2}} \tag{B1}$$

x_{g23} and x_{23} are given by equations (70) and (72) in Section 8.

For $|x_g| < x_{\mathrm{margin}}$

$$x = x_g/\xi \tag{B2}$$

For $x_g < -x_{\mathrm{margin}}$, proceed in the following steps

$$y_g = -x_g \tag{B3}$$

$$z = 1.25 y_g/\xi \tag{B4}$$

$$\eta = (1/2)\left\{z + 10 - \left[(z-6)^2 + 64\right]^{1/2}\right\} \tag{B5}$$

$$a = (y_g - \eta)^2 + G_f^2(\eta + 1) \tag{B6}$$

$$c = 2(y_g - \eta) - G_f^2 \tag{B7}$$

$$\tau = -\eta + \ln(a/G_f^2) \tag{B8}$$

$$y_0 = \eta + \sigma(a, c, \tau) \tag{B9}$$

$$\Delta_0 = \exp(y_0) \tag{B10}$$

$$\Delta_1 = 1/\Delta_0 \tag{B11}$$

$$p = 2(y_g - y_0) + G_f^2[\Delta_0 - 1 + \Delta_n(2 - \Delta_0 - \Delta_1)] \tag{B12}$$

$$q = (y_g - y_0)^2 + G_f^2[y_0 - \Delta_0 + 1 + \Delta_n(\Delta_0 - \Delta_1 - 2y_0)] \tag{B13}$$

$$x = -y_0 - \frac{2q}{p + \sqrt{p^2 - 2q\left\{2 - G_f^2[\Delta_0 + \Delta_n(\Delta_1 - \Delta_0)]\right\}}} \tag{B14}$$

For $x_{\mathrm{margin}} < x_g < x_{g23}$ compute

$$\bar{x} = (x_g/\xi)[1 + x_g(\xi x_{23} - x_{g23})/x_{g23}^2] \tag{B15}$$

$$\bar{E} = \exp(-\bar{x}) \tag{B16}$$

$$\omega = 1 - \bar{E} - \Delta_n(\bar{E}^{-1} - \bar{E} - 2\bar{x}) \tag{B17}$$

$$x_0 = x_g + G_f^2/2 - G_f(x_g + G_f^2/4 - \omega)^{1/2} \tag{B18}$$

$$\Delta_0 = \exp(x_0) \tag{B19}$$

$$\Delta_1 = 1/\Delta_0 \tag{B20}$$

$$p = 2(x_g - x_0) + G_f^2[1 - \Delta_1 + \Delta_n(\Delta_0 + \Delta_1 - 2)] \tag{B21}$$

$$q = (x_g - x_0)^2 - G_f^2[x_0 + \Delta_1 - 1 + \Delta_n(\Delta_0 - \Delta_1 - 2x_0)] \tag{B22}$$

$$x = x_0 + \frac{2q}{p + \sqrt{p^2 - 2q\{2 - G_f^2[\Delta_1 + \Delta_n(\Delta_0 - \Delta_1)]\}}} \tag{B23}$$

Finally, for $x_g > x_{g23}$ (B19)-(B23) remain unchanged,but instead of (B18) x_0 is computed as follows:

$$x_{sub} = x_g + G_f^2/2 - G_f(x_g + G_f^2/4 - 1)^{1/2} \tag{B24}$$

$$\eta = \mathrm{MINA}(x_{sub}, x_n + 0.5 + 2.5f_s, 5) \tag{B25}$$

$$a = (x_g - \eta)^2 - G_f^2\eta + G_f^2 \tag{B26}$$

$$c = 2(x_g - \eta) + G_f^2 \tag{B27}$$

$$\tau = x_n - \eta + \ln(a/G^2) \tag{B28}$$

$$x_0 = \eta + \sigma(a, c, \tau) \tag{B29}$$

Appendix C Evaluation of $\phi = \phi_{sd} - \phi_{ss}$ for $x_g < x_{g23}$

We use normalized variable $\varphi = \phi/V_t$ which satisfies equation

$$\varphi^2 - 2x_{gs}\varphi = G_f^2 J(\varphi) \quad \text{(C1)}$$

where

$$\begin{aligned} J_\varphi = \quad & \varphi + E_s(e^{-\varphi} - 1) + \Delta_{ns}\left[E_s^{-1}(ke^{\varphi} - 1)\right. \\ & \left. -E_s(ke^{-\varphi} - 1) - 2x_s(k-1) - 2k\varphi\right] \end{aligned} \quad \text{(C2)}$$

E_s is given by (40) and

$$k = \exp(-V_{dse}/V_t) \quad \text{(C3)}$$

Variables E_s, Δ_{ns} and D_s used below are defined in section 6.

The approximate solution of (C1) which we use for $x_g < x_{g23}$ is given by

$$\varphi = 2q/\left(p + \sqrt{p^2 - 4\xi q}\right) \quad \text{(C4)}$$

where

$$q = G_f^2(1-k)D_s \quad \text{(C5)}$$

$$p = 2x_{gs} + G_f^2\left\{1 - E_s + k[\Delta_s + \Delta_{ns}(E_s - 2)]\right\} \quad \text{(C6)}$$

and

$$\xi = 1 - 0.5G_f^2\left[E_s + k\Delta_{ns}(E_s^{-1} - E_s)\right] \quad \text{(C7)}$$

Equation (C4) is used for $x_g < x_{g23}$ but remains accurate well above x_{g23}. Hence the problem of matching (C4) with expression $\phi = \phi_{sd} - \phi_{ss}$ used for $x_g > x_{g23}$ does not arise.

Appendix D Core Model Local Parameters

Effective channel dimensions: **L**, **W**

Oxide thickness: **TOX**

Channel doping: $\mathbf{N_{sub}}$

Flat-band voltage: $\mathbf{V_{fb}}$

Mobility model: **MU0**, $\mu_{\mathbf{E}}, \theta_{\mathbf{MU}}, \mathbf{CS}, \mathbf{X_{cor}}$

Saturation velocity model: $\mathbf{u_{sat}}, \mathbf{G_{hf}}, \mathbf{K_{sm}}, \mathbf{STX}$

Lateral field gradient parameters: $\mathbf{F_0}, \mathbf{A_f}, \mathbf{B_f}, \mathbf{C_f}, \mathbf{DF}, \mathbf{EF}$

Channel-length modulation: **CLM3**, $\mathbf{L_{q2d}}$

Series resistance model: $\mathbf{R_{t1}}, \mathbf{R_g}, \mathbf{RB}$

Triode-saturation transition parameter: $\mathbf{a_X}$

Polysilicon gate doping: **NP**

Quantum correction magnitude: **QMC**

Subthreshold slope parameter: **cT**

Appendix E Core Model Global Parameters

Parameters **TOX**, **DF**, **EF**, **MU0**, **CS**, **CLM3**, **STX**, **NP**, **QMC** and **RB** are both local and global. They are described in Appendix D above.

Geometry (channel length): **DL0**, **DLL**, **DLW**

Geometry (channel width): **DW0**, **DWL**, **DWW**, **DWP**

Flat-band voltage: **FB0**, **FB1**, **FB2**

Reverse short-channel effect: **FB3**, **FB4**, **FB5**, **FB6**, **FB7**

Substrate doping: **NSUB**, **LPKT**, **NPKT**, **YPKT**, **VNSUB**, **NSLP**

Mobility: **MU1**, **MU1W**, **MU2**, **MU3**, **NU0**, **NUL**, **NUW**

Saturation velocity, including gate bias dependence: **VSAT**, **ST0**, **ST1**

Triode to saturation transition: **AS0**, **ASL**, **S0**

Velocity field relation: **GH0**, **GH1**, **GH2**, **GH3**, **GH4**

Lateral Gradient Factor: **FL1**, **FL2**, **AF0**, **AFL**, **BFL**, **CF0**, **CFL**, **KL**, **KW**

Channel-length modulation: **CLM0**, **CLM1**, **CLM2**, **GDL**

Series resistance: **R0**, **R1**, **R2**, **R3**, **R4**, **R5**, **R6**

subthreshold slope (scaling of interface state density): **ITL**

Appendix F Scaling Equations

The drawn channel dimensions are denoted as L_{DR}, W_{DR} (in m) or as $L_{DR,\mu m}$, $W_{DR,\mu m}$ (in μm). The minimum device dimensions for a given technology are L_{REF}, W_{REF} (in m) or $L_{REF,\mu m}, W_{REF,\mu m}$ (in μm).

Effective channel length in μm

$$L_{\mu m} = L_{DR,\mu m} - \mathbf{DL0} - \mathbf{DLL} \cdot A_L - \mathbf{DLW} \cdot B_W \tag{F1}$$

where

$$A_L = \frac{1}{L_{REF,\mu m}} - \frac{1}{L_{DR,\mu m}} \tag{F2}$$

$$B_W = \frac{1}{W_{REF,\mu m}} - \frac{1}{W_{DR,\mu m}} \tag{F3}$$

Effective channel length in m

$$L = 10^{-6} L_{\mu m} \tag{F4}$$

Effective channel width in μm

$$W_{\mu m} = W_{DR,\mu m} - \mathbf{DW0} - \mathbf{DWL} \cdot A_L - \mathbf{DWW} \cdot B_W - \mathbf{DWP} \cdot A_L \cdot B_W \tag{F5}$$

Effective channel width in m

$$W = 10^{-6} W_{\mu m} \tag{F6}$$

Total oxide capacitance

$$C_{oxt} = C_{ox} \left(L + 10^{-6} \cdot \mathbf{DLQ}\right) \left(W + 10^{-6} \cdot \mathbf{DWQ}\right) \tag{F7}$$

Flat-band voltage (which in SP includes reverse short-channel effect if any)

$$\mathbf{V_{fb}} = \mathbf{FB0} + \frac{\mathbf{FB1}}{W_{\mu m}} + \frac{\mathbf{FB2}}{W_{\mu m}^2} + \Delta V_{RSE} \tag{F8}$$

$$\Delta V_{RSE} = \left(1 + \frac{\mathbf{FB3}}{W_{\mu m}} + \frac{\mathbf{FB4}}{W_{\mu m}^2}\right) \cdot \left(\frac{\mathbf{FB5}}{L_{DR,\mu m}} + \frac{\mathbf{FB6}}{L_{DR,\mu m}^2} + \frac{\mathbf{FB7}}{L_{DR,\mu m}^3}\right) \tag{F9}$$

Drift velocity local parameters

$$\mathbf{K_{sm}} = \mathbf{ST0} + \mathbf{ST1} \cdot B_W \tag{F10}$$

$$\mathbf{G_{hf}} = \left(\mathbf{GH0} + \frac{\mathbf{GH1}}{L_{\mu m}} + \frac{\mathbf{GH2}}{L_{\mu m}^2}\right) \cdot \left(1 + \frac{\mathbf{GH3}}{W_{\mu m}}\right) + \frac{\mathbf{GH4}}{L_{\mu m}^2 W_{\mu m}^2} \tag{F11}$$

Local parameters for the lateral field gradient

$$\mathbf{F_0} = 1 - \frac{\mathbf{FL1}}{L_{\mu m}} - \frac{\mathbf{FL2}}{L_{\mu m}^2} \tag{F12}$$

$$\mathbf{A_f} = \left(\mathbf{AF0} + \frac{\mathbf{AFL}}{L_{\mu m}^2}\right) \cdot C_{LW} \tag{F13}$$

$$\mathbf{B_f} = \min\left\{\frac{\mathbf{BFL}}{L_{\mu m}^2}, \frac{1 - \mathbf{F_0}}{\mathbf{F_0} + 0.01}\right\} \tag{F14}$$

$$\mathbf{C_f} = \left(\mathbf{CF0} + \frac{\mathbf{CFL}}{L_{\mu m}^2}\right)\left(1 + \mathbf{KL} \cdot \frac{A_L}{L_{\mu m}}\right) C_{LW} \tag{F15}$$

and

$$C_{LW} = \frac{1}{1 + \mathbf{KW}/W_{\mu m}} \tag{F16}$$

Mobility model parameter

$$\mu_{\mathbf{E}} = \mathbf{MU1}\left(1 + \frac{\mathbf{MU1W}}{W_{\mu m}}\right) \tag{F17}$$

$$\theta_{MU} = \mathbf{MU2}\left(1 + \frac{\mathbf{MU3}}{W_{\mu m}}\right) \tag{F18}$$

Mobility model parameter (correction for ”non-universality”)

$$\mathbf{X_{cor}} = \mathbf{NU0} + \frac{\mathbf{NUL}}{L_{\mu m}}(1 + \mathbf{NUW} \cdot W_{\mu m}) \tag{F19}$$

Bias-independent part of the series resistance

$$\mathbf{R_{t1}} = \mathbf{R0} + \mathbf{R1} \cdot A_L + \mathbf{R2} \cdot B_W + \mathbf{R3} \cdot A_L \cdot B_W \tag{F20}$$

Constant used to describe gate bias dependence of the series resistance

$$\mathbf{R_g} = \mathbf{R4} + \mathbf{R5} \cdot A_L + \mathbf{R6} \cdot W_{\mu\mathrm{m}} \tag{F21}$$

Triode-saturation transition variable

$$a_{\mathbf{x}} = \frac{\mathbf{AS0}}{1 + \mathbf{ASL}/L_{\mu m}} \tag{F22}$$

Characteristic length of the quasi-2D theory

$$\mathbf{L_{q2d}} = (1 + \mathbf{GDL} \cdot L_{\mu m})(\mathbf{CLM0} + \mathbf{CLM1} \cdot A_L + \mathbf{CLM2} \cdot B_W)\sqrt{2 \cdot 10^{-7} \varepsilon_{si}/C_{OX}} \tag{F23}$$

Subthreshold slope parameter

$$\mathbf{cT} = 1 + \frac{T_n}{\mathbf{TABS}} \cdot \frac{\mathbf{ITL}}{L_{\mu m}^2} \tag{F24}$$

Appendix G Ranges of SP Parameters

In what follows $L_{\mathrm{CLAMP}}(W_{\mathrm{CLAMP}})$ is a minimum drawn channel length (width) for a particular parameter set. L_{CLAMP} and W_{CLAMP} are selected by users before extracting model parameters and can be set as minimum channel length for a modelled process or below that if extrapolation to smaller geometries is intended. Reducing L_{CLAMP} or W_{CLAMP} narrows down the allowed range of some parameters.
Default values

$$L_{\mathrm{CLAMP}} = 0.18 \cdot 10^{-6} m \tag{G1}$$

$$W_{\mathrm{CLAMP}} = 0.6 \cdot 10^{-6} m \tag{G2}$$

The following notations are used in the tables below.

$$A_{mr} = \frac{1}{L_{\mathrm{CLAMP},\mu m}} - \frac{1}{L_{\mathrm{REF},\mu m}} + 10^{-10} \tag{G3}$$

$$B_{mr} = \frac{1}{W_{\mathrm{CLAMP},\mu m}} - \frac{1}{W_{\mathrm{REF},\mu m}} + 10^{-10} \tag{G4}$$

where

$$L_{\mathrm{CLAMP},\mu m} = 10^{6} \cdot L_{\mathrm{CLAMP}} \tag{G5}$$

$$W_{\mathrm{CLAMP},\mu m} = 10^{6} \cdot W_{\mathrm{CLAMP}} \tag{G6}$$

Table 1: Process parameters group

Parameter	Unit	Description	Default	MIN	MAX
ITL	μm^2	Interface states scaling factor	0	0	$2P_L^2 L^2_{\text{CLAMP},\mu m}$
LPKT	μm	Pocket length	0	$-\frac{3}{4}P_L L_{\text{CLAMP},\mu m}$	$9L_{\text{CLAMP},\mu m}$
NP	cm^{-3}	Polysilicon doping	10^{22}	$\max(3 \cdot 10^{19}, 80/\mathbf{TOX}^2)$ (See Note[2])	none
NSUB	cm^{-3}	Substrate doping	$5 \cdot 10^{17}$	10^{15}	$5 \cdot 10^{18}$
QMC	None	QM correction factor	0	0	$\min(0.6, 3 \cdot 10^{26} \cdot \mathbf{TOX}/\mathbf{NSUB})$
TOX	m	Oxide thickness	$4 \cdot 10^{-9}$	10^{-9}	$2 \cdot 10^{-7}$

At present, $P_L = 0.2$.

[2]Setting **NP**=0 or **NP** $> 10^{28}\text{m}^{-3}$ turns off polysilicon depletion effect.

Table 2: Effective geometry group

Parameter	Unit	Description	Default	MIN	MAX
DL0	μm	Channel length offset	0		
DLL	μm^2	Channel length adjustment (L)	0	See Note [3]	
DLW	μm^2	Channel length adjustment (W)	0		
DW0	μm	Channel width offset	0		
DWL	μm^2	Channel width adjustment (L)	0		
DWW	μm^2	Channel width adjustment (W)	0	See Note [4]	
DWP	μm^3	Channel width perimeter factor	0		
DLQ	μm	Decoupling parameter	0	$-L_{\mu m}/2$	none
DWQ	μm	Decoupling parameter	0	$-W_{\mu m}/2$	none

[3]Instead of limiting the values of **DL0**, **DLL** and **DLW**, **SP** sets the channel length offset as

$$DL_{\mu m} = \mathbf{DL0} + \mathbf{DLL} \cdot A_L + \mathbf{DLW} \cdot B_W \tag{G7}$$

and the effective channel length (in μm) as

$$L_{\mu m} = \max\{L_{\mathrm{DR},\mu m} - DL_{\mu m}, P_L L_{\mathrm{CLAMP},\mu m}\} \tag{G8}$$

[4]Instead of limiting parameter values of **DW0**, **DWL**, **DWW** and **DWP**, SP sets the channel width offset as

$$DW_{\mu m} = \mathbf{DW0} + \mathbf{DWL} \cdot A_L + \mathbf{DWW} \cdot B_W + \mathbf{DWP} \cdot A_L \cdot B_W \tag{G9}$$

and the effective channel length (in μm) as

$$W_{\mu m} = \max\{W_{\mathrm{DR},\mu m} - DW_{\mu m}, P_W W_{\mathrm{CLAMP},\mu m}\} \tag{G10}$$

At present, $P_W = 1/4$.

Table 3: Mobility group

Parameter	Unit	Description	Default	MIN	MAX
MU0	$\mathrm{cm}^2/\mathrm{Vs}$	Low-field mobility	500	0.01	10^4
NU0	V^{-1}	Non-universality factor	0	0	1
NUL	μm	Non-universality factor(L)	0	See Note [5]	
NUW	μm^{-1}	Non-universality factor(W)	0		
MU1	m/V	Magnitude of the vertical field dependence	0.5	0	$5 \cdot 10^8\mathbf{TOX}$
MU1W	μm	Scaling parameter (W)	0	$-0.9P_W W_{\mathrm{CLAMP}\mu m}$	$0.9P_W W_{\mathrm{CLAMP}\mu m}$
MU2	None	Sharpness of the vertical field dependence	1.5	0	3
MU3	μm	Scaling parameter(W)	0	$-0.9P_W W_{\mathrm{CLAMP}\mu m}$	$0.9P_W W_{\mathrm{CLAMP}\mu m}$
CS	None	Coulomb scattering	0	0	10

[5]Instead of limiting **NU0**, **NUL** and **NUW**, SP sets

$$\mathbf{X_{cor}} = \max\{\mathbf{X_{cor}}, 0\} \tag{G11}$$

Table 4: Series resistance group

Parameter	Unit	Description	Default	MIN	MAX
R0	$\Omega \cdot \mathrm{m}$	Fixed component of series resistance	$2 \cdot 10^{-3}$	See Note [6]	
R1	$\Omega \cdot \mathrm{m} \cdot \mu\mathrm{m}$	Scaling factor(L)	0		
R2	$\Omega \cdot \mathrm{m} \cdot \mu\mathrm{m}$	Scaling factor(W)	0		
R3	$\Omega \cdot \mathrm{m} \cdot \mu\mathrm{m}^2$	Scaling factor(L,W)	0		
R4	V^{-1}	Gate bias dependence	0	0	None
R5	$\mu\mathrm{m/V}$	Scaling factor(L) for gate bias dependence	0.02	$-\frac{P_L}{2}\mathbf{R_4} L_{\mathrm{CLAMP},\mu\mathrm{m}}$	$\frac{\mathbf{R_4}}{2A_{mr}}$
R6	$\mu\mathrm{m/V}$	Scaling factor(W) for gate bias dependence	0	See Note [7]	
RB	V^{-1}	Back bias factor	0	0	1.0

[6] Instead of limiting the values of **R0**, **R1**, **R2** and **R3**, SP sets

$$\mathbf{R_{t1}} = \max\{\mathbf{R_0} + \mathbf{R_1} \cdot A_L + \mathbf{R_2} \cdot B_W + \mathbf{R_3} \cdot A_L \cdot B_W, 0\} \quad \text{(G12)}$$

[7] Instead of limiting the values of **R6**, SP sets

$$\mathbf{R_g} = \max\{\mathbf{R_4} + \mathbf{R_5} \cdot A_L + \mathbf{R_6} \cdot W_{\mu\mathrm{m}}, 0\} \quad \text{(G13)}$$

Table 5: Velocity saturation group

Parameter	Unit	Description	Default	MIN	MAX
VSAT	m/s	Saturation velocity	80,000	50,000	150,000
ST0	V^{-1}	Gate bias dependence of saturation velocity	0	0	0.3
ST1	μm/V	Adjustment of saturation velocity (W)	0	$ST1_{min}$ (See Note [8])	$ST1_{max}$ (See Note [8])
STX	V^{-1}	Back bias dependence of saturation velocity	0	0	1
GH0	None	Grotjohn/Hofflinger (GH)factor	0.5	0.05	5
GH1	μm	GH Scaling parameter (L^{-1})	0	See Note [9]	
GH2	μm^2	GH Scaling parameter (L^{-2})	0	See Note [9]	
GH3	μm^3	GH Scaling parameter ($L^{-2}W^{-1}$)	0	See Note [9]	
GH4	μm^4	GH Scaling parameter ($L^{-2}W^{-2}$)	0	See Note [9]	
AS0	None	Transition from triode to saturation	12	6	100
ASL	None	Scaling factor(L) for triode-saturation transition	0.6	See Note [10]	
S0	None	V_{dsat} adjustment	0.98	0.9	0.99

[8]

$$\mathrm{ST1_{min}} = -\min\{(0.3 - \mathbf{ST0})/B_{mr}, \mathbf{ST0} \cdot W_{\mathrm{CLAMP},\mu\mathrm{m}}\} \tag{G14}$$

$$\mathrm{ST1_{max}} = \min\{(0.3 - \mathbf{ST0})W_{\mathrm{CLAMP},\mu\mathrm{m}}, \mathbf{ST0}/B_{mr}\} \tag{G15}$$

[9]Instead of limiting the values of **GH1**, **GH2**, **GH3** and **GH4**, SP forces $\mathbf{G_{hf}}$ to be in the range [0.05, 5]:

$$\mathbf{G_{hf}} = \min\left\{5, \max\left[0.05, \left(\mathbf{GH0} + \frac{\mathbf{GH1}}{L_{\mu\mathrm{m}}} + \frac{\mathbf{GH2}}{L_{\mu\mathrm{m}}^2}\right)\left(1 + \frac{\mathbf{GH3}}{W_{\mu\mathrm{m}}}\right) + \frac{\mathbf{GH4}}{L_{\mu\mathrm{m}}^2 W_{\mu\mathrm{m}}^2}\right]\right\} \tag{G16}$$

Table 6: Flat-band voltage group

Parameter	Unit	Description	Default
FB0	V	V_{fb} for long wide devices (L, W $\rightarrow \infty$)	-1
FB1	V·μm	Scaling parameter (W^{-1})	0
FB2	V·μm^2	Scaling parameter (W^{-2})	0
FB3	μm	RSE parameter (W^{-1})	0
FB4	μm^2	RSE parameter (W^{-2})	0
FB5	V·μm	RSE parameter (L^{-1})	0
FB6	V·μm^2	RSE parameter (L^{-2})	0
FB7	V·μm^3	RSE parameter (L^{-3})	0

There are no limits on flat-band voltage parameters.

[10]Instead of limiting the values of **ASL**, SP forces $\mathbf{a_x}$ to be in the range [2,20];

$$\mathbf{a_x} = \min\{20, \max\{2, \mathbf{a_x}\}\} \tag{G17}$$

Table 7: Lateral gradient factor group

Parameter	Unit	Description	Default	MIN	MAX
FL1	μm	Scaling parameter for $\mathbf{F_0}$	0.1	See Note [11]	
FL2	μm^2	Scaling parameter for $\mathbf{F_0}$	0.01		
AF0	V^{-1}	Scaling parameter for $\mathbf{A_f}$	0.004	0	10
AFL	μm^2/V	Scaling parameter for $\mathbf{A_f}$	0	-**AF0**$\cdot P_L^2 L_{\text{CLAMP},\mu\text{m}}^2$	10
BFL	μm^2/V	Scaling parameter for $\mathbf{B_f}$	0.015	0	10
CF0	V^{-1}	Scaling parameter for $\mathbf{C_f}$	0.0005	0	10
CFL	μm^2/V	Scaling parameter for $\mathbf{C_f}$	0.01	-**CF0**$\cdot P_L^2 L_{\text{CLAMP},\mu m}^2$	10
KL	μm^2	Scaling parameter for C_{LW}	0	-*KL0* (See Note [12])	*KL0*
KW	μm	Scaling parameter for C_{LW}	0	$-0.9 P_W W_{\text{CLAMP},\mu\text{m}}$	10
DF	None	Sharpness of $f(V_{\text{ds}})$ dependence	0	0	3
EF	None	Sharpness of $f(V_{\text{sb}})$ dependence	0	0	3

[10]Instead of limiting the values of **FL1** and **FL2**, SP forces $\mathbf{F_0}$ to be in the range [0.001, 1]:

$$\mathbf{F}_0 = \min\{1, \max\{0.001, \mathbf{F}_0\}\} \tag{G18}$$

Table 8: Channel length modulation group

Parameter	Unit	Description	Default	MIN	MAX
CLM0	None	$\mathbf{L_{q2d}}$ parameter	0.1	0	none
CLM1	μm	$\mathbf{L_{q2d}}$ scaling parameter(L)	0	$-\frac{1}{2}\mathbf{CLM0}\cdot L_{\mathrm{CLAMP},\mu m}$	$\min\{10, \mathbf{CLM0}/2A_{mr}\}$
CLM2	μm	$\mathbf{L_{q2d}}$ scaling parameter(W)	0	$-\frac{1}{2}\mathbf{CLM0}\cdot W_{\mathrm{CLAMP},\mu m}$	$\min\{10, \mathbf{CLM0}/2B_{mr}\}$
CLM3	V^{-1}	Logarithm dependence factor	10	0	1000
GDL	$\mu\mathrm{m}^{-1}$	Scaling parameter(L)	0	0	0.9

[11]Instead of limiting the values of **GDS1** and **GDS2**, SP forces

$$\frac{\partial}{\partial V_{\mathrm{dsx}}}\left(\frac{F_0}{f_0} - 1 - \mathbf{B_f} V_{\mathrm{sbx1}}\right) > 0 \tag{G19}$$

[12]

$$KL0 = min\{3.6L^2_{\mathrm{CLAMP},\mu m}, 0.9L_{\mathrm{CLAMP},\mu m}/A_{mr}\} \tag{G20}$$

Appendix H Temperature dependence (-55° to 150°)

SP uses up to 13 temperature coefficients

Flat-band voltage: **TK_VFB0**, **TK_VFBL**, **TK_VFBW**, **TK_VFBP**.

Mobility: **TK_MU0**, **TK_MUW**, **TK_MUL**, **TK_MUP**, **TK_MU1**, **TK_THM**, **TK_CS**.

Saturation velocity: **TK_VS**, **TK_AS**.

Coefficients **TK_VFBL**, **TK_VFBW**, **TK_VFBP**, **TK_MUL**, **TK_MUP** and **TK_AS** are expected to be zero for mature processes.

The temperature dependence of bulk and surface potentials is not adjusted and is obtained essentially from the first principles. The temperature dependence of the flat-band voltage, mobility and saturation velocity is as follows. In these equations T_n is nominal temperature and

$$\Delta T = \mathbf{TABS} - T_n \tag{H1}$$

Flat-band voltage

$$\mathrm{V_{fb}} = \mathrm{V_{fb}}(T_n) + \frac{k_B \Delta T}{q}\left(\mathbf{TK\_VFB} + \frac{\mathbf{TK\_VFBL}}{L_{\mu\mathrm{m}}} + \frac{\mathbf{TK\_VFBW}}{W_{\mu\mathrm{m}}} + \frac{\mathbf{TK\_VFBP}}{W_{\mu\mathrm{m}} L_{\mu\mathrm{m}}}\right) \tag{H2}$$

Mobility

$$\mathbf{MU0} = \mathbf{MU0}(T_n)\left(\frac{T_n}{\mathbf{TABS}}\right)^{n_{\mu 0}} \tag{H3}$$

$$n_{\mu 0} = \mathbf{TK\_MU0} + \frac{\Delta T}{T_n}\left(\frac{\mathbf{TK\_MUL}}{L_{\mu\mathrm{m}}} + \frac{\mathbf{TK\_MUW}}{W_{\mu\mathrm{m}}} + \frac{\mathbf{TK\_MUP}}{W_{\mu\mathrm{m}} L_{\mu\mathrm{m}}}\right) \tag{H4}$$

$$\theta_{mu} = \theta_{mu}(T_n)\left(\frac{T_n}{\mathbf{TABS}}\right)^{\mathbf{TK\_THM}} \tag{H5}$$

$$\mu_{\mathbf{E}} = \mu_E(T_n)\frac{1 + \mathbf{TK\_MU1}\exp(\Delta T/20)}{1 + \mathbf{TK\_MU1}} \tag{H6}$$

$$\mathbf{X_{cor}} = \mathrm{X_{cor}}(T_n)\left(\frac{T_n}{\mathbf{TABS}}\right)^{n_{\mu 0}} \tag{H7}$$

$$\mathbf{CS} = \mathrm{CS}(T_n)\left(\frac{T_n}{\mathbf{TABS}}\right)^{\mathbf{TK\_CS}} \tag{H8}$$

Saturation velocity

$$\mathbf{VSAT} = \mathrm{VSAT}(T_n)(1 + \mathbf{TK\_VS} \cdot \Delta T) \tag{H9}$$

$$\mathbf{G_{hf}} = G_{hf}(T_n)\frac{1 + \mathbf{TK\_AS}/W_{\mu m}}{1 + (\mathbf{TK\_AS}/W_{\mu m})\exp(\Delta T/20)} \tag{H10}$$

The default values and ranges for temperature coefficients are given in the table below.

Table 9: Temperature coefficients

Parameter	Unit	Description	Default	MIN	MAX
TK_VFB0	None	$V_{fb}(T)$ parameter	0	None	None
TK_VFBL	μm	$V_{fb}(T)$ scaling parameter(L)	0	None	None
TK_VFBW	μm	$V_{fb}(T)$ scaling parameter(W)	0	None	None
TK_VFBP	μm^2	$V_{fb}(T)$ scaling parameter(LW)	0	None	None
TK_MU0	None	MU0(T) parameter	1.5	See Note [13]	
TK_MUL	μm	MU0(T) scaling parameter(L)	0		
TK_MUW	μm	MU0(T) scaling parameter(W)	0		
TK_MUP	μm^2	MU0(T) scaling parameter(LW)	0		
TK_MU1	None	μ_E(T) parameter	0	0	0.1
TK_THM	None	θ_{mu}(T) parameter	0	-5	5
TK_CS	None	CS(T) parameter	0	-5	5
TK_VS	K^{-1}	VSAT(T) parameter	0	-0.005	0.005
TK_AS	μm	A_s(T) parameter	0	0	0.1

[13] Instead of limiting **TK_MU0**, **TK_MUL**, **TK_MUW** and **TK_MUP**, SP sets

$$n_{\mu 0} = \min\left\{5, \max\left[-5, \mathbf{TK\_MU0} + \frac{\Delta T}{T_n}\left(\frac{\mathbf{TK\_MUL}}{L_{\mu m}} + \frac{\mathbf{TK\_MUW}}{W_{\mu m}} + \frac{\mathbf{TK\_MUP}}{L_{\mu m} W_{\mu m}}\right)\right]\right\} \tag{H11}$$

Appendix I   Extrinsic Model Parameters

Table 10: Overlap Charge Parameters

Parameter	Unit	Description	Default	MIN	MAX
TOXOV	m	Overlap oxide thickness	**TOX**	10^{-9}	2×10^{-7}
NOV	cm^{-3}	Overlap doping	$5 \cdot 10^{19}$	10^{18}	$5 \cdot 10^{20}$
LOV	m	Overlap length	0	0	L_{CLAMP}
IFKJ	$\mathrm{C}/V^{1/2}$	Fringe capacitance parameter	0	0	None
IFCJ	1/V	Fringe capacitance parameter	0	0	None
IFVBI	V	Built in potential	1.2	1.12 (See Note[14])	2
CF	F/m	Out fringe capacitance per unit width	0	none	
CGBO	F/m	Bulk overlap capacitance per unit length	0	none	

Table 11: Gate Current Parameters

Parameter	Unit	Description	Default	MIN	MAX
GC0	none	Tunnelling energy adjustment	0	-10	10
GC1	none	Gate current overall level	1	0	10
GC2[15]	none	$\log I_{\mathrm{gate}} - V_g$ slope	1	0	10
GC3	none	$\log I_{\mathrm{gate}} - V_g$ curvature	0	-2	2

[14] In addition SP uses soft clamping to assure

$$\mathbf{IFVBI} + V_{\mathrm{sb}} - \phi_{ss} > 10^{-3} \tag{I1}$$

[15] In SP code if **GC3** < 0, then eq. (187) is modified as follows:

$$u_0 = \chi_B / \left(\mathbf{GC2} + 2\mathbf{GC3} \cdot z_g\right) \tag{I2}$$

$$z_g = \mathrm{MINA}\left(U_{oxm}/\chi_B, -\mathbf{GC2}/2\mathbf{GC3}, 10^{-12}\right) \tag{I3}$$

Table 12: Impact Ionization Substrate Current Parameters

Parameter	Unit	Description	Default	MIN	MAX
IIA1	none	Substrate current parameter	1	0	20
IIA2	V	Substrate current parameter	10	1	20
IIA3	none	Substrate current parameter	0.5	0.1	1.0
IIA4	$V^{-1/2}$	Substrate current parameter	0	0	1
IIA1L	μm	Substrate current scaling parameter	0	-1	1
IIA3L	μm	Substrate current scaling parameter	0	-1	1
IIA4L	$\mu m/V^{1/2}$	Substrate current scaling parameter	0	-1	1
IIPARTITION	none	Partition parameter	1	0	1

Table 13: Noise Parameters

Parameter	Unit	Description	Default	MIN	MAX
NDELTA	none	Thermal noise parameter	0	0	10
NOIA	$m^{-3}V^{-1}C^{-1}$	Flicker noise parameter	3×10^{22}	0	none
NOIB	$m^{-1}V^{-1}C^{-1}$	Flicker noise parameter	4×10^{7}	0	
NOIC	$mV^{-1}C^{-1}$	Flicker noise parameter	0	0	
NEF	none	Flicker noise parameter	1	0	2
DVDZ	none	Channel-induced gate noise parameter	1	0	10
KF	$A \cdot s^{\mathbf{NEF}-1}V^{-1}$	Legacy flicker noise parameter	0	0	none

Table 14: Series Resistances Parameters

Parameter	Unit	Description	Default	MIN	MAX
RSH	Ω/square	Source-drain sheet resistance	0	0	none
RGSH	Ω/square	Gate sheet resistance	0	0	
NRS	none	Number of squares in source	0	0	
NRD	none	Number of squares in drain	0	0	
NF	none	Number of fingers	1	1	

Table 15: Extrinsic Model Switches

Switch	Description	Default
SW_BSIMQOV	=1 use BSIM extrinsic charge model; $\neq 1$ use SP extrinsic charge model	0
SW_IGATE	=1 turn on gate current computation; $\neq 1$ turn off gate current computation	0
SW_IMPACT	=1 turn on impact ionization current computation; $\neq 1$ turn off impact ionization current computation	0
SW_RSRD	=1 include additional source and drain nodes; $\neq 1$ collapse additional source and drain nodes	0
SW_RG	=1 include additional gate node; $\neq 1$ collapse additional gate node	0
SW_FLICKER	=1 use g_m-based flicker noise model; $\neq 1$ use NOI model	0

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